Drifting subpulses and polar cap surface temperature in pulsars

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The drifting subpulse phenomenon is widely regarded as a powerful diagnostic tool in investigations of pulsar radio-emission mechanisms. We analyze single pulse data from PSR B0826-34 showing apparent changes of subpulse drift direction (Fig. 1), inconsistent with pulsar electrodynamics. We demonstrate that this unusual behaviour is not genuine, and results from aliasing in sampling of the intensity fluctuations. Aliasing resolved, drifting subpulses in PSR B0826-34 provide first direct evidence of a system of sparks circulating on the polar cap. This pulsar is perfectly consistent with the Ruderman-Sutherland (1975) ExB drift model. The polar cap surface is heated by sparks to temperature $T_s \sim 10^6$ K, slightly below the critical ion temperature T_i above which the thermionic emission of iron ions reaches the Goldreich-Julian charge density.

PSR B0826-34

The emission in PSR 0826-34 occurs in the entire pulsar period (Biggs et al. 1985), which indicates an almost aligned rotator, with the rotation and magnetic axes nearly parallel. Therefore, the observer's line-of-sight stays in the emission beam for most of the rotational period P_1. This provides a unique opportunity of scanning the polar cap along its circumference and, therefore, detecting radiation from a relatively large number N of subpulse-associated beams of radio emission. These beams are believed to rotate around the magnetic axis in the time interval P_4=NP_3 , where P_3 is the usual drift periodicity (vertical separation between drift-bands in pulsar periods P_1). Although the horizonthal drift-band separation is known ($P_2 \approx 25^0$), the real value of P_3 (and therefore the value of the actual drift rate $D_0=P_2/P_3$) cannot be determined without aliasing resolving. However, we can first determine the number of involved subpulse subbeams, using the fact that the magnetic and the spin axes of the pulsar are nearly aligned. In such case, the angular separation between adjacent sparks on the polar cap is almost the same as the observed P_2 and hence, $N \approx 360^0/P_2$. This yields a value of 14 sparks circulating on the polar cap.

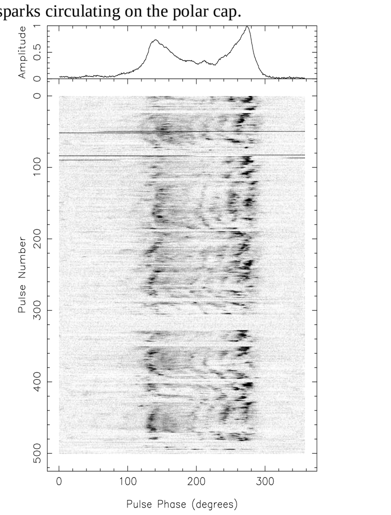

Fig. 1 A stacked sequence of 500 single pulses from PSR 0826-34 observed using Giant Metrewave Radio Telescope at a frequency 318 Mhz with a bandwidth of 16 MHz. The vertical axis represents the sequential pulse number (from the top to the bottom), each corresponding to one full rotation of the neutron star, represented on the vertical axis by 360 degrees of longitude. The upper panel shows the mean profile from these 500 pulses. Every single pulse contains a number (7-8) subpulses, shown using the grey-scale intensity coding. These subpulses (darker segments) form a multiple curved bands correlated over a long sequence of pulses. The adjacent drift-bands are separated from each other by about 25 deg of longitude. The apparent drift-rate varies systematically along each drift-band, including changes of drift direction. These variations are quasi-periodic and occur in cycles of about 100 pulse periods. This unusual behaviour is very different from the typical situation in pulsars with drifting subpulses.

In order to find the value of P_4 we have to determine P_3. This requires aliasing resolving, which can be achieved by realistic simulations of radiation associated with these 14 subbeams. However, this in turn requires the knowledge of geometrical parameters, such as: the inclination angle α (between the pulsar's rotation and magnetic axes), the impact angle β (of the closest approach of the line-of-sight to the magnetic axis) the circulation distance d of sparks from the pole and the emission altitude r at which the subpulse radiation is emitted tangently to dipolar magnetic field lines connected with the sparks. These geometrical parameters can be determined from measurements of the pulse width *W* and variations of the mean position angle ψ along the pulse longitude φ, as these quantities depend on different combinations of α, β and d. Using all the available observational information, we obtained $\alpha=2.5^0\pm0.2^0$, $\beta=1.0^0\pm0.1^0$ and $d=0.45r_p=33$ m for PSR 0826-34.

