Study of the Pulse Nulling Phenomenon in PSR J1701—3726 (Postprint)

Authors:

Date: 2024-10-15T09:46:43+00:00

Abstract

Utilizing observational data from the Parkes 64 m radio telescope at a central frequency of 1369 MHz, we analyzed the pulse nulling phenomenon of PSR J1701-3726 and found that this star's pulse nulling phenomenon exhibits quasi-periodicity, with a quasi-period value of approximately 81.25P, {where P is the spin period of PSR J1701-3726}, and calculated the nulling fraction {(Nulling Fraction, NF)} to be 27% ±~0.97%. Further investigation of the temporal variation of relative energy of single pulses within the pulse emission window region revealed four distinct switching modes (a, b, c, d) between the nulling and bursting states, with mode a occurring 23 times, mode b 6 times, mode c 5 times, and mode d 79 times, suggesting that state transitions may possess a certain degree of randomness.

Full Text

Acta Astronomica Sinica, Vol. 65, No. 5, September 2024

doi: 10.15940/j.cnki.0001-5245.2024.05.008

A Study of Pulse Nulling in PSR J1701-3726

CAI Yan-qing[12], LI Qing-ying[12], TIAN Jie[12], LI Wei[12], DANG Shi-jun[12], SHANG Lun-hua[12], XU Xin[12], ZHI Qi-jun[12], WU Jia-chao[12]

[1] School of Physics and Electronic Science, Guizhou Normal University, Guiyang 550025

[2] Guizhou Provincial Key Laboratory of Radio Astronomy and Data Processing, Guiyang 550025

Abstract

Using observation data from the Parkes 64 m radio telescope at a central frequency of 1369 MHz, we analyzed the pulse nulling phenomenon of PSR J1701-3726. We found that the pulse nulling exhibits quasi-periodicity with a period of approximately 81.25P, where P is the spin period of the pulsar, and calculated the nulling fraction (NF) to be 27% ± 0.97%. Further investigation of the temporal variation of relative energy in the on-pulse region revealed four distinct switching modes—labeled a, b, c, and d—between the null and burst states. Mode a occurred 23 times, mode b 6 times, mode c 5 times, and mode d 79 times, suggesting that state transitions may involve some degree of randomness.

Keywords: pulsars: individual: PSR J1701-3726, pulse nulling, methods: data analysis

1. Introduction

Pulsars are rapidly rotating neutron stars with strong magnetic fields. Since their discovery in the 1960s, pulsar radiation has remained a major focus of astronomical research. Observations show that individual pulse profiles vary considerably, but integrated profiles obtained by stacking hundreds or thousands of single pulses are remarkably stable. However, some pulsars exhibit integrated profiles that switch between two or more distinct shapes, a phenomenon known as mode changing. Other pulsars show intervals where pulse profiles cannot be detected by telescopes for certain periods, after which normal emission resumes. This is called pulse nulling or missing pulses, first discovered by Backer in 1970. Subsequently, Ritchings identified nulling in 32 pulsars using data from the MKIA radio telescope. To date, over 200 nulling pulsars have been observed, some displaying periodic nulling behavior.

Studying nulling phenomena provides deeper insight into pulsar radiation mechanisms. The nulling fraction (NF)—the ratio of time spent in the null state to total observation time—is a key parameter describing nulling behavior. NF varies widely among nulling pulsars, ranging from less than 1% to over 90%. Ritchings found that NF correlates with pulsar age, with older pulsars showing longer null durations. Statistical analyses of 72 nulling pulsars by Li et al. revealed a significant correlation between NF and pulse equivalent width. Wang et al. found positive correlations between NF and both pulsar age and period, noting that all pulsars with large NF are older than one million years, though NF shows little correlation with pulse profile shape. They proposed that mode changing and nulling may represent different manifestations of the same underlying phenomenon.

PSR J1701-3726 was discovered in 1992 by the Parkes 64 m telescope and exhibits both nulling and mode changing. Wang et al. analyzed 2 h of observations at 1518 MHz, finding frequent nulling within 60–500 s intervals and an NF of 14%. The pulsar's A and B modes were separated by null pulses, with the B mode being weaker and rarer, appearing only 7–8 times during the 2 h observation and lasting 1–2 min each time. Gajjar et al. later studied the pulsar at 610 MHz, obtaining an NF of 19%. In this work, we use 2 h of Parkes 64 m observations from 2014 to investigate the periodicity and switching processes of nulling in PSR J1701-3726.

