A MODEL FOR THE DRIFTING-SUBPULSE PHENOMENON

A. Z. Kazbegi, G. Z. Machabeli and G. I. Melikidze
Abastumani Astrophysical Observatory

The subpulse drift phenomena—that is, periodic subpulse phase variations in the individual-pulse sequences—was discovered by Drake and Craft (1968) in the beginning of the pulsar era. Many observational programs have been carried out since then, and it has been shown a) that only a minority of pulsars exhibit the phenomenon, and b) that only some of these can be characterized by a definite drift rate (Huguenin, Taylor, and Troland 1970, Backer 1970, Taylor and Huguenin 1971).

A consistent model explaining the origin of subpulse drift was published by Ruderman and Sutherland (1975) (see also, Cheng and Ruderman 1980). This model is based on the idea that sparks appear at definite places on the stellar surface within the polar cap gap. These sparks undergo $\boldsymbol{E}_0 \times \boldsymbol{B}_0$ drift which then manifests itself as a phase drift of the subpulses. Sparks provoke discharges that serve as a source of the subpulse associated plasma columns. Therefore the information about the spark drift is preserved.

The suggestion that a spiral wave is excited within the gap was first made by Arons (1981). This wave then modulates the particle density and explains the presence of the subpulses and their drift. The aim of this paper is to explain the phenomenon of drifting subpulses observed in the pulsar radio emission within the framework of the theory developed by authors [Kazbegi *et al.* 1989, 1992 (included in these Proceedings and hereafter Paper I)].

The observational data show that subpulse drift is primarily associated with conal single profiles (Rankin 1983a, 1986). As this paper deals with the subpulse-drift phenomenon we shall focus below on the condition [Paper I, eq.(16)] for the Cherenkov resonance

$$\frac{1}{2}\left(\frac{k_x}{k_\varphi}-\frac{u_x}{c}\right)^2+\frac{1}{2}\frac{k_r^2}{k_\varphi^2}-\delta=0. \tag{1}$$

Let us consider now the low frequency waves propagating nearly transverse to the magnetic field $\theta=\pi/2$. The dielectric permeability tensor is calculated in Paper I. Assume that $\omega=k_x u_x^b+k_\varphi v_\varphi+a$ and $k_x/k_\varphi \gg 1$. In the zero-order approximation of the series expansion over small parameter $\omega\gamma/\omega_{Be} \ll 1$ one obtains

$$1-\frac{3}{2\gamma_p^3}\frac{\omega_{pe}^2}{\omega^2}-\frac{\omega_{pe}^2}{2\omega^3}\frac{k_x u_x^p}{\gamma_p}-\frac{\omega_b^2}{\omega a}\frac{1}{\gamma_b^3}-\frac{\omega_b^2}{\omega a^2}\frac{k_x u_x^b}{\gamma_b}=\frac{k_\perp^2 c^2}{\omega^2}. \tag{2}$$

The indices "p" and "b" denote the plasma bulk and the beam respectively. The growth rate ($\Gamma_L=\Im a$) is greatest at

$$k_\perp^2 \ll \frac{\omega_p^2}{\gamma_p^3 c^2} \simeq 10^{-6}, \tag{3}$$

thus

$$\Gamma_L \simeq \sqrt{\frac{3}{2}}\left(\frac{n_b}{n_p}\right)^{\frac{1}{3}}\frac{\gamma_p^{\frac{3}{2}}}{\gamma_b^{\frac{1}{2}}}k_x u_x. \tag{4}$$

Hence the low-frequency wave (henceforth "drift wave")

$$\omega=k_x u_x+k_\varphi v_\varphi \tag{5}$$

is being excited on the left-hand slope of the distribution function corresponding to the beam. The wave draws energy from the longitudinal motion of the beam particles as in the case of an ordinary Cherenkov wave-particle interaction. However the wave is excited only if $k_x u_x^b \neq 0$—*i.e.*, in the presence of the drift motion.

