The Magnetic Reconnection Induced Coherent Emission on Pulsars

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Abstract

The pulsar radio emission mechanism remains an enigma since its discovery in 1967. The critical issue of origin of coherent emission is usually investigated separately from the micro-structure of individual pulses and characteristic emission frequency of pulsars… In this letter, these issues are interpreted in an unified scenario. The pulsar spin piles up magnetic field at the apex of last closed field line triggering magnetic reconnection. The resultant Alfven wave interacts with open field lines giving rise to coherent maser curvature and cyclotron emission. Such a scenario of coherent emission not only imposes new limit to emission site, nanoburst, and characteristic frequency, but also affects polarization and pair production required in maintaining a marginal stable circuit in radio emission of pulsars.

Full Text

Preamble

Magnetic Reconnection-Induced Coherent Emission in Pulsars

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The mechanism of pulsar radio emission has remained an enigma since the discovery of pulsars in 1967. The critical question of the origin of coherent emission has typically been investigated separately from the microstructure of individual pulses and the characteristic emission frequencies of pulsars. In this letter, these issues are interpreted within a unified framework. The rotation of the pulsar piles up magnetic field lines at the apex of the last closed field line, triggering magnetic reconnection. The resultant Alfvén wave interacts with open field lines, giving rise to coherent maser curvature and cyclotron emission. This scenario for coherent emission not only imposes new constraints on the emission site, nanoburst characteristics, and emission frequency, but also influences the polarization and pair production required to maintain a marginally stable circuit in pulsar radio emission.

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Introduction

Despite the enormous observational data on pulsars and numerous models attempting to interpret radio emission, the critical issue of the origin of coherent emission remains an open question. In early literature, the emission was assumed to be produced by bunches [?]. Although this assumption has been criticized [?], it remains implicit in more recent models based on other types of bunches, namely solitons [?].

A more general aspect of the origin of coherent emission is that a pulse profile is actually built up from a large number of localized, transient events described variously as intermittency, fine structures, discrete emissions, short-lived emission centers, microstructure, and nanoshots [?]. For example, the Crab pulsar exhibits GHz microbursts that vary dramatically on timescales shorter than a millisecond, which must be intrinsic to the radio emission process in the pulsar since it is too rapid to be caused by propagation through turbulence in the Crab nebula or the interstellar medium [?]. This constraint becomes even more severe in the case of nanobursts [?]. Such bright nanobursts must be coherent, radiating at a characteristic emission frequency and then passing through a highly transparent medium to avoid thermalization [?].

This letter presents a new scenario for achieving coherence. The pulsar's spin invokes a centrifugal force that drives plasma on closed field lines toward the light cylinder radius. As a result, the last closed field line becomes elongated and narrowed, as does the current sheet formed by frozen-in plasma, which triggers rapid magnetic reconnection through a chain of plasmoids responsible for nanoshots. Such a nanoburst invokes a coherent Alfvén wave (AW), whose interaction with the magnetic field of open field lines pumps coherent maser curvature and cyclotron emission at different pitch angles, giving rise to O-mode and X-mode radiation. This scenario of maser emission triggered by an AW stemming from reconnection near the light cylinder naturally avoids difficulties in models of maser coherent emission originating from plasma instability [?]. Furthermore, since reconnection always occurs at the end of the last closed field line or the end of a current sheet, the subsequent radiation can propagate in the density cavity formed by the tube of open field lines, which deviates from models of reconnection by coalescence of magnetic islands in the current sheet where magnetic perturbations must propagate in the dense current sheet [?].

II. The Reconnection Site and Coherency

It occurs that starting with a star possessing a surface charge and then releasing it results in positive particles from the equatorial zone simply popping out a short distance and being trapped by the intense closed magnetic field lines there [**?**, **?**]. Such oblique dome-disc models have been shown to be robust through detailed numerical modeling [**?**].

The frozen-in plasma trapped in closed field lines is driven by centrifugal force toward the last field line. As a result, the magnetic field near the light cylinder is enhanced significantly, and magnetic reconnection is triggered in the last closed line region. The resultant release of free energy gives rise to the seed of a coherent wave. The process of winding up and relaxation repeats, so that a new last closed field line takes the place of the previous one at the cost of both rotational energy and magnetic energy from the pulsar.