2. Observation and Data Processing

We used Parkes 64 m telescope observations of PSR J1701-3726 from April 2, 2014, with a central frequency of 1369 MHz, bandwidth of 256 MHz, 512 frequency channels, and the PDFB4 (Pulsar Digital Filter Bank 4) backend, for a total duration of 2 h.

The data were processed using pulsar analysis software. First, DSPSR (Digital Signal Processing Software for Pulsar) was used for dedispersion and period folding, with a subintegration time of one pulse period to facilitate nulling analysis. Next, the PAZ (Pulsar Archive Zapper) module in PSRCHIVE was applied for automated radio frequency interference (RFI) removal, and the lowest 5% signal-to-noise ratio regions at both band edges were excised. Manual RFI removal was then performed using the PAZI (Pulsar Archive Zapper Interface) module. Finally, the PAM (Pulsar Archive Manipulator) module folded the frequency and polarization signals. This processing yielded 2926 single pulses for detailed analysis.

3. Results

3.1 Single-Pulse Energy Distribution

To assess the impact of RFI, we examined the distribution of root-mean-square (rms) values in non-radio-emission regions across the 2926 single pulses. A Gaussian rms distribution indicates minimal RFI contamination, whereas a random, non-Gaussian distribution suggests strong interference. We generated a total average pulse profile and identified regions without significant pulse emission as off-pulse regions. Each single pulse was normalized using the peak of the total average profile, and the rms values in off-pulse regions were computed. Figure 1 [Figure 1: see original paper] shows the histogram of rms values, with the red dashed line representing the Gaussian fit (and σ denote the mean and standard deviation). The excellent Gaussian distribution indicates stable baseline noise and low RFI contamination, making the data suitable for single-pulse analysis.

Smith first used single-pulse energy histograms to study nulling. Following this approach, we defined the on-pulse window using regions with clear emission in the total average profile, with an off-pulse window of equal width. Energy values in both regions were calculated for each pulse and normalized by the mean on-pulse energy, yielding relative energies. Figure 2 [Figure 2: see original paper] shows the histogram of relative energies. The on-pulse region exhibits a clear bimodal distribution, with pulses near zero energy corresponding to null subpulses of PSR J1701-3726.

3.2 Pulse Nulling

PSR J1701-3726 exhibits both nulling and mode changing. Wang et al. reported an NF of 14%, while Gajjar et al. found 19% at lower frequencies, demonstrating that NF can vary with observing frequency and epoch. Using our 1369 MHz data, we further investigated the nulling behavior.

Wang et al. noted that A and B modes are separated by null pulses, with B mode being weaker and rarer. Since our focus is on periodicity and transitions between null and burst states, we do not distinguish between A and B modes. Pulses with detectable on-pulse emission are labeled burst-state pulses, while those without significant detection are null-state pulses.

We adopted a method similar to Bhattacharyya et al. to classify null and burst pulses. First, we computed the uncertainty in the energy measurement for each pulse as $\sigma_{ep} = \sigma_{off} \times \sqrt{N_{on}}$, where N_{on} is the number of bins in the on-pulse window and σ_{off} is the rms in off-pulse regions. Pulses with on-pulse energy exceeding a multiple of σ_{ep} were classified as burst-state; otherwise, they were null-state. The multiple was tuned iteratively: using $5\sigma_{ep}$ left weak emission in the null-state average profile, as did $3\sigma_{ep}$. To avoid including weak emission in the null state, we adopted $2\sigma_{ep}$ as the threshold (energy $> 2\sigma_{ep}$ for burst state). The resulting average profiles are shown in Figure 3 [Figure 3: see original paper]. The null-state average shows no significant pulse component, confirming that most weak emission was excluded, while the burst-state average reveals a multi-peaked structure.

The NF is given by N_{null}/N_{total}, where N_{null} is the number of null pulses and N_{total} is the total number of pulses. We obtained NF = 27% ± 0.97%, consistent with previous results.

The duration sequences of null and burst states were extracted. Figure 4 [Figure 4: see original paper] shows histograms of state durations. Most null states last 0–5 periods, with only a few longer events, indicating that nulling in this pulsar is dominated by short timescales.

Herfindal and Rankin first discovered periodic nulling in PSR B1133+16 in 2007, and similar periodicities have since been found in other pulsars. To test for periodicity in our data, we followed Gajjar et al. and created a binary sequence marking null pulses as 0 and burst pulses as 1. The Fourier transform of this sequence (Figure 5 [Figure 5: see original paper]) reveals clear periodicity at approximately 81.25P, where P is the spin period of PSR J1701-3726.