The growth rate of the drift wave is rather small. However the waves propagate nearly transverse to the magnetic field encircling the magnetosphere and stay in the resonance region for time τ. The duration of this period depends on the φ-component of the wave vector and its direction. Let us choose the direction of particle propagation, *i.e.* the motion away from the star, as positive. At the same time waves can propagate in both directions: to the light cylinder and back to the stellar surface. It is seen from eq.(5) that the waves propagate along the field lines with the speed of light and transfer only a small fraction of the entire wave energy defined by the ratio $k_\varphi/k_x \ll 1$. The particles give part of their energy to the waves as they are being carried out from the interaction region. New particles enter this region, give in their turn part of their energy to the waves, *etc.* The wave leaves the interaction region considerably slower than the particles. Hence there is no time for the inverse action of the waves upon the particles. The energy accumulation in the waves occurs without quasilinear saturation. The wave amplitude grows until nonlinear

https://doi.org/10.1017/S0002731600155374 Published online by Cambridge University Press

processes redistribute the energy over the spectrum. Of all the nonlinear processes the probability of the three-wave interaction and the induced scattering of waves on plasma particles is the highest. However the second-order current describing the decay interaction is proportional to e^3 (charge to an uneven power). Hence the contribution of electrons and positrons is compensated. At the same time the induced scattering is proportional to an even power (e^4) of the charge. Therefore the induced scattering occurs at the resonance on the bulk of plasma

$$\omega - \omega' - (k_\varphi - k'_\varphi)v_\varphi \simeq 0\,.$$

Substituting eq.(5) into this resonance condition one obtains

$$\frac{k_x - k'_x}{k_\varphi - k'_\varphi} = \mp \frac{c}{u_x^b}\frac{1}{2\gamma_p^2} \sim \mp 10\,. \qquad (6)$$

The upper sign corresponds to the waves propagating from the pulsar to the light cylinder ($k_\varphi > 0$). For such waves the scattering increases the values of $k_\varphi (k'_\varphi > k_\varphi)$, *i.e.*, each scattering event accelerates the energy outflow from the interaction region. Whereas at $k_\varphi < 0$ each scattering event decreases the longitudinal component of the wave vector $k'_\varphi < k_\varphi$, and k_x decreases too ($k'_x < k_x$). This process leads to wave-energy pumping in the long-wave region of the spectrum. Low frequency waves with $k_x \gg k_\varphi$ propagate along the spiral to the neutron star with the step defined by $k_x/k_\varphi \geq c/u_x \approx 10 \sim 10^2$. In the generation region $k_x^0 \sim 10^{-3}$ [eq.(3)], $k_\varphi^0 \sim 10^{-10}$ (from the magnetosphere dimensions) and $k_x^0/k_\varphi^0 \simeq 10^7$, consequently 10^{-7} of the energy flows along the field lines with the speed of light and each scattering event increases the fraction of this energy because $k'_x/k'_\varphi < k_x^0/k_\varphi^0$. Therefore the low frequency waves are being excited in the vicinity of the light cylinder ($R \simeq 5 \times 10^9$ cm) where $c/u_x \simeq 10$. They propagate to the pulsar until $c/u_x \simeq 3 \times 10^2$ ($R \simeq 10^9$ cm). The waves undergo scattering until $k_x/k_\varphi \gg c/u_x \simeq 10^2$ [for the fulfillment of the resonance eq.(5)]. At this distance the minimal value of k_x is equal to $10^{-8}\,\mathrm{cm}^{-1}$. The latter coincides with the estimate $k_x^{\min} \sim 1/d$, where d is the transverse dimension of the magnetosphere at a distance of $R \simeq 10^9$ cm—*i.e.*, one wavelength (minimal wavelength) can fit in the transverse dimension of the magnetosphere. In this case the frequency $\omega \simeq k_x u_x$ turns out to be of the order of the pulsar angular velocity $\Omega \simeq 2\pi/1$ s. For the energy to accumulate just in this wavelength region a sufficiently high rate of nonlinear pumping into the region with $k \simeq k_x^{\min}$ is necessary. In this case the energy will not accumulate in the intermediate wavelength region and will have enough time to replenish the "reservoir" with energy (in $\boldsymbol{k}$ space) for $k_x \simeq 10^{-8}\,\mathrm{cm}^{-1}$ from which the energy is transferred along the field lines (k_φ). The outflow of the $k_\varphi/k_x \simeq 10^{-2}$ fraction of energy takes a time $\tau' \simeq R/c \simeq 10^{-2}$; consequently the "reservoir" will be exhausted in time $\tau = 10^2\tau' \simeq 10$ s.