Simulations

We can now simulate the radiation of PSR 0826-34, assuming that its single pulse structure reflects the circumferential motion of 14 sparks at a distance of about 33 meters from the pole. The spark-associated subpulses are emitted tangently to dipolar field lines at an altitude r determined by radius-to-frequency mapping (Kijak & Gil 1998).

The number of subpulses and their phases in a single pulse are determined by the angles α and β, as well as by the angular drift rate $D_r=360^0 P_4$. Since the latter is not known a priori, we performed an experiment with time varying drift rates, starting with $D_r=0$ and incrementing it by $\Delta D_r=0.03^0$ every pulsar period P_1. Such value of ΔD_r was chosen to make sure that cycles of gradual variations of the drift rate have duration of about $100P_1$, as observed. The idea is to find a sequence of about 100 pulses with varying $D_r=n\Delta D_r$ in a range appropriate to produce curved drift-bands similar to those visible in Fig. 1. The sample result of our simulations is presented in Fig. 2, with all important information written in the top panel and on both sides of the pulse window. The last column indicates the actual value of $D_r=n0.03^0/P_1$, where n is the sequential pulse number indicated on the vertical axis. Next to D_r we show values of $P_4/P_1=360^0/D_r$. On the other side of the pulse window we show values of $P_3/P_1=P_4/(14P_1)$ and the column just next to it shows the fluctuation frequency $f_3P_1=P_1/P_3$.

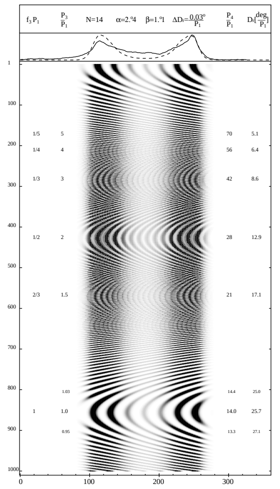

Fig. 2 Simulations of subpulse drift phenomenon with time varying drift rate $D_r(n)=T_n\,\Delta D_r$, where $\Delta D_r=0.03^0/P_1$, $T_n=nP_1$ and n is the sequential pulse number. The quasi-periodic patterns of drifting subpulses observed in PSR 0826-34 (Fig. 1) are well modelled by a sector lying between n=800 and n=900, with D_r increasing from $25^0/P_1$ to $27.1^0/P_1$. The upper panel shows the average profile of sumulated pulses (dashed line) overlapped with the actual profile of PSR 0826-34 (solid line).

What can we learn from simulated patterns presented in Fig.2? First of all, pulse n=1 shows that were there no drift (D_r=0), the observer ($\alpha=2.^04$ and $\beta=1.^01$) would clearly see 7 out of 14 sparks in the form of longitude stationary subpulses. As the drift rate increases with the increasing pulse number, the subpulse drift with time varying rate becomes more and more apparent. However, up to about pulse number n=100, the subpulse drift is relatively slow, non-aliased and proceeds from the leading to the trailing edge of the profile. This is the real drift direction and the observed drift-bands are formed by the same sparks/subbeams. This is, however, not true in the region well above pulse n=100, where all kinds of stroboscopic effects become visible. We have marked regions where the apparent drift-bands are formed by subpulses appearing at approximately the same phase every m-th pulse period P_1, where m=5,4,3,2 and so on. It is worth nothing that the number of apparent drift-bands is about 7m. The drift-bands change the apparent drift direction due to the aliasing effect, every time f_3 crosses a multiple of the Nyquist frequency.

Obviously, the region below pulse n=800 does not correspond to drifting subpulses in PSR 0826-34, because it shows alternating, longitude stationary intensity modulations, which are not observed in this pulsar. It seems, however, that its drifting subpulse patterns are well modelled by the region between pulses n≈800 and n≈900, which represents just one cycle of multiple curved drift-bands visible in Fig. 1. A clear pattern of seven drift-bands is visible, moving in an aliased direction from the trailing to the leading edge in the first half of the cycle, and in the true direction from the leading to the trailing edge in the second half of the cycle. The drift direction change occurs at $f_3=1/P_1$ (or $P_3=P_1$), which is twice the conventional Nyquist frequency. At this stage the carousel advances exactly by one subbeam per one pulsar period P_1 and the apparent drift-bands are formed by successive adjacent subbeams. The corresponding values of $P_4/P_1=14$ and $D_r=25.7^0/P_1$. However, 50 pulses earlier, at the beginning of a cycle, $P_4/P_1=14.4$ and $D_r=25^0/P_1$, while 50 pulses later, at the end of a cycle, $P_4/P_1=13.3$ and $D_r=27.1^0/P_1$. This means that the carousel speeds up along each cycle, increasing D_r by about 8%. This can be converted into drift velocities of sparks circulating at a distance d=33 m from the pole. Since P_1=1.84 s and $P_4=2\pi d/v_d$, we obtain v_d=7.8, 8.0 and 8.5 m/s at the beginning, at the reversal phase and at the end of a cycle, respectively.

