AT2020hur: A Possible Optical Counterpart of FRB 180916B

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Abstract

The physical origin of fast radio bursts (FRBs) remains unclear. Finding multiwavelength counterparts of FRBs can provide a breakthrough for understanding their nature. In this work, we perform a systematic search for astronomical transients whose positions are consistent with FRBs. We find an unclassified optical transient AT2020hur (α = 01°58′00″.750 ± 1″, δ = 65°43′00″.530 ± 1″) that is spatially coincident with the repeating FRB 180916B (α = 01°58′00″.7502 ± 2.3 mas, δ = 65°43′00″.3152 ± 2.3 mas; Marcote et al. 2020). The chance possibility of the AT2020hur–FRB 180916B association is about 0.04%, which corresponds to a significance of 3.5σ. We develop a giant flare (GF) afterglow model to fit AT2020hur. Although the GF afterglow model can interpret the observations of AT2020hur, the derived kinetic energy of such a GF is at least three orders of magnitude larger than that of a typical GF, and a lot of fine-tuning and coincidences are required for this model. Another possible explanation is that AT2020hur might consist of two or more optical flares originating from the FRB source, e.g., fast optical bursts produced by the inverse Compton scattering of FRB emission. Besides, AT2020hur is located in one of the activity windows of FRB 180916B, which provides independent support for the association. This coincidence may be due to the optical counterparts being subject to the same periodic modulation as FRB 180916B, as implied by the prompt FRB counterparts. Future simultaneous observations of FRBs and their optical counterparts may help to reveal their physical origin.

Unified Astronomy Thesaurus concepts: Radio bursts (1339); Radio transient sources (2008); Magnetars (992)

1. Introduction

Fast radio bursts (FRBs) are transient radio pulses of millisecond duration with extremely high brightness temperatures (e.g., Lorimer et al. 2007; Thornton et al. 2013; Cordes & Chatterjee 2019; Petroff et al. 2019), and their physical origin remains a puzzle (see Katz 2018; Cordes & Chatterjee 2019; Petroff et al. 2019; Platts et al. 2019; Zhang 2020; Xiao et al. 2021). They usually have a large dispersion measure (DM), exceeding the Galactic contribution, which suggests that most FRBs are extragalactic (e.g., Lorimer et al. 2007; Thornton et al. 2013). FRB 200428 is the first discovered Galactic FRB to be associated with an X-ray burst from the Galactic magnetar SGR 1935+2154 (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020b; Mereghetti et al. 2020; Li et al. 2021a; Ridnaia et al. 2021; Tavani et al. 2021). The association between FRB 200428 and the X-ray burst has been discussed in relation to various models (e.g., Dai 2020; Lu et al. 2020; Lyutikov & Popov 2020; Margalit et al. 2020). The discovery of FRB 200428 suggests that at least some FRBs are of magnetar origin.

Most FRBs appear to be one-offs, and only about 20 FRBs are now known to repeat. In general, repeating FRBs seem to repeat in an irregular way. However, a period of 16.35 days, with a ~5 day active window, has been reported for FRB 180916B (CHIME/FRB Collaboration et al. 2020a). Follow-up broadband radio observations of FRB 180916B updated the period to 16.29 days, with a 6.1 day active window (Aggarwal et al. 2020; Marthi et al. 2020; Sand et al. 2020; Pastor-Marazuela et al. 2021). Several models were proposed to explain the periodic activity of FRB 180916B (e.g., Dai & Zhong 2020; Ioka & Zhang 2020; Levin et al. 2020; Lyutikov et al. 2020; Tong et al. 2020; Yang & Zou 2020; Zanazzi & Lai 2020; Deng et al. 2021; Geng et al. 2021; Li et al. 2021b; Wei et al. 2022). Besides, a possible period of ~157 days for FRB 121102 was also suggested by Rajwade et al. (2020). The luminosity distance of FRB 180916B is about an order of magnitude lower than that of FRB 121102 (Tendulkar et al. 2017; Marcote et al. 2020). Thus, it will be easier for multiwavelength counterparts of FRB 180916B to be detected. For FRB 180916B, there have been a lot of multiwavelength follow-up observations, simultaneously or during the active phase, in the optical, X-ray, and gamma-ray frequency bands, but with no transient counterparts (e.g., Andreoni et al. 2020; Casentini et al. 2020; Scholz et al. 2020; Tavani et al. 2020a; Kilpatrick et al. 2021).

So far, there are two repeating FRBs (FRB 121102 and FRB 190520B) accompanied by compact persistent radio emissions, with specific luminosities of the order ~10^{39} erg s^{-1} Hz^{-1} at GHz frequencies (Chatterjee et al. 2017; Niu et al. 2021). It is generally believed that the persistent radio emission of FRB 121102 is related to a young magnetar wind nebula (Murase et al. 2016; Beloborodov 2017; Metzger et al. 2017; Margalit &
Metzger 2018; Li et al. 2020). Notably, there is a radio emission coincident with the superluminous supernova (SLSN) PTF10hgi, with the luminosity and frequency consistent with the persistent radio emission of FRB 121102 (Eftekhari et al. 2019). This implies that some connections may exist between FRBs and other transient sources. However, following the late-time radio observations of some type I SLSNe and gamma-ray burst (GRB) remnants, still no FRBs have been detected (Law et al. 2019; Men et al. 2019).

Except for the X-ray burst associated with FRB 200428 and the persistent radio emissions associated with FRB 121102 and FRB 190520B, there are no confirmed multiwavelength counterparts that are associated with other FRBs (e.g., Petroff et al. 2015; Callister et al. 2016; Gao & Zhang 2017; Zhang & Yang 2017; MAGIC Collaboration et al. 2018; Tingay & Yang 2019; Zhang et al. 2020a). Many FRB models predict various multiwavelength counterparts, which can be classified into the following categories: (1) prompt FRB multiwavelength counterparts (e.g., Metzger et al. 2019; Yang et al. 2019b; Beloborodov 2020; Chen et al. 2020; Dai 2020); (2) FRB multiwavelength afterglows (e.g., Yi et al. 2014); (3) counterparts arising from circumburst environments (e.g., the surrounding nebula emission; various “cosmic combs” associated with FRBs, as suggested by Zhang (2017), or optical counterparts from FRBs heating companion stars in close binary systems, as suggested by Yang (2021); and (4) counterparts produced by the progenitor systems of FRBs (e.g., Zhang 2014; Murase et al. 2016; Metzger et al. 2017; Wang et al. 2020a, 2020b). The prompt multiwavelength counterparts, which usually have short durations (≤100 s), are summarized and discussed by Chen et al. (2020), including the predicted theoretical counterparts from the Metzger et al. (2019) model and the Beloborodov (2020) model, magnetar giant flares (GFs) as FRB counterparts, and fast optical bursts associated with FRBs, as suggested by Yang et al. (2019b). The other types of FRB counterparts usually have long durations (>100 s), e.g., long-lasting multiwavelength FRB afterglows, persistent radio emission possibly associated with the surrounding nebula, or SNe that may have originated in the FRB progenitor systems.