For the nonlinear decrement one obtains the following estimate

$$\Gamma_{\mathrm{NL}} \simeq \frac{I}{mc^2 n_p \gamma_p}\frac{\omega_p^2}{\omega_k \gamma_p^2}\,, \qquad (7)$$

where I is the energy density of the waves. It follows from eq.(7) that Γ_{NL} equals Γ_{L} (linear growth rate) for sufficiently low turbulence level, *i.e.*, $I/mc^2 n_p \gamma_p \ll 1$. The pumping rate of the excited waves in the long wave region $\sim 1/\Gamma_{\mathrm{NL}}$ appears to be of the order of time τ. Hence a balance sets in between the energy inflow and outflow in the region of maximal wavelength $k_x = k_x^{\min} = 10^{-8}\,\mathrm{cm}^{-1}$. For the initial k_x^0 and intermediate k_x the pumping rate is substantially higher ($k_\varphi^0/k_x^0 \sim 10^{-7}$). In the long wave part of spectrum the pumping rate slows down. The frequency of the accumulated drift waves $\omega = k_x u_x \sim 1\,\mathrm{s}^{-1}$ can be of the same order as the pulsar angular velocity Ω.

From Paper I it follows that at distances $\sim 10^9$ cm and at small angles with respect to the pulsar magnetic field, pulsar radio-wave generation can occur. Also at the same distances the existence of accumulated drift waves propagating almost transverse to the magnetic field ($k_x \gg k_\varphi$) with frequency of the order of the pulsar angular velocity

$$\omega \approx \Omega \pm \Delta \qquad (8)$$

is possible. The resonance condition eq.(1) will be fulfilled only for definite phases of the drift wave. If the frequency ω coincides with Ω exactly ($\Delta = 0$), the generation region rotates together with the magnetosphere, and an observer should see steady subpulses. If $\omega = \Omega + \Delta$ and $\Delta \ll \Omega$ the necessary drift wave phase overcomes the magnetospheric rotation and subpulse drift in the direction of pulsar rotation should be observed. In the case $\omega = \Omega - \Delta$, the wave phase falls behind the pulsar rotation and subpulse drift in an opposite direction should be observed. After a definite time $P_3 \approx \Omega/\Delta$ the phase returns to the original position and the process is repeated.

Let us discuss briefly the problem of describing the subpulse within our model. Evidently it should be connected with the resonance condition, eq.(1). Given this condition the term $1/\gamma_{\mathrm{res}}^2$ is negligibly small, and if for simplicity one neglects also the term $k_r^2/2k_\varphi^2$ then one obtains from the quadratic equation (1)

$$\theta_{1,2} = u_x \pm \sqrt{\delta}\,. \qquad (9)$$

Consequently the intensity maximum should be within the angles θ_1 and θ_2. Depending on the place where the sight line cuts the emission cone one can observe for a given pulsar between one to four subpulses. The distance between the subpulses P_2 is defined by the difference $\theta_1 - \theta_2 \approx 2\sqrt{\delta}$ and by the values $2\theta_1$ and $2\theta_2$. Recalling that $u_x/c \simeq 10^{-2}$ and $\delta \simeq 10^{-2}$ to 10^{-3} one has an estimate $P_2 \sim 3°$ to $30°$ confirmed by the observations (Manchester and Taylor 1977).

We have discussed the resonance condition only for t-waves here. However, the excitation condition for the lt-mode could be satisfied as well (with $\boldsymbol{E}^{\rm lt}$ perpendicular to $\boldsymbol{E}^{\rm t}$). This condition has the following form

$$\theta = \pm \frac{u_x}{c} \frac{\omega_{\rm p}}{\omega^{\rm lt}} \sqrt{2} \gamma^{1/2} . \qquad (10)$$

Of course, the wave excitation should not necessarily occur at the same distances. At different heights the frequencies of the low frequency drift waves should differ also, *e.g.*

$$\omega \simeq \Omega \pm \Delta_{1,2,3,\ldots} \qquad (11)$$

where $\Delta_1 \neq \Delta_2 \neq \Delta_3$. We believe that PSR 2319+60 is an example of just this situation (Wright and Fowler 1981), where all three components have different values of P_3: 8 P for the A-mode (*i.e.*, $\Omega/\Delta_1 = 8$), 4 P for the B-mode ($\Omega/\Delta_2 = 4$). The central component does not drift at all. This means that at the heights where the central component is being generated either $\Delta_3 = 0$ (less probable), $\omega \gg \Omega$ and we observe some smeared picture (quite probable), or there is no drift wave at all (most probable).

We believe that we have found a possible mechanism that can serve as a qualitative explanation of the subpulse drift phenomenon. Surely more work is required to transform this result into a model of subpulse drift.

Acknowledgments: We thank Jan Gil for help with preparing this manuscript. We also thank the organizers of IAU Colloquium No. 128 for creating a wonderful atmosphere which stimulated very fruitful scientific discussions.