A Simple Model of Coherent Emission Confronting a Number of Puzzles on Pulsars, Magnetars, and Fast Radio Bursts

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Abstract

Fifty years after the discovery of radio pulsars, mainstream theories based on the polar cap still face difficulties in both self-consistency and comparison with observations [1]. Mounting observational evidence from individual subpulses—including the high brightness temperature, strong polarization, and narrowband nanosecond flashes of the Crab pulsar [2, 3]—suggests these phenomena are associated with fundamental radiation cells within the pulse window. Furthermore, the high degree of circular polarization observed in micropulses from pulsars and Fast Radio Bursts (FRBs), together with rapid orthogonal jumps in linear polarization position angle [3–6], requires such small radiation cells to possess rapidly varying cone-core patterns rather than the simple high-energy-density blobs widely accepted in the literature. These observations pose unprecedented challenges—and opportunities—for understanding the origin of coherent radiation in pulsars.

This paper addresses these challenges through a simple model of alternative emission sites and mechanisms. In this model, pulsar winds emanate from the open magnetic field line region, while coherent radiation is triggered by forced magnetic reconnection at the tip of the last closed magnetic field line near the light cylinder. The high energy density at such a minute reconnection site spontaneously excites Alfvén waves, generates electron-positron pairs, and accelerates them to relativistic speeds. The resulting particle-wave interactions produce coherent clumps that are intrinsically endowed with cone-core structures, capable of explaining observations of pulsars, magnetars, and FRBs. For the first time, a unified model accounts for the puzzles of coherence, polarization, the correlation between coherent radiation and winds, and the energy budget across pulsars, magnetars, and FRBs.

A Simple Model of Coherent Emission Confronting a Number of Puzzles on Pulsars, Magnetars, and Fast Radio Bursts

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Preamble

Five decades after the discovery of radio pulsars, mainstream theories based on the polar cap still suffer from difficulties in both self-consistency and confrontation with observations [?]. Increasing observations of individual subpulses of pulsars—i.e., high brightness temperature, highly polarized, and narrowband nanoshots of the Crab pulsar [?, ?]—indicate that they relate to basic emission elements in a pulse window. Moreover, a high degree of circular polarization and rapid orthogonal jump in the position angle of linear polarization are observed in micropulses of both pulsars and Fast Radio Bursts (FRBs) \cite{3-6}, which further requires that such a small element of emission has a cone-core configuration varying rapidly from one subpulse to another. These represent both unprecedented challenges and opportunities to understand the origin of pulsar coherent emission.

This paper for the first time directly confronts the critical question—the origin of a microstructure with cone-core pattern—by proposing an accumulated magnetic reservoir and tiny dissipation site. The resultant coherent emission expects a position angle jump of 90 degrees occurring simultaneously with sign change of circular polarization and a minimum of linear polarization, which is supported by a large number of polarization observations on both pulsars and FRBs and in both microstructures and single pulses. Such a unified model not only interprets a number of other puzzling questions, but also provides an efficient radiation site for the disk-dome configuration [?, ?], which sheds new light on the mechanism of coherent emission of pulsars and FRBs.

Introduction

Although no consensus has been achieved, investigation of pulsar radiation over five decades has formed widely accepted ingredients in the emission mechanism of pulsars [?]. Firstly, the very high brightness temperature requires some form of coherent emission; secondly, the emission involves relativistic electrons and positrons [?] generated in pair cascades [?]; and finally, the emission stems from bipolar regions above the polar cap [?, ?].

Coherent curvature emission (CCE) was the first suggested emission mechanism [?, ?]. As pointed out by Melrose [?], CCE suffers from difficulties of bunch formation and maintenance. Relativistic plasma emission (RPE) [?] involves a streaming instability generating waves analogous to Langmuir waves, and nonlinear processes in the plasma are required in order to partially convert these waves into escaping radiation. Various suggested instabilities in the first stage are too slow to be effective, and the difficulty with the second stage has been referred to as a "bottleneck" [?]. Linear acceleration emission (LAE) and free-electron maser emission (FEM) [?, ?] may be regarded as the second stage of an RPE mechanism [?]. However, radiation from solitons and soliton-like waves undergoing wave collapse has been simulated by more generic 2D cases, which casts doubt on the correctness of soliton radio emission models of neutron stars [?].

Perhaps it is incorrect to assume that the radio source arises from the polar-cap region populated by relativistically outflowing pair plasma [?, ?, ?]. In other words, the polar-cap gap may be unfavorable for invoking rapid and stable instabilities required in coherent emission. Reconnection involving Alfvén waves (AW) tends to reproduce coherent emission more easily than rotation-driven mechanisms, which has been suggested to be responsible for radio pulsars [?], magnetars [?], and FRBs [?, ?]. However, these reconnection-driven radio emission models have been restricted to the Crab pulsar rather than normal pulsars \cite{24-27}. Because in such Force-free Inside, Dissipative Outside (FIDO) models, the magnetic strength imposed on the current sheet a few light cylinder radii long is approximately the light cylinder magnetic field, which is too weak to account for normal pulsars.