The nondetection of multiwavelength counterparts of FRBs may be due to the following reasons (e.g., Wang et al. 2020b): (1) the fluxes of the multiwavelength counterparts are too faint to be detected, such as the multiwavelength afterglows of FRBs (Yi et al. 2014); (2) the durations of the multiwavelength counterparts are too short relative to the time resolution of the detector, e.g., the fast optical burst produced by the one-zone inverse Compton (IC) scattering process could be as short as the duration of the FRB itself (Yang et al. 2019b); or (3) the delay times between FRBs and their multiwavelength counterparts are too long compared with the observation times, e.g., the SNe and GRBs that may be produced in the FRB progenitor systems may have a very long time delay with respect to the FRB itself. Many efforts have been made to search for the multiwavelength counterparts of FRBs (e.g., Bannister et al. 2012; Palaniswamy et al. 2014; DeLanay et al. 2016; Scholz et al. 2016; Yamasaki et al. 2016; Xi et al. 2017; Zhang & Yang 2017; Cunningham et al. 2019; Guidorzi et al. 2019; Men et al. 2019; Yang et al. 2019a; Tavani et al. 2020a; Wang et al. 2020b). However, there are no confirmed results so far.

In this paper, we perform a systematic search for astronomical transients (ATs) that might be associated with FRBs. We find one possible association between FRB 180916B and AT2020hur. The paper is organized as follows. In Section 2, we present the search method and results. In Section 3, we give possible explanations for the association between FRB 180916B and AT2020hur. Our discussion and conclusions can be found in Sections 4 and 5.

2. Search for Astronomical Transients Associated with Fast Radio Bursts

In order to find ATs that may be associated with FRBs, we perform a systematic search for ATs whose positions are consistent with FRBs. The sample of ATs comes from the Open Supernova Catalog (OSC) and Transient Name Server (TNS), most of which are SNe or unclassified optical transients, while a few are GRBs. As of 2021 October 1, there are 90,617 ATs in OSC, 3771 of which have no coordinate information, and there are 82,798 ATs in TNS. Excluding duplicate sources (55,633), there are a total of 112,915 ATs with certain coordinates. Recently, CHIME released a catalog of 535 FRBs, which includes 474 nonrepeating FRBs and 62 bursts from 18 previously reported repeaters (CHIME/FRB Collaboration et al. 2021). By 2021 October 1, the total number of FRBs had reached 791, including 587 nonrepeating FRBs and 204 bursts from 22 repeaters.

For each AT–FRB pair, we calculate the distance and the chance possibility between them. Assuming that the spatial distribution of ATs is isotropic, the number of ATs within a specific sky area satisfies the Poisson distribution. The chance probability of finding at least one AT in the vicinity of one FRB is

\[ P_1 = 1 - \exp(-\lambda)/0! = 1 - \exp(-\lambda), \]

where \( \lambda = \rho S \) is the expected number of ATs in a given area \( S \). The surface number density of ATs is \( \rho \approx 112915/\text{deg}^2 \approx 2.737/\text{deg}^2 \). For an AT–FRB pair with distance \( D \) (in units of deg), the area can be written as \( S \approx [41252.96(1 - \cos D)]/2 \). To estimate the chance probability conservatively, the distance should include the positional uncertainty of FRB \( \delta_{\text{FRB}} \) and the positional uncertainty of AT \( \delta_{\text{AT}} \). The chance probability of having at least one AT at a distance less than \( D \) for all 609 FRBs (including 587 nonrepeating FRBs and 22 repeaters) can be estimated as

\[ P = 1 - (1 - P_1)^{609}. \]

Appendix A lists the 50 AT–FRB pairs with the nearest distances. It is found that, except for the AT2020hur–FRB 180916B pair, all other AT–FRB pairs have a large chance possibility (all being close to 100%), which means that they are unlikely to be associated. The distance of the second-nearest pair is 0.0019 deg. If one neglects the positional uncertainty, the chance possibility would be \( P \approx 0.02\% \), which corresponds to a 3.7\( \sigma \) confidence level. However, the derived chance possibility is still close to 100% when the large positional uncertainty of FRB 20200405A (1.5 deg) is taken into account. The other pairs possess both a large distance (from 0.01 to 0.1 deg) and a large positional uncertainty of the FRB (\( \sigma_{\text{FRB}} \approx 0.2 \) deg). Besides, Appendix A also shows the results of the GRB 110715A–FRB 171209 pair. A detailed discussion of the association between GRB 110715A and FRB 171209 has been presented in Wang et al. (2020b)
FRB 180916B is a well-localized repeating FRB, with $\alpha = 01\text{h}58^m00^s7502 \pm 2.3$ mas, $\delta = 65^\circ 43'00".3152 \pm 2.3$ mas (Marcote et al. 2020), and AT2020hur has an optical transient, with $\alpha = 01\text{h}58^m00^s750 \pm 1^\prime$, $\delta = 65^\circ 43'00".30 \pm 1''$ (Lipunov et al. 2020). The distance between FRB 180916B and AT2020hur is 0.0000042 deg (15 mas). Thus, FRB 180916B is well located inside the error circle of AT2020hur. In order to verify the estimated chance possibility, Monte Carlo simulations are employed. We randomly generate 171,349 ATs and 609 FRBs in the sky. Based on $10^3$ simulations, the probability of having at least one FRB well located inside the error circle of one AT with an error radius of 1" is $\approx 0.04\%$, consistent with the analytical estimate, which corresponds to a 3.5$\sigma$ confidence level for the AT2020hur–FRB 180916B association.

