A Search for Radio Pulsars in Supernova Remnants Using FAST with One Pulsar Discovered

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We report the results of a search for radio pulsars in five supernova remnants (SNRs) with the FAST telescope. The observations were made using the 19-beam receiver in "snapshot" mode. The integration time for each pointing was 10 min. We discovered a new pulsar, PSR J1845–0306, which has a spin period of 983.6 ms and a dispersion measure of $444.6 \pm 2.0\,\mathrm{cm}^{-3}\cdot\mathrm{pc}$, in observations of SNR G29.6+0.1. To judge the association between the pulsar and the SNR, further verification is needed. We also re-detected some known pulsars in the data from SNRs G29.6+0.1 and G29.7–0.3. No pulsars were detected in the observations of the other three SNRs.

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Before the discovery of pulsars, Baade and Zwicky proposed that supernova explosions could produce neutron stars.[1] Currently, it is generally believed that pulsars are fast-spinning, highly magnetized neutron stars. According to the standard model of pulsar evolution,[2] pulsars are born in supernova explosions, so young pulsars with fast rotation are highly likely to be surrounded by supernova remnant (SNR) materials. The best two examples supporting this model are the famous Vela and Crab pulsars. The Vela pulsar was discovered in 1968 at the edge of the Vela SNR.[3] Its distance and age are the same as those of the SNR. Also in 1968, the Crab pulsar was discovered at the center of the Crab Nebula[4] and was subsequently shown to be associated with the Crab Nebula. The confirmation of the association of the Vela and Crab pulsars with their respective SNRs provided important observational evidence for the model of neutron stars produced by supernova explosions.

Finding pulsars in their parent SNRs is vital to studying pulsar formation and the supernova explosion mechanism. Attempts to search for pulsars in SNRs with large radio telescopes have been ongoing since the 1990s. Gorham *et al.*[5] searched for pulsars in 18 SNRs using the Arecibo 305 m telescope at 430 and 1420 MHz but did not find any new pulsars. Kaspi *et al.*[6] conducted a pulsar search in 40 SNRs using the Parkes 64 m radio telescope at three frequencies of 436, 660, and 1520 MHz and discovered two new pulsars. Biggs *et al.*[7] used the Lovell 76 m radio telescope to search for pulsars in 29 SNRs at 610 MHz and found no new pulsars. Lorimer *et al.*[8] searched for pulsars in 33 SNRs using the Lovell 76 m radio telescope at 606 MHz and discovered two new pulsars. Camilo *et al.*[9] detected a 136 ms pulsar in SNR G54.1+0.3 using the Arecibo radio telescope. Gupta *et al.*[10] used the GMRT radio telescope to discover a 61.86 ms pulsar in SNR G21.5–0.9. Zhang *et al.* (2018) employed the Parkes 64 m radio telescope to search for pulsars in SNR 1987A, but no new pulsars were detected. Straal and van Leeuwen[11] conducted a search for steep-spectrum pulsars in eight SNRs and pulsar wind nebulae using the LOFAR telescope and discovered a pulsar candidate. Sett *et al.*[12] searched five SNRs for pulsars using the Green Bank radio telescope at 820 MHz, but no new pulsars were found. In the Pulsar Galactic Surface Survey (GPPS) project, Han *et al.*[13] discovered several pulsars in three known SNRs using the FAST telescope. Further verification is needed to determine whether these pulsars are associated with SNRs.

FAST has unprecedented search sensitivity, and it is expected to make breakthroughs in searching for pulsars in SNRs. In this Letter, we report on the search for radio

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pulsars in a sample of five SNRs (see Table 1 for details) with FAST. We select sources that have no associated pulsar or black hole and are located outside the sky coverage of two high-priority pulsar searching projects: CRAFTS [14] and GPPS. We also require that the angular size of the source is smaller than the field of view (FoV) of the "snapshot" mode of FAST, so that one snapshot observation can completely cover the source. Based on these criteria, the five SNRs shown in Table 1 are selected.