3.3 Study of the Nulling Process

Investigating transitions between null and burst states provides insight into pulsar radiation physics. Bhattacharyya et al. found that PSR B0818-41 switches gradually from burst to null state (gradual mode) but abruptly from null to burst (abrupt mode). Wen et al. discovered another pattern in PSR J1727-2739, where both gradual and abrupt transitions occur from burst to null. These patterns had not been studied in PSR J1701-3726. Following Bhattacharyya et al. and Wen et al., we examined the switching processes.

Figure 6 [Figure 6: see original paper] shows the temporal variation of relative on-pulse energy for selected pulses. Four distinct switching modes are identified: (a) gradual null-to-burst and abrupt burst-to-null; (b) gradual both ways; (c) abrupt null-to-burst and gradual burst-to-null; (d) abrupt both ways.

In our 2 h observation, mode d occurred 79 times, mode a 23 times, while modes b and c were rare (6 and 5 times, respectively). This suggests that abrupt transitions dominate. We hypothesize that these modes may be modulated by a randomly occurring weak emission component: when present, transitions are gradual; when absent, they are abrupt.

4. Summary and Discussion

Our analysis of Parkes 64 m data reveals an NF of 27% ± 0.97% for PSR J1701-3726, with quasi-periodic nulling at ~81.25P. We identified four switching modes between null and burst states: (a) gradual null-to-burst and abrupt burst-to-null; (b) gradual both ways; (c) abrupt null-to-burst and gradual burst-to-null; (d) abrupt both ways. Mode d dominates, followed by mode a, while modes b and c are rare. We propose that these modes may be modulated by a stochastic weak emission component, with gradual transitions occurring when this component is present.

Two main theories explain nulling: geometric effects (where emission continues but misses our line of sight) and intrinsic cessation of radiation. The RS model posits that nulling occurs when electron-positron pair discharge stops in the polar gap. However, Filippenko and Radhakrishnan noted that the RS model struggles to explain associated phenomena like mode changing. They proposed that radio emission originates in limited regions (flux tubes) within the gap. In normal states, avalanching discharge occurs; in null states, this becomes continuous, stable, and low-energy. This modification successfully links nulling and mode changing. Wang et al. suggested that PSR J1701-3726's nulling and mode changing are closely related, which can be explained by the FR modification. However, the absence of significant emission in our null-state average profile suggests that discharge may actually cease in the flux tubes during nulls.

References

[1] Backer D C. Nature, 1970, 228: 1297
[2] Backer D C. Nature, 1970, 228: 42
[3] Ritchings R T. MNRAS, 1976, 176: 249
[4] Wang P F, Han J L, Han L, et al. A&A, 2020, 644: A73
[5] Herfindal J L, Rankin J M. MNRAS, 2007, 380: 430
[6] Herfindal J L, Rankin J M. MNRAS, 2009, 393: 1391
[7] Gajjar V, Joshi B C, Kramer M. MNRAS, 2012, 424:

[8] Basu R, Mitra D. MNRAS, 2018, 476: 1345
[9] Basu R, Mitra D. MNRAS, 2019, 487: 4536
[10] Wang N, Manchester R N, Johnston S. MNRAS, 2007, 377: 1383
[11] 李向东, 汪珍如. 天文学报, 1995, 36: 1
[12] Li X D, Wang Z R. ChA&A, 1995, 19: 302
[13] Johnston S, Lyne A G, Manchester R N, et al. MNRAS, 1992, 255: 401
[14] Van Straten W, Bailes M. PASA, 2011, 28: 1
[15] Hotan A W, Bunton J D, Harvey-Smith L, et al. PASA, 2004, 21: 302
[16] Rejep R, Wang N, Yan W M, et al. MNRAS, 2022, 509:
[17] Smith F G. MNRAS, 1973, 161: 9P
[18] Bhattacharyya B, Gupta Y, Gil J. MNRAS, 2010, 408:
[19] Gajjar V, Yuan J P, Yuen R, et al. ApJ, 2017, 850: 173
[20] Wen Z G, Wang N, Yuan J P, et al. A&A, 2016, 592:
[21] Ruderman M A, Sutherland P G. ApJ, 1975, 196: 51
[22] Filippenko A V, Radhakrishnan V. ApJ, 1982, 263: 828

Note: Figure translations are in progress. See original paper for figures.