There are several caveats for the 3.5$\sigma$ confidence level. First, FRB 180916B and AT2020hur have a milliarcsecond and an arcsecond precision localization, respectively, and FRB 180916B is well located inside the error circle of AT2020hur. One may directly use the angular distance between FRB 180916B and AT2020hur to calculate the chance possibility. The derived chance possibility is $P = 0.00001\%$, which corresponds to a 5.34$\sigma$ confidence level. Second, the spatial distribution of the 112,915 ATs is not isotropic, as shown in Figure 1. In Figure 2, we plot the distribution of the angular distance and the cumulative probability distribution of the angular distance derived from the observed data and simulated data. The deviation of the observed data from the simulated data may be due to the anisotropic distribution of FRBs and ATs. We can use the effective density of ATs near FRBs to calculate the chance probability, i.e., $P = 1 - \prod_{i=1}^{N_\text{FRB}} \left(1 - P_{i,\text{fr}}\right)$, where $P_{i,\text{fr}} = 1 - \exp\left(-\rho \delta\right)$. For each FRB, we count the number of ATs $N_i$ whose angular distance from the FRB is less than 10 deg (which corresponds to a solid angle of about 313 deg$^2$), thus the effective surface density of the ATs near each FRB is $\rho_i \approx N_i/313$. We update the chance probability to 0.0438$\%$ (3.5$\sigma$), or 0.00001$\%$ (5.34$\sigma$), if one directly uses the angular distance between FRB 180916B and AT2020hur to calculate the chance possibility, which is consistent with the results derived by assuming an isotropic distribution. Third, as shown in Figure 3, AT2020hur occurs in one of the active windows of FRB 180916B, which provides independent support for the association.

3. AT2020hur: A Possible Optical Counterpart of FRB 180916B

3.1. Observational Properties of AT2020hur

AT2020hur is an optical transient that was first discovered on 2020 April 08 at 23:18:41.184 (MJD = 58,947.97130787) by the MASTER-Kislovodsk robotic telescope (Lipunov et al. 2020). The unfiltered magnitude at the time of discovery was 18.4 mag (Vega system; Lipunov et al. 2020). On 2020 April 09 at 19:07:30 (MJD = 58,948.79687500), about 0.8 days after its discovery, MASTER-Kislovodsk again reported an optical observation of AT2020hur, which was as bright as when it was first discovered (Lipunov et al. 2020).

We follow the procedure of Gorbovskoy et al. (2012) to convert the unfiltered magnitudes of MASTER-Kislovodsk into fluxes. The calculated Vega flux in the CCD spectral band of MASTER-Kislovodsk is $F^W = \int F_{\text{Vega}}(\lambda) W(\lambda) d\lambda = 1.33 \times 10^{-5} \text{ cm}^{-2} \text{s}^{-1}$. The unfiltered magnitude can be converted into the absolute flux value by using the Pogson equation

$$F^W = F_0^W \times 10^{-0.4W}.$$  

The flux density at the wavelength of the CCD response maximum (5500 Å) can be derived by dividing the flux by an effective frequency interval $\Delta\nu_{\text{eff}} \approx 3.9 \times 10^{14} \text{ Hz}$ of the CCD response function. In the above equations, one can derive the optical flux for the MASTER-Kislovodsk unfiltered magnitude 13.4 mag as being about $5.8 \times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1}$, and the flux density at 5500 Å as being about 0.15 mJy.

If AT2020hur is indeed associated with FRB 180916B, according to the redshift $z = 0.0337$ of the host galaxy of FRB 180916B (Marcote et al. 2020), which corresponds to a luminosity distance of $D_L = 153.7 \text{ Mpc}$, using the cosmological parameters from the Planck 2018 results (Planck Collaboration et al. 2020), the isotropic luminosity of AT2020hur is about $1.64 \times 10^{47} \text{ erg s}^{-1}$. For the first and second optical observations, the exposure times are 290 and 60 s, thus the average isotropic energies released during the two exposures are $4.60 \times 10^{44} \text{ erg}$ and $9.52 \times 10^{43} \text{ erg}$, respectively. Assuming a constant luminosity over the 0.8 days, the isotropic energy released during this interval is about $1.13 \times 10^{47} \text{ erg}$.

3.2. Fitting AT2020hur with the Giant Flare Afterglow Model

One possible explanation for the AT2020hur–FRB 180916B association is that FRB 180916B is powered by a flaring magnetar, as suggested by the popular FRB models, while AT2020hur originates from the afterglow of one or more energetic GFs. Relativistic outflow can be launched during the GF. When the relativistic outflow propagates outward and interacts with the surrounding medium, a pair of shocks is formed. The forward shock (FS) propagates into the surrounding medium, and the reverse shock (RS) propagates into the outflow. If the magnetization parameter of the outflow is high enough, the short-lived RS can be suppressed (Zhang & Kobayashi 2005; Mimica et al. 2009; Mizuno et al. 2009). Here we only consider the contribution of the emission from the FS.

We develop a standard FS afterglow model, in which the dynamical evolution of the outflow follows Huang et al. (1999, 2000), and synchrotron radiation from the electrons, with a segmented power-law distribution (Sari et al. 1998), is invoked to calculate the afterglow lightcurves. Both on-axis and off-axis configurations are considered in our model. The free parameters in our model include the half-opening angle of the outflow $\theta_\text{e}$ (since the outflow can be anisotropic), the viewing angle $\theta_v$ (valid only in off-axis configurations, and $\theta_v > \theta_\text{e}$ is
required), the isotropic kinetic energy of the outflow $E_{K,\text{iso}}$, the initial Lorentz factor of the outflow $\Gamma_0$, the number density of the surrounding medium $n$ (considering a constant medium density), the fraction of the shock’s internal energy that is partitioned to magnetic fields $\epsilon_B$, the fraction of the shock’s internal energy that is partitioned to electrons $\epsilon_e$, the electron energy spectral index $p$, and the time interval between the discovery time of AT2020hur and the launch time of the assumed GF $t_{\text{shift}}$.

