Intriguing Drifting Subpulses in the Vela Pulsar

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Abstract

We report on the discovery of drifting subpulses from the Vela pulsar, observed using the Yunnan 40 m radio telescope at 6800 MHz observing frequency. The single pulses show the presence of two distinct drifting patterns, where the central component is modulated in longitude and amplitude simultaneously with a period of 9 pulses, and the trailing component remains stationary within the pulse window but periodically changes in intensity with a period of 29 pulses. The leading component emission remains constant in intensity and pulse phase. Such periodic modulation in the Vela pulsar is a separate phenomenon from periodic nulling and traditional subpulse drifting, which may lead to a greater understanding of the pulse emission mechanism.

Unified Astronomy Thesaurus concepts: Pulsars (1306)

1. Introduction

Pulsars are famous for their extremely stable averaged pulse profiles. Nevertheless, the single pulses present highly variable shapes from pulse to pulse. In certain pulsars, the single pulses are modulated in a highly organized and fascinating way: the phenomenon of subpulse drifting (Drake & Craft 1968). A periodic variation within the pulse window either in phase or amplitude or both is exhibited in their individual subpulses, which is supposed to be an intrinsic property of the emission mechanism. The pattern can be described with two periodicities in a phase-time diagram: the spacing between two consecutive subpulses in rotational phase ($P_2$) and the separation between the diagonal drift bands in pulse number or pulse periods $P_1$ ($P_2$). Drifting subpulses are relatively common, around 120 pulsars have been reported to possess this phenomenon over timescales ranging from a few seconds to several minutes (Weltevrede et al. 2006, 2007). Such modulations have only been seen in normal pulsars with rotational periods larger than 0.1 s (Basu et al. 2020). It appears that the drifting phenomenon becomes more and more ordered for pulsars with a higher age, and the youngest pulsars have the most disordered subpulses (Weltevrede et al. 2008).

The mechanism of subpulse drifting seems to be associated with the inclination angle $\alpha$ between the magnetic axis and the rotation angle (Weltevrede et al. 2008). More specific physical characteristics related with subpulse drifting are revealed from recent studies (Basu et al. 2016). Subpulse drifting is dependent on profile type and spin-down luminosity. Furthermore, the physics of the emission mechanism between periodic amplitude modulation and phase drifting is distinct (Basu et al. 2020).

The Vela pulsar (J0835−4510) is the brightest pulsar of all and is associated with the Vela supernova remnant. It has a spin period of $P = 89.3$ ms and a period derivation of $\dot{P} = 1.25 \times 10^{-13}$ s s$^{-1}$, giving a characteristic age of $\tau_c = 11.3$ kyr and a spin-down energy loss of $\dot{E} = 6.9 \times 10^{36}$ erg s$^{-1}$ (Manchester et al. 2005). Vela has been focused on either long-term timing or short-term single-pulse studies. Regular glitches were demonstrated every three years approximately (Dodson et al. 2007). Giant micropulses were detected in the leading edge of the pulse profile (Johnston et al. 2001). Nevertheless, no periodic modulation from pulse to pulse has been mentioned in the literature. One primary reason for this maybe that there is a real divide between the Vela pulsar and known drifting pulsars. On the other hand, such studies require long observations covering a large number of consecutive single pulses. The previous observations concentrated on high signal-to-noise ratio from short integration times since the Vela pulsar is strong enough. In this work, we have characterized the subpulse drifting of the Vela pulsar using around 4 hr consecutive single-pulse observations at the C band.