The physics near the last closed field line or the separatrices can be described by the equation of motion of magnetohydrostatics,

$$0 = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}$$

where the current, $\mathbf{j} = \nabla \times \mathbf{B}/\mu$, can be simplified by $j_y = 1/\delta$ (where δ is the thickness of the current layer) in Cartesian coordinates as shown in [Figure 1: see original paper]a. The centrifugal and gravitational acceleration on a particle, $a = v^2/R$ and $g = GM/R^2$, are balanced at a radius of $R_{\mathrm{eq}}^3 = GM/\omega^2$. Consequently, with $R_{\mathrm{lc}} = c/\Omega$ denoting the light cylinder radius, the centrifugal force overwhelms gravity for $R \geq 10^{-1} R_{\mathrm{lc}}$ in the case of millisecond pulsars, and for $R \geq 10^{-2} R_{\mathrm{lc}}$ for pulsars with spin periods of a few seconds.

As the closed field lines where plasma is frozen in extend to the light cylinder, the equation becomes dominated by $\rho v^2/R = |\mathbf{j} \times \mathbf{B}|$. In other words, the centrifugal force is in equilibrium with the centripetal force originating from magnetic tension near the light cylinder. In such a case, the frequency of the corresponding AW can be estimated from the plasmoid size of $\lambda \sim \delta \sim 10^{-2}$ m under a magnetic field strength of $B \sim 10^4$ T as shown in Equation (3). The wave frequency, $\omega_r \approx k v_A$, corresponds to a timescale of

$$\tau_i \sim \frac{2\pi}{\omega_i} \sim 2\pi \left(\frac{1 \times 10^{-2}}{3 \times 10^8} \right) \sim 2 \times 10^{-10} \mathrm{s}$$

where m_e and e are the mass and charge of an electron, v' is the speed of charge corresponding to the current j_y, which is parallel to the thickness direction δ of the current layer as shown in [Figure 1: see original paper]a (L and b are the length and width of the sheet). Equation (2) can be further simplified as

$$B \approx 10^{-3} \frac{c}{\Omega}$$

Equation (3) indicates that once the magnetosphere is deformed to the extent of a small layer thickness δ at the apex of the last closed field lines, the magnetic field becomes much greater than that of the light cylinder $B \gg B_{\mathrm{lc}}$ where $B_{\mathrm{lc}} = B_s(R_s/R_{\mathrm{lc}})^3$.

The effect of bent magnetic field lines as indicated by Equation (3) has been investigated as a critical role of ballooning instability in the near-Earth plasma sheet responsible for the onset of substorm expansion [**?**]. The linear ballooning mode is unstable, and its nonlinear development leads to the formation of a series of plasmoid structures in the near-Earth and middle magnetotail regions of the plasma sheet.

This model is supported by experiment [**?**], in which a weak external magnetic field perpendicular to the plasma propagation is applied, where the magnetic field is directly coupled with electrons. Since the kinetic pressure of the plasma is much larger than the magnetic pressure, the magnetic field is distorted and locally anti-parallel. Plasma collimations, cusp and plasmoid-like features with optical diagnostics are reported. Moreover, the plasmoid propagates at the electron Alfvén velocity, indicating reconnection driven by electron dynamics [**?**]. Such ballooning instability-triggered reconnection is also consistent with simulated chains of plasmoids in pulsar magnetospheres [**?**].

The effect of magnetic diffusion at the reconnection site can be simplified by combining the induction equation,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

with the equation of motion as shown in Equation (1) (neglecting ∇p and $\rho \mathbf{g}$). Making the usual wave assumption, $\exp(-\omega_i t)\exp(i\omega_r t)$, a simple dissipation relation is obtained [**?**]:

$$\omega^2 = k^2 v_A^2 - i\omega \frac{k^2 v_A^2}{R_m}$$

where R_m is the magnetic Reynolds number.

On the other hand, the damping of such an AW is determined by $\omega_i = -k v_A/(2R_m)$, so that

$$\tau_i \sim \frac{2\pi}{\omega_i} \sim 2\pi\mu_0 \left(\frac{1\times 10^{-2}}{10^4}\right)^2 \left(\frac{10^4}{10^{-2}}\right) \sim 8\times 10^{-10}\mathrm{s}$$

Consequently, Equation (6) and Equation (7) predict a wave train of length $s \sim \tau_i c \sim 2\times 10^{-1}$ m, wave number $k \sim 1/\delta \sim 10^2$, and hence $ks \sim 20 \gg 1$, which corresponds to a GHz nanoburst of short frequency range, $\Delta\omega/\omega \sim 0.03$ comparable to a typical FRB.