The Markov Chain Monte Carlo method implemented in the emcee Python package (Foreman-Mackey et al. 2013) is employed to determine the posterior probability distributions and the best-fit parameter values. We set a range for the priors that is wide enough to explore a parameter space as large as possible, except for $E_{K,\text{iso}}$. To date, there are four GFs and two GF candidates that have been discussed in the literature. The most energetic GF releases a total isotropic energy $E_{\gamma,\text{iso}} \sim 10^{47}$ erg (Frederiks et al. 2007; Yang et al. 2020; Zhang et al. 2020b). The isotropic kinetic energy of the outflow can be written as $E_{K,\text{iso}} = E_{\gamma,\text{iso}}(1/\eta - 1)$. The radiative efficiency $\eta$ has a large uncertainty, depending on the specific radiation mechanism. Observationally, the GRB radiative efficiency is found to vary from less than 0.1% to more than 90% (Fan & Piran 2006; Zhang et al. 2007; Wang et al. 2015). If GFs and GRBs share the similar radiation mechanisms, then GFs may have the same distribution of $\eta$. Conservatively, we set the prior of $E_{K,\text{iso}}$ to range from $10^{47}$ to $10^{50}$ erg.

In addition to the two optical points reported by MASTER-Kislovodsk, we also searched for other multiwavelength observations of FRB 180916B. The multiwavelength data used for the fit are shown in Figure 3. Figure 3 also shows the fitting results from the on-axis configuration. In Appendix B, we show the fitting results from the off-axis configuration. We find that the overall quality of the fitting is good for both configurations, indicating that the standard FS afterglow model can interpret the lightcurve of AT2020hur. Table 1 shows the parameters, priors, and fitting results of our model. Appendix C shows the one- and two-dimensional projections of the posterior probability distributions of the parameters with corner plots. As shown in the corner plots, the posterior probability distributions of several parameters are dispersed, due to the lack of data. However, the posterior probability distributions of $E_{K,\text{iso}}$ are gathered and close to the upper limit of its prior, i.e., $10^{50}$ erg, which suggests the large kinetic energy of the outflow. For the on-axis configuration, the isotropic kinetic energy of the outflow ranges from $2.3 \times 10^{49}$ to $7.9 \times 10^{49}$ erg, and the half-opening angle of the outflow ranges from 0.68 to 2.59 rad, thus the true (beaming-corrected) kinetic energy of the outflow $E_k = E_{K,\text{iso}}(1 - \cos \theta) / 2$ ranges from $2.5 \times 10^{48}$ to $7.4 \times 10^{49}$ erg. For the off-axis configuration, $E_k$ ranges from

![Figure 2. The distributions of the angular distance (upper panels) and the cumulative probability distributions of the angular distance (lower panels) derived from the observed data (blue) and the simulated data (orange). The left panels are displayed in linear scale, and the right panels are displayed in logarithmic scale.](image-url)
8.0 \times 10^{48} \text{ to } 7.9 \times 10^{49} \text{ erg. According to the derived initial Lorentz factor, ranging from 14} (15) \text{ to } 71 (91), the total mass of the outflow } M_{ej} = E_K / \left[ (\Gamma_0 - 1)c^2 \right] \text{ ranges from } 4 \times 10^{25} \text{ (1 \times 10^{25}) to } 6 \times 10^{27} \text{ g (6 \times 10^{27} g) for the on-axis (off-axis) configuration.}

4. Discussion

4.1. Can the Giant Flare Afterglow Model Explain AT2020hur?

Although the GF afterglow model can interpret the observations of AT2020hur and the multiwavelength constraints on FRB 180916B, there are some issues with this model.

First, the derived isotropic kinetic energy is \(\sim 10^{48} - 10^{49} \text{ erg, which is more than three orders of magnitude larger than the kinetic energy inferred by the typical GFs. For example, GRB 200415A is one of the most energetic extragalactic GFs, with the isotropic energy released in the initial pulse and following tail being } \sim 10^{46} \text{ erg (Yang et al. 2020; Zhang et al. 2020b; Castro-Tirado et al. 2021; Fermi-LAT Collaboration et al. 2021; Roberts et al. 2021; Svinink et al. 2021). GRB 200415A is also the first GF accompanied by GeV emission that is generally believed to originate from the GF afterglow (Yang et al. 2020; Zhang et al. 2020b; Fermi-LAT Collaboration et al. 2021). The inferred kinetic energy of the outflow is comparable to the total radiated energy of GRB 200415A (Zhang et al. 2020b; Fermi-LAT Collaboration et al. 2021). Besides, it is suggested that the outflow is ultra-relativistic, with a bulk Lorentz factor of } \sim 100 \text{ (Zhang et al. 2020b; Fermi-LAT Collaboration et al. 2021), which is comparable to our results. However, our derived baryon loading is three orders of magnitude larger than the estimated baryon loading in the relativistic outflow of GRB 200415A, i.e., } \sim 10^{21} \text{ g (Zhang et al. 2020b). Another two galactic GFs from the soft gamma-ray repeaters SGR 1806-20 and SGR 1900+14 were accompanied by radio afterglows (Frail et al. 1999; Cameron et al. 2005; Gaensler et al. 2005), and the inferred kinetic energies were of the order of } 10^{44} - 10^{46} \text{ erg (e.g., Cheng &}

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Figure 3. The standard FS afterglow model fit to AT2020hur and multiwavelength observations of FRB 180916B. Upper left: the optical and radio lightcurves in a linear timescale. The green circles are the C-band observations of AT2020hur (Lipunov et al. 2020). The green upside-down triangles are the C-band upper limits of FRB 180916B (Zhirkov et al. 2020). The cyan, blue, and purple upside-down triangles are the g-, r-, and i-band upper limits of FRB 180916B observed by Apache Point Observatory (APO; Kilpatrick et al. 2021). The orange and yellow upside-down triangles are the upper limits on the persistent radio emission associated with FRB 180916B observed by the European Very-long-baseline-interferometry Network (EVN) and the Karl G. Jansky Very Large Array (VLA; Marcote et al. 2020). The gray horizontal line is the single-epoch sensitivity of the 3 GHz VLA Sky Survey (VLASS; Lacy et al. 2020). Upper right: the optical and radio lightcurves in a logarithmic timescale. The navy upside-down triangles are the X-ray and gamma-ray lightcurves in a logarithmic timescale. The gray shaded regions in the upper left and right panels correspond to the predicted activity days of FRB 180916B for a period of 16.29 days and 6.1 day activity windows (Pastor-Marazuela et al. 2021).
Wang 2003; Dai et al. 2005; Ioka et al. 2005; Nakar et al. 2005; Wang et al. 2005). For the GF from SGR 1900+14, the extremely high luminosity, hard spectrum, and short duration suggest that a relativistic fireball ($\Gamma \gtrsim 10$) with very low baryon contamination was launched by a neutron star with a magnetic field of $10^{15}$ G (Thompson & Duncan 2001). Obviously, if AT2020hour is indeed powered by an energetic GF afterglow, the GF does not belong to the class of typical GFs. If the large kinetic energy is powered by internal magnetic energy dissipation, one can place a lower limit on the internal magnetic field $B \gtrsim (6E_{k,0}/R_{NS}^{3/2})^{1/2} \times 8 \times 10^{15} E_{k,0}^{1/2} n_{f,i}^{-3/2} G$, where $R_{NS}$ is the neutron star radius, $E_{k,49} = E_{k}/10^{49}$ erg, $R_{NS,6} = R_{NS}/10^{6}$ cm.