Ruderman & Sutherland model

It is now desirable to check whether the derived drift velocity v_d=8 m/s is consistent with the Ruderman & Sutherland model, in which

$$v_d = c\,\Delta V / r_p\, B_s \qquad (1)$$

where *c* is the speed of light, r_p=73 m is the polar cap radius, $B_s=2.7\times10^{12}$ G is the surface magnetic field at the pole, and

$$\Delta V = (2\pi/cP_1) B_s h^2 \qquad (2)$$

is the potential drop across the vacuum gap of height h. Thus, the actual drift velocity is $v_d=(2\pi/P_1)(h^2/r_p)$. The height of the gap is approximately equal to the distance between the adjacent sparks. Since at $P_3=P_1$ the sparks cover this distance in exactly one pulsar period P_1=1.84 s, moving with v_d=8 m/s, we can reasonably adopt that the effective gap height $h \approx v_d P_1$=14.7 m in PSR 0826-34. Thus, the estimated drift velocity v_d=9.8 m/s, in very good agreement with the observationally derived value v_d=8 m/s. The perfect agreement requires h=13.3 m, which implies the effective potential drop above the polar cap $\Delta V=2.6\times10^{11}$ V. To explain the curved subpulse drift-bands this potential drop has to vary systematically by several percent during a 100 period cycles. The mechanism of these quasi-periodic variations remains to be understood.

Alternatively, the polar gap potential drop (Eq. 2) can be written in the Ruderman & Sutherland form

$$\Delta V = \eta\, 1.6\times10^{12} (B_s/10^{12}\,\mathrm{G})^{-1/7} P_1^{-1/7}\ \mathrm{V}, \qquad (3)$$

where $\eta=(1-\rho_i/\rho_{GJ})$ is the screening factor, ρ_i is the charge density of the thermionic $^{56}Fe_{26}$ ions and ρ_{GJ} is the co-rotational Goldreich-Julian charge density. In the original RS paper ρ_i=0 and η=1, and a possibility of partial thermionic screening was proposed later as a natural modification of the pure vacuum gap model (Cheng & Ruderman 1980). For the parameters of PSR 0826-34 (P_1=1.85 s, $dP/dt=10^{-15}$) we obtain from Eqs. (1) and (2) that $v_d \approx 66$ m/s for η=1. This is much too fast as compared with $v_d \approx 8$ m/s inferred from our data and simulations. We conclude that in PSR 0826-34 the actual value of the screening parameter η is about 0.22, and thus ρ_i is about 80% of the Goldreich-Julian charge density. However, since v_d increases from 7.8 to 8.5 m/s during a 200 s cycle, η should increase from about 0.21 to about 0.23, respectively. Following Cheng & Ruderman 1980, one can show that the screening factor

$$\eta = 1 - \exp[30(1 - T_i/T_s)]\ , \qquad (4)$$

where $T_i \sim 10^6$ K is the so-called ion critical temperature, above which the thermionic ion flow reaches the Goldreich-Julian value and screens the gap completely, and T_s is the actual temperature of the polar cap surface heated by backflowing electrons produced by sparks. Taking η=0.21-0.23 we obtain T_s/T_i=0.992-0.991, thus the surface temperature T_s is just a few thousands K below the ion critical temperature $T_i \sim 10^6$K. During the 200 s cycle this temperature drops by a value $\Delta T_s=10^{-3}\ T_i \sim 1000$K, indicating a cooling rate of about 5 K/s. (However, after each cycle the temperature must rapidly rise back by about 1000 K during a time scale shorter than one pulsar period). Such a minute cooling results in a several percent increase of drift velocity, which can have a noticeable (even a dramatic) effect on the drift patterns, when combined with aliasing effects of the kind inferred by us for PSR 0826-34. In pulsars with non-aliased drift (e.g. PSR 0809+74) such small variations of the drift velocity do not affect the drift patterns, except perhaps for a slight bending of drift-bands. A detailed discussion of thermostatic effects in a number of drifting subpulse pulsars is presented in Gil et al. 2003 (astro-ph/ 0305463).