Observations and Analysis. Our data used in this work were obtained from the FAST observation project PT2020_0050. The observations were made between February and May 2021 using the 19-beam L-band receiver of FAST in snapshot mode, [13] which covers the 1.0–1.5 GHz frequency band. [15] All data from the 19 beams were recorded using the search-mode PSRFITS data format [16] with a sampling time of 49.152 μs. The snapshot observations lasted 10 min for each pointing. Following Pan *et al.*, [17] we calculated the search sensitivities shown in Table 1 using the radiometer equation

$$S_{\min} = \frac{\beta(S/N_{\min})T_{\rm sys}}{G\sqrt{n_{\rm p}t_{\rm int}\Delta f}}\sqrt{\frac{W}{P-W}}. \quad (1)$$

Here, with our observing setup, the sampling efficiency β is equal to 1, the width of the pulsar profile is $W = 10\%$, the minimum signal-to-noise ratio is $S/N_{\min} = 10$, the antenna gain is $G = 16\,{\rm K\cdot Jy^{-1}}$, the number of polarizations is $n_{\rm p} = 2$, the integration time $t_{\rm int}$ is given in units of seconds, the bandwidth is $\Delta f = 300$ MHz in consideration of the radio-frequency interference (RFI), and P is the spin period. The system temperature $T_{\rm sys}$ consists of three components: the receiver noise $T_{\rm rcvr} = 24$ K, the sky background noise $T_{\rm sky}$, which was calculated at 1250 MHz using the 408 MHz all-sky survey and a spectral index of -2.7, and the contribution from the SNR radio radiation $T_{\rm rem}$. Following the steps of Lorimer *et al.*, [8] we estimated $T_{\rm rem}$ for each SNR, and the results are given in Table 1.

Table 1. Properties of five SNRs*.

SNR	RA (hh:mm:ss)	DEC (dd:mm:ss)	Size (arcmin)	Distance (kpc)	DM** ($\rm cm^{-3}\cdot pc$)	$T_{\rm sky}$ (K)	$T_{\rm rem}$ (K)	Sensitivity (mJy)
G29.6+0.1	18:44:52	−02:57:00	5	4.4–5	315–475	23	12	0.02
G29.7–0.3	18:46:25	−02:59:00	3	5.3–5.9	559–759	23	210	0.09
G30.7–2.0	18:54:25	−02:54:00	16	4.7	210	14	1	0.01
G31.5–0.6	18:51:10	−01:31:00	18	6.3	643	19	1	0.02
G96.0+2.0	21:30:30	+53:59:00	26	4–4.9	180–226	6	1	0.01

*RA, DEC, size, and distance are taken from the SNRcat [18] and references therein.