Second, for the off-axis configuration, the contribution of the shocked material to the DM and the rotation measure (RM) of FRB 180916B must be taken into account. There are four regions where the relativistic outflow interacts with the surrounding medium: (1) the unshocked surrounding medium; (2) the shocked surrounding medium; (3) the shocked outflow; and (4) the unshocked outflow. The two shocked, ionized regions provide free electrons and a magnetic field that affect the DM and RM. For the long-term evolution of the DM and RM, the contribution from the shocked outflow can be neglected, since the shocked material is dominated by the shocked surrounding medium. The DM of the shocked surrounding medium is given by Yu (2014):

$$\text{DM}_{s} = \int \frac{D}{1 + z} n_i' d{\xi} = \frac{D}{1 + z} n_i' \Delta R_i'$$

where $D \equiv [\Gamma(1 - \beta \cos \theta)]^{-1}$ is the Doppler factor due to the relativistic motion of the shocked material, $n_i'$ is the comoving number density of the shocked material, and $\Delta R_i'$ is the comoving width of the shocked material (in this paper, we use the superscript prime to denote the quantities in the shock-comoving frame). Here, we have neglected the internal structure of the blast wave (Blandford & McKee 1976). According to the jump condition $n_i'/n = (\gamma_i \Gamma + 1)/(\gamma_i - 1)$ (where $\gamma_i$ is the adiabatic index, and $\Gamma$ is the Lorentz factor of the blast wave), $\Delta R_i'$ can be written as

$$\Delta R_i' = \frac{R(\gamma_i - 1)}{3(\gamma_i \Gamma + 1)},$$

where $R$ is the blast wave radius. The RM for a plasma shocked by relativistic shock can be written in the form

$$\text{RM}_{s} = \frac{e^3}{2\pi m_e c^2} \frac{D^2}{(1 + z)^2} B_i' \Delta R_i'$$

$$\times \int_{\gamma_{m}'}^{\gamma_{e}'} \max \left(1, \frac{\ln \gamma_i' \gamma_{e}'}{2 \gamma_{e}'} \right) \frac{dN_{e}'}{d{\gamma_e'}} d{\gamma_e'}$$

$$= 0.812 \frac{D^2}{(1 + z)^2} \frac{B_i' \Delta R_i'}{\mu G}$$

$$\times \int_{\gamma_{m}'}^{\gamma_{e}'} \max \left(1, \frac{\ln \gamma_i' \gamma_{e}'}{2 \gamma_{e}'} \right) \frac{dN_{e}'}{d{\gamma_e'}} d{\gamma_e'} \text{rad m}^{-2},$$

where $B_i'$ is the component of the magnetic field along the line of sight, $dN_{e}'/d{\gamma_e'}$ is the electron distribution of the shocked material, and $\gamma_{m}', \gamma_{e}'$, and $\gamma_{M}'$ are the corresponding minimum Lorentz factor, the cooling Lorentz factor, and the maximum Lorentz factor. The $\ln \gamma_{e}'/(2 \gamma_{e}')^2$ term accounts for the suppression of the RM contributed by ultra-relativistic electrons (Quataert & Gruzinov 2000), and the $1/(\gamma_{e}')^2$ term is an approximate correction factor for the RM contributed by nonrelativistic and ultra-relativistic electrons.

Figure 4 shows the evolution of the DM$_s$, $B_i'$, and RM$_s$, derived from a sample of parameters within the 1σ posterior probability distributions. Due to the poor constraints on the parameters, the distribution of the DM spans a wide range, from $\sim 10^{-3}$ to $\sim 10^2$ pc cm$^{-3}$. Observationally, the DM of FRB 180916B is about $350$ pc cm$^{-3}$. Excluding the contribution of our Galaxy, the excess DM in this line of sight is estimated to be about $150$ pc cm$^{-3}$ or $25$ pc cm$^{-3}$, based on the NE2001 or YMW2016 models (Cordes & Lazio 2002, 2003; Yao et al. 2017). The excess DM should be treated as a stringent upper limit of the DM$_s$. As shown in Figure 4, DM$_s \lesssim 25$ pc cm$^{-3}$ always holds within $\lesssim 10^9$ s ($\lesssim 30$ yr) following the GF. Since the DM$_s$ increases slowly at late time, future observations of such a trend may help to verify our model. The distribution of RM$_s$ also spans a wide range, from $\sim 10^{-2}$ to $\sim 10^6$ rad m$^{-2}$. CHIME/FRB Collaboration et al. (2019) reported that FRB 180916B has a measured RM of $\sim -14.6 \pm 0.6$ rad m$^{-2}$. The RM$_{MW}$ contributed by the Milky Way along this line of sight is RM$_{MW} \approx -72 \pm 23$ rad m$^{-2}$ (Oppermann et al. 2015) or RM$_{MW} \approx -115 \pm 12$ rad m$^{-2}$ (Ordóñez et al. 2019), which suggests that the excess RM only ranges from zero to several tens of rad m$^{-2}$. As shown in Figure 4, due to the strong magnetic field amplified by the relativistic shock, the derived RM$_s$ is usually too large with respect to the excess DM, especially at late time, when the relativistic electrons are so few that RM$_s$ cannot be suppressed efficiently. However, a small fraction of RM$_s$ still satisfy the observational requirements, which means the on-axis configuration is still possible. For the off-axis configuration, since there is no shocked material contributing to the DM and RM along the line of sight, the standard FS afterglow with the off-axis geometry always holds. Third, the single-GF afterglow model suggests that the first optical detection corresponds to the first tens or hundreds of seconds of the rising phase of the GF afterglow. This is unlikely, since the rise time of the afterglow is only a small part