The required rapid reconnection can be achieved by a new last closed field line (b) catching up to the old one (a) as shown in [Figure 1: see original paper]a, which leads to rapid reconnection of plasmoids. As a result, such reconnection always occurs at the end of the current sheet.

Moreover, pair production can be triggered in the diffusing region, where half the plasma ejects outward contributing to the pulsar wind, and the other half returns to the pulsar surface along separatrices, consistent with simulations [**?**].

The duration of a microstructure much shorter than a nanoburst is constrained by both the characteristic frequency of GHz and the coherent condition $ks \gg 1$. A microstructure much longer than a nanoburst is also restricted, because a much longer timescale τ_i would require a much smaller magnetic diffusivity η in Equation (7), which prevents rapid reconnection and pair production from occurring. Therefore, the characteristic frequency, nanoburst properties, and magnetic field at the light cylinder as shown in Equation (3) are closely related in the context of reconnection-induced radio emission.

The coherency of an outward AW interacting with magnetic fields can be analyzed by the energy radiated per unit solid angle per unit frequency interval from a bunch with length L and N particles moving along a curved field line [**?**]:

$$\frac{d^2 I}{d\omega d\Omega} = F_\omega(N)\frac{q^2\omega^2}{4\pi^2 c}\left|\int_0^L \mathbf{n}\times(\mathbf{n}\times\beta)\exp\left[i\omega\left(t-\frac{\mathbf{n}\cdot\mathbf{r}}{c}\right)\right]dt\right|^2$$

where $F_\omega(N)$ is a dimensionless parameter denoting the enhancement factor due to coherence, defined as

$$F_\omega(N) = \left|\sum_{j=1}^{N} e^{-i\omega(\mathbf{n}\cdot\Delta\mathbf{r}_j/c)}\right|^2$$

where $\mathbf{n}$ is the unit vector to the observer and $\Delta\mathbf{r}_j$ is a section of the bunch length L. For a non-coherent bunch of length L, only if all electrons are at one point ($\Delta\mathbf{r}_j = 0$) can one obtain $F_\omega(N) = N^2$.

In contrast, the AW with wavelength $\lambda \sim \delta \sim 1\times10^{-2}$ m and coherent length $L_i \sim c\tau_i \sim 2\times10^{-1}$ m corresponds to a wave train of length $\sum\Delta\mathbf{r}_j = \sum\lambda = L_i \sim 20\lambda$, under a uniform distribution of electrons (positrons) numbering N along L_i. Then simply applying half-wave superposition, the enhancement factor of the whole length L_i yields $F_\omega(N_i) = N_i^2$, which ensures the coherency of a nanoburst.

On the other hand, as proposed in [**?**], microbursts are incoherent superpositions of short-lived, narrowband nanoshots, and all microbursts are clumps of nanoshots. In such a scenario, the broadband nature of each microburst can be interpreted by the wide frequency range of the center frequencies of the nanoshots (each narrow in frequency range) within a microburst [**?**].

In the context of Sweet-Parker reconnection, with a current sheet of length L and thickness δ, conservation of mass implies

$$Lv_i = \delta v_{Ai}$$

As the reconnection region corresponds to a diffusion speed of $v_i = \eta/\delta \sim 10^2$ m/s with parameters adopted in Equation (7), we have a layer length of $L \sim 10^4$ m, which composes numerous nanoshots stemming from fast reconnection of plasmoids at the end of such a sheet. The swing of this dynamic current sheet through a pulse window results in the single pulse of a pulsar, which corresponds to an enhancement factor of Equation (9) of

$$F_\omega(N_i, N) = NN_i^2$$

where N_i and N are the number of particles in a nanoburst and the number of nanoshots in a single pulse, respectively. This explains why the single pulse of a pulsar appears much dimmer than a nanoburst.