**DM is calculated using the YMW16 electron-density model. [19]

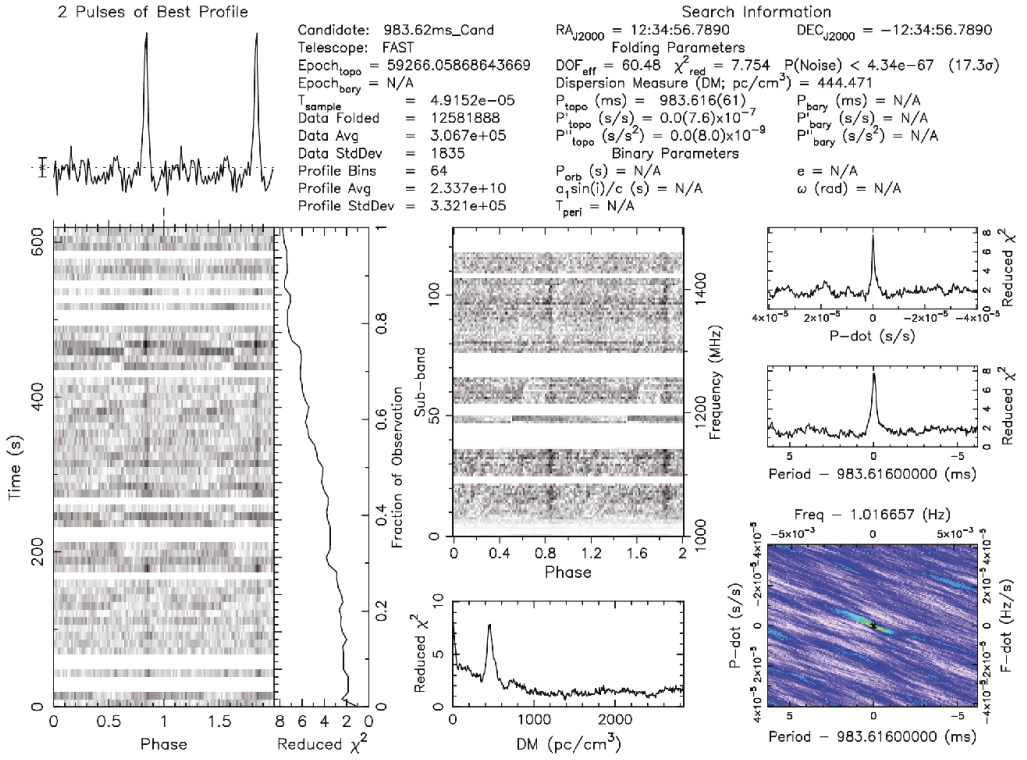

Fig. 1. The PRESTO discovery plot of the 983.6 ms pulsar.

We performed periodicity and single-pulse searches using the pulsar searching software package `PRESTO`.[20–22] RFI was checked and zapped using the routine `rfifind`. The range of trial dispersion measure (DM) was 0–2000 cm^{-3}·pc with steps of dmstep = 0.1. The routine `accelsearch` was used to search periodic signals in the Fourier domain. We set $z_{\max} = 200$ to search for signals drifting up to 200 Fourier bins. The routine `single_pulse_search.py` was used to search for single pulses with a signal-to-noise ratio larger than five.

G30.7–2.0, G31.5–0.6, and G96.0+2.0. No pulsars were detected in these observations. However, we were able to obtain an upper limit (see the Sensitivity column in Table 1) on the pulsed radio emission from pulsars in these SNRs if any pulsars exist in these regions.

G29.7–0.3. In observations of this SNR, we re-detected a known pulsar, PSR J1845–0316, and a known rotating radio transient (RRAT), PSR J1846–0257. The DM of PSR J1846–257 is much smaller than that of G29.7–0.3, which implies that they are unlikely to be associated with each other. Although G29.7–0.3 and PSR J1845–0316 have similar DMs, it is difficult to unambiguously identify an association between them without accurate measurements of the distance to the pulsar and the remnant.[23]

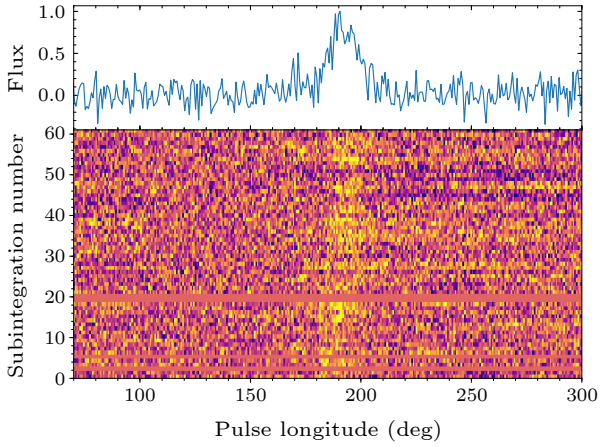

Fig. 2. The pulse profile (upper) and single-pulse stack (lower) folded using the `DSPSR` package for the 983.6 ms pulsar.