Table 1

| Parameter | Prior | Result (on-axis) | Result (off-axis) |
|-----------|-------|-----------------|------------------|
| $\theta_0 (\text{rad})$ | $[0, \pi]$ | ... | 1.97$^{+0.81}_{-0.91}$ |
| $\theta_1 (\text{rad})$ | $[0, \pi]$ | 1.56$^{+1.03}_{-0.88}$ | 1.83$^{+0.91}_{-0.77}$ |
| $\log (E_{k, \text{iso}} \text{erg})$ | $[47, 50]$ | 49.68$^{+0.32}_{-0.41}$ | 49.80$^{+0.19}_{-0.40}$ |
| $T_\text{B}$ | $[1, 3]$ | 1.44$^{+0.29}_{-0.48}$ | 1.48$^{+0.31}_{-0.98}$ |
| $\log (n \text{ cm}^{-3})$ | $[-6, 3]$ | 1.44$^{+1.29}_{-1.01}$ | 1.95$^{+1.60}_{-0.80}$ |
| $\log (e^+)$ | $[-7, -0.5]$ | -1.15$^{+0.68}_{-0.71}$ | -1.10$^{+0.53}_{-0.56}$ |
| $\log (e^-)$ | $[-7, -0.5]$ | -0.79$^{+0.22}_{-0.35}$ | -0.72$^{+0.22}_{-0.35}$ |
| $p$ | $[2, 3]$ | 2.54$^{+0.25}_{-0.28}$ | 2.53$^{+0.18}_{-0.22}$ |
| $\log (I_{\text{iso}})$ | $[0, 7]$ | 1.11$^{+0.83}_{-0.62}$ | 3.38$^{+0.70}_{-0.52}$ |

Note. The uncertainties of the best-fit parameters are measured at 1σ confidence ranges.

11 Previous observations of FRB 180916B did not indicate a significant variation in DM (e.g., CHIME/FRB Collaboration et al. 2020a; Nimmo et al. 2021; Sand et al. 2021), which is consistent with our model.
of the total afterglow duration. For example, if an optical telescope detects such a GF afterglow, the probability of detecting the optical afterglow within $\sim 10^{-100}$ s after the GF is $\sim 0.01\%-0.1\%$ (assuming that the duration of the afterglow above the fluence threshold is $\sim 10^5$ s).

Within the framework of the GF afterglow model, AT2020hur might be associated with multiple GFs. Assuming that the two observation times of AT2020hur correspond to the peak times of two GF afterglows, one can find (Sari et al. 1998)

$$F_{\gamma, \text{max}} = 1.1 \times 10^5 \epsilon_B^{1/2} E_{K,\text{iso},52}^{1/2} D_{L,28}^{-2} \mu Jy \approx 150 \mu Jy,$$

where $E_{K,\text{iso},52} = E_{K,\text{iso}}/10^{52}$ erg and $D_{L,28} = D_L/10^{28}$ cm. For AT2020hur, the derived isotropic kinetic energy of the outflow $E_{K,\text{iso}} \approx 3.1 \times 10^{46} \epsilon_B^{-1/2} n^{-1/2}$ erg, which is about two to three orders of magnitude lower than the one derived from the single-GF afterglow model for typical parameters (e.g., $\epsilon_B = 0.1$, $n = 1$ cm$^{-3}$). Although the multiple-GF afterglow model derives a much lower kinetic energy, it would be more difficult for a magnetar to produce multiple energetic GFs in less than a day. Besides, if there are two GFs accounting for the optical counterpart, the two optical detections would correspond to the peaks of the GF optical afterglow, which would have a much lower probability in such a scenario. Unless the multiple-GF afterglow model has an off-axis configuration, the contribution of the shocked material induced by each GF to the DM and RM of FRB 180916B may increase significantly with the increase of GF. In order to be consistent with the small observed DM and RM for FRB 180916B, smaller values of $n$ and $\epsilon_B$ are needed. However, this results in a larger kinetic energy (see Equation (6)).

We therefore conclude that the GF afterglow model is unlikely to explain the optical counterpart of FRB 180916B, AT2020hur, since a lot of fine-tuning and coincidences are required for this specific model. As shown in Figures 3 and 5, the radio flux density is still likely to be above the single-epoch sensitivity of VLASS (Lacy et al. 2020) in the future. Thus, further observations of the radio counterpart of FRB 180916B may help to verify the GF afterglow model.

### 4.2. Other Possible Origins of AT2020hur

We here discuss the other possible origins of AT2020hur. Due to FRB 180916B being a repeating FRB, the optical counterparts associated with catastrophic FRB models are unlikely to be the origin of AT2020hur. For instance, a type Ia SN associated with an FRB produced by a double white dwarf merger (Kashiyama et al. 2013), a GRB afterglow or a kilonova associated with an FRB produced by binary neutron star mergers (e.g., Totani 2013; Wang et al. 2016, 2018), or a
GRB associated with an FRB produced by a neutron star collapsing into a black hole (Zhang 2014). AT2020hur is also unlikely to originate from the progenitor systems of FRBs, such as SNe, which may have a very long time delay with respect to the FRB itself, which is inconsistent with the case of AT2020hur and FRB 180916B.

For the optical counterparts arising from circumburst environments, a “cosmic comb” model is a promising model that can produce both FRBs and optical counterparts, where the optical counterparts can originate from a variety of “combs”, including active galactic nuclei, GRBs, SNe, etc. (Zhang 2017). However, this model cannot explain the periodicity of FRB 180916B. The binary comb model is an upgraded version of the “cosmic comb” model that can explain periodic FRBs, but the model does not predict an optical counterpart (Ioka & Zhang 2020). Although Yang (2021) suggested that an optical transient is expected from FRB heating companion stars in close binary systems, the optical emission is so weak that only the counterparts of those galactic FRBs can be detected (Yang 2021). Besides, AT2020hur seems to be consistent with the optical counterpart of a periodic FRB from a luminous X-ray binary (Sridhar et al. 2021).

We next consider the prompt FRB counterparts that usually have short durations ($\lesssim 100$ s), as discussed and summarized in Chen et al. (2020). For the Metzger et al. (2019) model, a weak optical counterpart is expected if the upstream plasma is composed of electrons and positrons, but there is no quantitative prediction about the luminosity and duration of the optical counterpart. For the Beloborodov (2020) model, a bright optical flash is produced when the blast wave strikes the hot wind bubble, and it is expected that the duration of the optical flash is $\lesssim 1$ s and the upper limit of the energy released is $\sim 10^{48}$ erg, which is comparable to the isotropic energy released during the two exposures of AT2020hur.