2. Observations

The single-pulse observations used in our analysis below come from a program carried out with the Yunnan 40 m radio telescope in a frequency band centered at 6800 MHz from MJD 58712.107 to MJD 58712.263 (2019 August 17). Use of an 800 MHz bandwidth, across which 1024 channels were digitally divided by a filterbank system, and a 40.96 $\mu$s time resolution reduced dispersion delay across the subchannel to negligible levels. The resolution was then essentially the sampling time of 0.165 longitude. No continuum source observation was available to calibrate flux and polarization. The data were recorded in the format of PSRFITS (Hotan et al. 2004) with 8-bit quantization. After checking for and excising radio

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3. Analysis and Results

We have used the fluctuation spectral analysis to estimate the periodicity in the single-pulse behavior as described in Backer (1970). First, the pulse stack is divided into 588 blocks of nominal 256 successive pulses. Subsequently, the longitude-resolved fluctuation spectra (LRFS) are calculated by performing the discrete Fourier transform on these blocks. The final spectral power of fluctuations as a function of rotational longitude is obtained by averaging the fluctuation power spectra of different blocks, which is shown in Figure 1. The units of the horizontal axis are in cycles per period (cpp), which corresponds to $P_1$ in the case of drifting (where $P_1$ is the pulsar rotational period, $P_3$ is the interval over which the subpulses repeat at any specific location within the pulse window). The vertical axis is the pulse longitude in degrees. A 256-point Fourier transform is used and averaged over the blocks of the whole pulse sequence. The units of brightness are arbitrary, since the data were not flux calibrated. The total power profile is plotted and aligned with the LRFS in the left panel. The boundaries are plotted with dashed lines to distinguish leading, central, and trailing components. The integral power spectra from leading, central, and trailing emission windows are presented with red solid, blue dashed-dotted, and magenta dashed lines at the bottom of the figure, respectively.

In order to determine whether the periodic modulations are originated from phase drifting or amplitude fluctuation, the two-dimensional fluctuation spectrum (2DFS; Edwards & Stappers 2002) is calculated. Following the same procedure used while calculating the LRFS, the two-dimensional discrete Fourier transforms are carried out on the central and trailing longitude ranges, respectively. Finally, the spectra of the different blocks are averaged to obtain the final spectra. In Figures 2 and 3, the 2DFSs corresponding to the central and trailing components are plotted respectively. One can see the main features at the same horizontal positions as in the LRFS (corresponding to the same $P_1$ values). The pattern repetition frequency along the pulse longitude is denoted in the vertical axis of the 2DFS, which is expressed as $P_1/P_2$. The values of $P_2$ are measured to be infinite since no phase offsets corresponding to the peak frequencies are presented, which may suggest that the center and trailing emission components are longitude stationary across the pulse window but periodically change in intensity.
In order to rule out the possibility that the occasional occurrence of strong subpulses are dominating the spectra and therefore lead to misleading conclusions, a similar method is adopted to further demonstrate the authenticity of periodic fluctuations (Weltevrede et al. 2006). The order of the pulse sequence is randomized and then the LRFS and 2DFSs are calculated from the newly formed pulse stack. No well-defined $P_3$ in this process is detected in the emission window and noise window, which proves the significance of drift features.

To visualize the time-averaged properties of subpulse modulation, a completely different method independent of the Fourier-based technique is adopted by folding the pulse stack over the modulation cycle (Deshpande & Rankin 2001). Figures 4 and 5 present the resulting $P_3$-folded pulse stacks after averaging at periods of $P_3 = 9.09P_1$ and $P_3 = 28.57P_1$, respectively. As shown in the main panel of Figure 4, the center component clearly presents negative drift, that is, subpulses moving toward the earlier longitude by around $6^\circ$ in a drift band. Furthermore, the energy of center component shoots up at the first pulse in the drift band, then goes down for the following pulses. In Figure 2, the phase drifting is not detected with the Fourier transform technique, which means that the drifting of the center component manifests itself more as an amplitude modulation rather than as a phase modulation. As shown in Figure 5, the power in the trailing component does not clearly show phase drifting, which indicates that the trailing component is indeed periodically modulated in amplitude. The phase and intensity of the leading and center components remain constant approximately, while the trailing component rises to a maximum intensity in two pulses, along with broadening in pulse width.

4. Discussion

It is generally accepted that the subpulse drifting phenomenon is originated in the inner acceleration region of pulsars (Ruderman & Sutherland 1975). The radio emission is generated via a rotating “carousel” of sparking discharges that circulate around the magnetic axis governed by an $E \times B$ drift (Gil et al. 2003). Alternative explanations are also proposed, such as nonradial pulsations of neutron stars (Ruderman 1968) and the interaction between the outer magnetosphere and the polar cap (Wright 2003). However, these models are generally focused on the phase-modulated drifting and do not take into account the nature of periodic amplitude modulation. The physical mechanism of periodic amplitude modulation is currently unknown, but is expected to be originated from large-scale variations affecting the plasma generation process in the inner acceleration region.