G29.6+0.1. In observations of this SNR, we re-detected four known pulsars, PSRs J1844–0244, J1844–0256, J1844–0302, and J1844–0310, and discovered a new pulsar, J1845–0306. We checked with the CRAFTS and GPPS teams, but neither project had detected PSR J1845–0306. We also searched for this pulsar in the online Pulsar Survey Scraper,[24] which contains the results of many pulsar survey projects, but we did not find any pulsar with a similar period and DM at the location of PSR J1845–0306. Therefore, we claim that PSR J1845–0306 is a newly discovered pulsar in this work. PSR J1845–0306 was detected in the M11 beam in the third pointing and the M12 beam in the first pointing. The `PRESTO` discovery plot is shown in Fig. 1. The RA and DEC values were estimated according to the centers of two beams in which the pulsar signal was detected. Next, we fixed the RA and DEC, and fit for the period and DM only with the observational data using TEMPO2. The derived values are given in Table 2. We also dedispersed and folded the data using these values and the `DSPSR` package, and the results are presented in Fig. 2. This pulsar has a rotation period of $P = 983.6$ ms and a dispersion measure of $\mathrm{DM} = 444.6 \pm 2.0\,\mathrm{cm}^{-3}$·pc. Follow-up timing observations for this pulsar will be needed to determine the astrometric and spin parameters, such as position, spin period, and DM, more accurately. Gaensler *et al.*[25] proposed that G29.6+0.1 is physically associated with the x-ray pulsar AX J1845–0258. However, the distance of AX J1845–0258 is estimated to be $\sim$10 kpc, which is significantly larger than that of G29.6+0.1. The DM of PSR J1845–0306 is in good agreement with that of G29.6+0.1. Similar to G29.7–0.3 and PSR J1845–0316, further investigations are needed to determine whether G29.6+0.1 is associated with PSR J1845–0306.

Table 2. The discovery parameters of the 983.6 ms pulsar.

PSR	J1845–0306
RA (J2000)	18:45:25
DEC (J2000)	−03:06:32
Spin period, P (ms)	983.641
Timing epoch (MJD)	59266
DM (cm^{-3}·pc)	444.6 ± 2.0

Discussion. To date, nearly 4000 pulsars[26] and 383 SNRs[27] have been discovered in the Milky Way. Among these, 110 pulsars have been identified as being associated with SNRs.[28] That is, less than one-third of known SNRs are observed to be associated with pulsars. The possible causes of the lack of detection of associated pulsars in SNRs are as follows: First, the radio emission beam of the pulsar may not sweep across the Earth, causing us to miss the pulsar. Second, the sensitivity limitations of the radio telescope may prevent us from detecting the pulsar.[11] Third, the pulsar may have been born with a high kick velocity, and therefore may have moved out of the SNR. Fourth, some models suggest that some supernova explosions may not produce neutron stars, or that the neutron stars they produce cannot be detected because they do not have the radio emission characteristics of radio pulsars.[29–32]

In this work, we did not detect any pulsar signals in observations of three SNRs, G30.7–2.0, G31.5–0.6, and G96.0+2.0. As the most sensitive single-aperture radio telescope in the world, FAST can give the most stringent upper limit for pulsed radio emissions from potential pulsars within these SNR areas. We re-detected some known pulsars in observations of G29.7–0.3 and G29.6+0.1, and discovered a new pulsar, J1845–0306, in observations of G29.6+0.1. The association between PSR J1845–0306 and SNR G29.6+0.1 is still unclear. On the one hand, PSR J1845–0306 is very close to the center of SNR G29.6+0.1,

and they have consistent DMs, which supports the hypothesis that they are associated; however, on the other hand, the spin period of PSR J1845–0306 is longer than that of 75% of pulsars associated with SNRs, which implies that PSR J1845–0306 is unlikely to be associated with an SNR. Judging the associations between pulsars and SNRs depends on various criteria, such as consistency in distance and in age, positional coincidence, and evidence for interaction, among which age and distance are the most fundamental. Follow-up timing observations using FAST will help to estimate the age and distance of PSR J1845–0306 and SNR G29.6+0.1.

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