Another possible origin of AT2020hur is that it may comprise two fast optical bursts (FOBs) produced by the IC scattering of FRB emissions, as suggested by Yang et al. (2019b). The IC scattering process can occur in the FRB emission region, i.e., in the pulsar magnetosphere or in the maser outflow. For the “one-zone” IC scattering model, the optical flux of the FOB is $\sim 5 \times 10^{-13} - 10^{-12}$ Jy, or $\lesssim 1.6 \times 10^{-6}$ Jy for both FOBs and FRBs formed in the pulsar magnetosphere or in the maser outflow, and the duration of the FOB is $\sim \text{ms}$ in these two cases. One can find that the energy released in the optical band is $\sim 10^{30}-10^{41}$ erg or $\lesssim 5 \times 10^{40}$ erg, respectively, which do not meet the energy requirement of AT2020hur. The IC scattering process can also occur in a different region from the FRB emission, e.g., the IC scattering region is in the nebula, while the FRB is formed via coherent radiation near the neutron star. For the “two-zone” IC scattering model, one has the upper limit of the FOB flux $\lesssim 8.8 \times 10^{-3}$ Jy and the duration of the FOB $\sim 5 \times 10^{3}$ s, which correspond to the energy released being $\lesssim 10^{47}$ erg. Therefore, the “two-zone” IC scattering model is a promising model for explaining AT2020hur. Yang et al. (2019b) also discussed the FOB being produced by the same emission mechanism as the FRB. However, the derived flux in the optical band is extremely low.

4.3. The Coincidence between AT2020hur and the Activity Window of FRB 180916B

In Figure 3, we plot the lightcurve of AT2020hur and the predicted activity days of FRB 180916B for a period of 16.29 days and 6.1 day activity windows (Pastor-Marazuela et al. 2021). As shown in Figure 3, AT2020hur is located in one of the activity windows (MJD from 58,945.5 to 58,951.6). The coincidence between AT2020hur and the activity window of FRB 180916B is interesting, and provides independent confirmation of the FRB 180916B–AT2020hur association. Since the observation details of the MASTER-Kislovodsk telescope are unknown, this coincidence may be due to an observational selection effect. Another possibility is that the optical counterpart is subject to the same periodic modulation as FRB 180916B. This may be due to the optical counterpart being directly related to the FRB emission, and the optical emission and FRB emission having a similar Doppler beaming angle and direction, as implied by the prompt FRB multi-wavelength counterparts (e.g., Metzger et al. 2019; Yang et al. 2019b; Beloborodov 2020). In this case, each optical counterpart may correspond to an FRB. So we checked the transit times of CHIME on 2020 April 08 and 2020 April 09, but the exposure times of AT2020hur did not overlap with the CHIME observations. There are no reported FRBs at the exposure times of AT2020hur. Interestingly, a total of nine low-frequency FRBs down to 120MHz were detected by LOFAR in the same activity window (Pastor-Marazuela et al. 2021), which have a time delay of $\sim 1$–$3$ days with respect to AT2020hur. Whether there is a link between low-frequency FRBs and optical counterparts needs to be confirmed by further observations.

5. Conclusions

In this paper, we perform a systematic search for ATs whose positions are consistent with FRBs. We find that one unclassified optical transient, AT2020hur, is spatially coincident with the repeating FRB 180916B. The chance possibility for the AT2020hur–FRB 180916B association is about 0.04%, which corresponds to a significance of $3.5\sigma$. We first give a possible explanation for the AT2020hur–FRB 180916B association, in which FRB 180916B is powered by a flaring magnetar, while AT2020hur originates from the afterglow of one or more energetic GFs. However, the derived isotropic kinetic energy of the GF is too large compared to typical GFs, and a lot of fine-tuning and coincidences are required for this specific model. Therefore, we conclude that the GF afterglow model is not a promising model for explaining AT2020hur. We also discuss other possible origins of AT2020hur. One possibility is that AT2020hur may consist of two or more optical flares originating from short-duration prompt FRB counterparts. These optical flares might be consistent with the theoretical predictions of the models of Metzger et al. (2019) and Beloborodov (2020), or the model in which such flares originate from the “two-zone” IC scattering of FRB emission. Besides, the coincidence between AT2020hur and the activity window of FRB 180916B provides independent confirmation of the FRB 180916B–AT2020hur association, and this coincidence may suggest that the optical counterparts are subject to the same periodic modulation as FRB 180916B. If AT2020hur originates from prompt FRB counterparts, future simultaneous detections of FRBs and their optical counterparts may reveal the physical origin of FRBs.

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Table 2
The 50 FRB–AT Pairs with Nearest Distances