During the glitch of 2016 in the Vela pulsar, it experienced a single null followed by two low linear polarized pulses, which suggests that the magnetosphere was affected by the glitch event (Palfreyman et al. 2018). Periodic nulling is seen as an extreme periodic amplitude modulation across the entire profile, where the core component vanishes along with cones in the same periodic manner (Herfindal & Rankin 2007). The longer modulation periodicity is demonstrated to be associated with nulling, and the shorter periodicity usually originates from phase-modulated subpulse drifting (Basu et al. 2017). The periodic nulling is supposed to be associated with the empty line of sight passing extinguished subbeam emission regions (Herfindal & Rankin 2007), which is probably not applicable to the Vela pulsar. For the probable central core component in the Vela pulsar, it is measured to be modulated both in phase and amplitude with the same period, which is shorter than the period of amplitude modulation in the trailing component.
However, in the picture of a rotating subbeam carousel model, the core component is expected to be phase stationary and does not participate in the carousel rotation.

The phase-modulated drifting was seen as subpulse variation affecting each component differently in PSR J2006–0807 (Basu et al. 2019). Basu et al. (2016) found clear differences between physical parameters of phase-modulated drifting and amplitude-modulated drifting. Subpulse drifting is profile dependent, phase modulation is only shown in the conal components and absent in the central core emission, and amplitude modulation is seen across all components. Pulsars with lower spin-down luminosity (\( \dot{E} < 2 \times 10^{32} \text{ erg s}^{-1} \)) possess a higher possibility of showing phase-modulated drifting. Furthermore, the phase-modulated drifting periodicity is anticorrelated with spin-down luminosity. No clear dependence between amplitude-modulated drifting and spin-down luminosity was shown. The physical mechanism of distinct periodic amplitude and longitude modulations in the Vela pulsar is currently unknown, but is expected to be different from the general subpulse drifting.

Generally, pulsars rotate at extremely stable speeds, but occasionally they speed up in short events described as “glitches.” Two types of discrete discontinuities in the rotation of pulsars are detected. The conventional glitches are characterized by a sudden increase in the rotation frequency (\( \nu \)) and usually are accompanied by an increase in the magnitude of the spin-down rate (\( \dot{\nu} \)). The discrete discontinuities in the rotation frequency (\( \Delta \nu \)) and the spin-down rate (\( \Delta \dot{\nu} \)) have magnitudes in the ranges of \( 10^{-10} \nu \text{ to } 10^{-6} \nu \) and \( 10^{-5} \dot{\nu} \text{ to } 10^{-3} \dot{\nu} \), respectively (Janssen & Stappers 2006; Melatos et al. 2008). On the other hand, the microglitches constitute a class of small amplitude, but resolvable, jumps in both, or either of the pulsar rotation frequency and its spin-down rate. The amplitude of the jumps vary over a wide range, but are generally supposed to be within \( \Delta \nu < 10^{-10} \nu \) and \( \Delta \dot{\nu} < 10^{-3} \dot{\nu} \) (Cordes et al. 1988). Recently, an intensive single-pulse observation campaign of the Vela pulsar at 1376 MHz showed that the pulse profile changed temporally and was affected by a microglitch (Palfreyman et al. 2016). Sudden changes in the pulse shape coincident with the 2016 glitch were detected, which indicates that the glitch altered the Vela pulsar magnetosphere (Palfreyman et al. 2018). Furthermore, the consecutive bright radio pulses with five times the flux of the average pulse were detected at 1440 MHz for the first time, which was suggested to be related to the glitch in late 2010 (Palfreyman et al. 2011). The investigation of the fluctuation spectrum immediately following the glitch is encouraged. Furthermore, polarimetric observations at multifrequencies are required to validate the presence of periodic behavior.

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