III. Waves and Circuit

The energetic electrons and positrons injected from the reconnection site with velocity $\mathbf{v}$, as discussed in the previous section, undergo resonant wave-particle interaction, $\omega - \mathbf{k} \cdot \mathbf{v} = 0$, in an unmagnetized plasma. This relation can be applied to the center of the open field lines (zero pitch angle) as shown in [Figure 1: see original paper]b, where the strength of the surrounding magnetic field cancels out. The coherence of such an AW is ensured by Equation (6) and Equation (7).

In the case of larger pitch angles as shown in [Figure 1: see original paper]b, the AW interacts with surrounding open field lines, giving rise to coherent cyclotron and curvature emission. As the interaction timescale is much shorter than the coherence time of Equation (7), $\tau \sim \hbar/(\gamma m_{ec}^2) \ll 1$ ns, the coherence of this seed AW is actually undisturbed by further cyclotron and curvature processes, whereas their polarizations are profoundly affected.

The propagation of reconnection-induced AW in a magnetic field can energize electrons, resulting in a new cyclotron maser instability with a timescale indicated by Equation (6) and Equation (7). The resonance condition in the presence of a magnetic field is

$$\omega = \frac{s\Omega_e}{\gamma} + k_\parallel v_\parallel$$

The right-hand side of Equation (12) corresponds to an effective cyclotron phase angle advancing at the rate of the effective cyclotron frequency, $\Omega_{\text{eff}} = s\Omega_e/\gamma + k_\parallel v_\parallel$. Resonance takes place when the electron (positron) remains in phase with the wave. In other words, the interaction described by Equation (12) is equivalent to lifting the electrons collectively into a higher energy level, providing sufficient free energy to induce substantially intense coherent radiation.

The influence of AWs on maser emission in coronal loops has also been calculated in detail [**?**, **?**, **?**], which shows that AWs can qualitatively affect the velocity distribution of energetic electrons via pitch-angle scattering while simultaneously modifying the usual cyclotron resonance processes. As a result, O-mode emission is effectively amplified further by AWs while X-mode emission is hardly affected.

On the other hand, with $s = 1$ and $\Omega_c = \Omega_e$, the right-hand side of Equation (12) can also describe the effective curvature phase angle advancing at the rate of the effective curvature frequency, $\Omega_{\text{eff}} = \Omega_c/\gamma + k_\parallel v_\parallel$, so that AW-affected curvature emission can be studied in a similar approach. The relative energy density between the cone and core, as well as the corresponding polarization, depends on the ratio of energy density of cyclotron and curvature maser emission, which awaits further investigation.

At the reconnection site, both the outflow and inward beams are accelerated by the reconnection electric field near the X-line. The presence of a guided field in the X-line region of the reconnection site leads to a strongly field-aligned distribution of electron and positron beams [**?**]. One pair of electrons and positrons returns to the pulsar directly along separatrices of the X-line, as shown in [Figure 1: see original paper]b. Correspondingly, the other pair of energetic electron and positron beams moves along the opposite pair of separatrices of the X-line away from the pulsar, most of which contribute to the pulsar wind. As a result, a net loss of charged particles in such a process is inevitable. Fortunately, the pair production addressed at the end of the previous section provides additional charge supply to the circuit as shown in [Figure 1: see original paper]c, so that the whole process can proceed in a marginally stable circuit.

As shown in [Figure 1: see original paper]bc, the return current is similar to both the simulated configuration of the electric charge and the electric current of the equatorial current sheet [**?**], and the current configuration responsible for aurora observed by satellites passing through the acceleration region [**?**]. The return current formed by the downward pair of electrons and positrons can screen the inductive electric field at the pulsar surface (in the case of charge starvation) with a circuit as shown in [Figure 1: see original paper]c.

A simple and unified scenario for where and how coherent radio emission is generated is proposed in this letter, which naturally relates coherency, microstructure, characteristic frequency, emission site, density cavity, circuit, and polarization of a pulsar.

[Figure 1: see original paper] The schematic configuration of reconnection-induced radio emission. Panel a: Spin-deformed last closed field lines surrounded by open field line tubes. Small circles denote plasmoids inside the upper last closed field line; their annihilation gives rise to outward emission and return current (dotted arrows). The current sheet is shown at the bottom of the spiral. Panel b: Reconnection site with guided field which separates the electron and positron beams. The outward beams interact with the open field lines, invoking maser emission. The return beams contribute to the circuit as shown in Panel c. Panel c: The circuit formed by return current and pair production.

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