| FRB Name          | FRB R.A. (deg) | FRB Decl. (deg) | FRB DM (pc cm$^{-3}$) | AT Name        | AT R.A. (deg) | AT Decl. (deg) | AT Type | AT Redshift | $\Delta$r (days) | Distance (deg) | Chance Possibility |
|-------------------|----------------|-----------------|------------------------|----------------|---------------|---------------|---------|-------------|-----------------|----------------|------------------|
| FRB 20100916B (rep) | 29.5031258     | ±0.00000006     | ±0.0000006             | AT2020hir     | 29.503125     | ±0.0003       | 65.71675    | ...          | ...             | 570             | 0.0000042 (15 mas) | 0.0418% |
| FRB 20200405A     | 198.36 ± 1.50  | 36.59 ± 1.50    | 212.298                | AT2019wur     | 198.3646667   | ±0.0003       | 36.5938     | ...          | ...             | 113             | 0.00019 (3.5$\sigma$) |
| FRB 20120127A     | 348.78 ± 0.13  | −18.43 ± 0.13   | 553.3                  | AT2020abj     | 348.7736792   | ±18.49370833 | SN Ia      | 59.5431111   | 0.045077        | −598            | 0.01         |
| FRB 20190502A     | 165.01 ± 0.14  | 95.95 ± 0.13    | 626                    | SN2020adi     | 164.9729197   | ±18.49370833 | SN II     | 59.5431111   | 0.045077        | −598            | 0.01         |
| FRB 20190531E     | 15.20 ± 0.26   | 0.54 ± 0.37     | 328.4                  | SDSS J171902  | 15.19566      | 0.517973      | IA        | ...          | ...             | 4277            | 0.02         |
| FRB 20181027A     | 131.90 ± 0.22  | −4.24 ± 0.34    | 726.3                  | AT2019tcp     | 131.8896917   | −4.261511111 | ...       | ...          | ...             | −92             | 0.02         |
| FRB 20200405A     | 198.36 ± 1.50  | 36.59 ± 1.50    | 212.298                | AT2020hir     | 198.3646667   | ±0.0003       | 36.5938     | ...          | ...             | 113             | 0.00019 (3.5$\sigma$) |
| FRB 20190502A     | 165.01 ± 0.14  | 95.95 ± 0.13    | 626                    | SN2020adi     | 164.9729197   | ±18.49370833 | SN II     | 59.5431111   | 0.045077        | −598            | 0.01         |
| FRB 20190531E     | 15.20 ± 0.26   | 0.54 ± 0.37     | 328.4                  | SDSS J171902  | 15.19566      | 0.517973      | IA        | ...          | ...             | 4277            | 0.02         |
| FRB 20181027A     | 131.90 ± 0.22  | −4.24 ± 0.34    | 726.3                  | AT2019tcp     | 131.8896917   | −4.261511111 | ...       | ...          | ...             | −92             | 0.02         |
| FRB 20200405A     | 198.36 ± 1.50  | 36.59 ± 1.50    | 212.298                | AT2020hir     | 198.3646667   | ±0.0003       | 36.5938     | ...          | ...             | 113             | 0.00019 (3.5$\sigma$) |
| FRB 20190502A     | 165.01 ± 0.14  | 95.95 ± 0.13    | 626                    | SN2020adi     | 164.9729197   | ±18.49370833 | SN II     | 59.5431111   | 0.045077        | −598            | 0.01         |
| FRB 20190531E     | 15.20 ± 0.26   | 0.54 ± 0.37     | 328.4                  | SDSS J171902  | 15.19566      | 0.517973      | IA        | ...          | ...             | 4277            | 0.02         |

Note: The table lists the FRB name, FRB R.A. and Decl., FRB DM, AT name, AT R.A. and Decl., AT type, AT redshift, $\Delta$r, distance, and chance possibility for the closest AT Pair. The distances are in degrees, and the chance possibility is given as a percentage.
| FRB Name | FRB R.A. (deg) | FRB Decl. (deg) | FRB DM (pc cm\(^{-3}\)) | AT Name     | AT R.A. (deg) | AT Decl. (deg) | AT Type | AT Redshift | $\Delta t$ (days) | Distance (deg) | Chance Possibility |
|----------|----------------|-----------------|--------------------------|-------------|---------------|---------------|---------|-------------|-----------------|-----------------|---------------------|
| FRB 20190125B | 231.45 ± 0.25 | 50.54 ± 0.23 | 177.9 | 1993U | 231.3122917 | 50.57741944 | QSO | ... | 9351 | 0.10 | 100% |
| FRB 20190621B | 193.14 ± 0.23 | 55.64 ± 0.23 | 1059.5 | AT2019jwr | 193.3057958 | 55.66150833 | ... | ... | 13 | 0.10 | 100% |
| FRB 20181017D | 9.12 | 11.33 | 1845.2 | PS15bvm | 9.117583333 | 11.23697222 | ... | ... | 1138 | 0.10 | ... |
| FRB 20190531E | 15.20 ± 0.26 | 0.54 ± 0.37 | 328.4 | SDSS-IISN15565 | 15.113 | 0.58986111 | SN II | ... | 4659 | 0.10 | 100% |

**Note.** The chance possibility $P$ can be calculated as $P = 1 - (1 - P_1)^{609}$, where $P_1 = 1 - \exp\left[-112915[1 - \cos(D + \delta_{\text{FRB}} + \delta_{\text{AT}})]/2\right]$. Here, 609 is the total number of FRBs, 112,915 is the total number of ATs, $D$ is the distance between an FRB and an AT, $\delta_{\text{FRB}} = \sqrt{\delta_{\text{RA,FRB}}^2 + \delta_{\text{Dec,FRB}}^2}$ is the error radius of an FRB, and $\delta_{\text{AT}}$ is the error radius of an AT with a typical value $\delta_{\text{AT}} \sim 1''$. 

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Software: emcee (Foreman-Mackey et al. 2013).

Appendix A
A List of the 50 FRB–AT Pairs with the Nearest Distances

We list the 50 FRB–AT pairs with nearest distances in Table 2.

Appendix B
Fitting Results from the Off-axis Configuration

We also show the fitting results from the off-axis configuration in Figure 5.

Appendix C
Corner Plots

We show the corner plots for the standard FS afterglow model with on-axis and off-axis configurations in Figure 6.

Figure 5. The standard FS afterglow model fit to AT2020hur and multiwavelength observations of FRB 180916B. Upper left: the optical and radio lightcurves in a linear timescale. The green circles are the C-band observations of AT2020hur (Lipunov et al. 2020). The green upside-down triangles are the C-band upper limits of FRB 180916B (Zhirkov et al. 2020). The cyan, blue, and purple upside-down triangles are the g-, r-, and i-band upper limits of FRB 180916B observed by APO (Kilpatrick et al. 2021). The orange and yellow upside-down triangles are the upper limits on the persistent radio emission associated with FRB 180916B observed by EVN and VLA (Marcote et al. 2020). The gray horizontal line is the single-epoch sensitivity of VLASS (Lacy et al. 2020). Upper right: the optical and radio lightcurves in a logarithmic timescale. Lower left: the X-ray and gamma-ray lightcurves in a linear timescale. The gray horizontal line is the single-epoch sensitivity of VLASS (Lacy et al. 2020). Upper right: the optical and radio lightcurves in a logarithmic timescale. Lower left: the X-ray and gamma-ray lightcurves in a linear timescale. The gray shaded regions in the upper left and right panels correspond to the predicted activity days of FRB 180916B for a period of 16.29 days and 6.1 day activity windows (Pastor-Marazuela et al. 2021).
Figure 6. Corner plots showing the one- and two-dimensional projections of the posterior probability distributions of the parameters for the standard FS afterglow model, with on-axis and off-axis configurations, respectively.