On the other hand, in these reconnection-based models, the reconnections occur either in the whole magnetosphere of the Crab pulsar [?], or with wave and radiation perpendicular to the magnetic field lines of a long equatorial current sheet [?], which do not expect a conal-core pattern on pulsar subpulses and pulse profiles [?, ?]. Apparent similarities appear in pulse morphology between radio pulses from PSR B0950+08, a repeating FRB source, and a magnetar [?], indicating that the same emission mechanism is at play in them. On the other hand, a correlation relating subpulses in pulsed emission of radio-emitting neutron stars to their rotational period ($\tau \sim 10^{-3}P$) is seen not only in magnetars but in members of all classes of radio-emitting rotating neutron stars, regardless of their evolutionary history, power source, or inferred magnetic field strength [?].

Even shorter subpulses with time scales of $10^{-6}P$ have been found, i.e., nanoshots at a timescale of 2 ns in the Crab pulsar, which has a brightness temperature comparable to that of a typical FRB. Therefore, a rapid energy relaxation with an extremely high energy density and length scale of sub-meter [?] is required. Strikingly, FRB 20121102A, the first known repeating FRB source, shows isolated microsecond-duration bursts (also $10^{-6}P$) [?], as does FRB 20220912A with short-duration structures ($\sim 16\mu$s), or 'microshots' [?].

Furthermore, correlations of coherent radio emission with in-phase and offset high-energy counterparts are shown in pulsars, magnetars, and FRBs \cite{32-34}, the origins of which are not well understood. Previous reconnection models have difficulty not only in extending to normal pulsars, giving rise to cone-core beams of subpulses, and accounting for rapid Position Angle (PA) jumps \cite{3-6}, but also in understanding the huge luminosity discrepancy between pulsars and FRBs [**?**, **?**], as do polar-cap gap models.

This paper directly confronts these long-standing and recent problems through a simple scenario. Firstly, it allows a solar dynamo-like building up of magnetic helicity at the last closed field line region near the light cylinder, playing the role of an energy reservoir. Secondly, plasma condensations eject from such a reservoir carrying field lines out of the light cylinder, which suffers from extremely high differential rotation triggering a forced reconnection at the tip of the last closed field region.

The high energy density at the tiny reconnection site is sufficient to produce electron-positron pairs and accelerate them to relativistic speeds. Moreover, along with AWs generated by the reconnection, those relativistic pairs undergo efficient particle-wave interaction, which reproduces coherent bunches efficiently. Furthermore, the guide field at the reconnection site distributes the outward jet into triple beams analogous to reconnection occurring in the solar wind and near-Earth magnetotail \cite{37-39}, which well accounts for the conal-core pattern exhibited in, e.g., nano-shots of the Crab pulsar [**?**] and subpulses of pulsars B0950+08 and B1642-03 [**?**], and FRBs [**?**, **?**, **?**]. Finally, the coherent emission occurring at the very end of the last closed field line region ensures that the emission propagates in a "density cavity" without being thermalized by dense plasma [**?**].

This paper is structured as follows. Section II discusses magnetic helicity building up and relaxation in the form of pulsar wind. Section III examines forced reconnection reproducing coherent bunches, responsible for narrow radio band and giant pulses. Section IV addresses the origin of rapid PA jump and its correlation with circular polarization and minimum linear polarization. Section V explores states of energy accumulation and relaxation in various sources, and the absence of spin & gamma-ray radiation. Section VI discusses association with early magnetosphere models, particularly the disk-dome model, and presents predictions.

II. Magnetic Helicity Building Up, Relaxation and Pulsar Wind

In the FIDO models, reconnection occurs by exerting a strength of light cylinder magnetic field upon a long current sheet which is too weak to invoke radiation responsible for normal pulsars. In fact, the magnetic energy relaxation through reconnection in the current sheet can change the force-free condition in the magnetosphere, which allows magnetic helicity to build up near the light cylinder. That is, the reconnection at the edge of the reservoir (the tip of the last closed field line) provides a non-ideal magnetohydrodynamic (MHD) effect resisting the strong magnetic tension, which allows magnetic helicity buildup. If all rotating neutron stars involve more or less magnetic helicity buildup, then it is easy to understand that coherent emission can occur not only in normal pulsars and magnetars, but also in pulsars located beyond the death line.

The helicity built up can be investigated by taking into account the centrifugal effect, described by means of the MHD equations for a fluid with infinite conductivity \cite{42-47}. Under such a perfect MHD condition, self-similar magnetosphere solutions are sought for flow from a disk. Therefore, with a magnetic cloud of velocity $\mathbf{v} = u\mathbf{e}_r + v_\phi \mathbf{e}_\phi$ and magnetic field $\mathbf{B} = B_r\mathbf{e}_r + B_\phi \mathbf{e}_\phi$ in the spherical coordinate system $(\mathbf{e}_r, \mathbf{e}_\theta, \mathbf{e}_\phi)$, a simple azimuthal equation of motion can be obtained, in which the sum of the angular-momentum term rv_ϕ and the magnetic-torque term $-B_{rB_\phi}/(\mu\rho u)$ is exactly equal to L_0 [**?**]:

$$rv_\phi - \frac{rB_\phi B_r}{\mu\rho u} = \text{const.} = L_0,$$

where μ is the magnetic permeability and ρ is the mass density. In such a case, any increase in the plasma angular momentum is exactly balanced by a decrease in the torque.

Equation (1) depicting conservation of total angular momentum corresponds to a conservation of total energy flux, $S = \rho ur^2(...)$, where Ω is the angular velocity of the roots of field lines. The first term is the kinetic energy flux associated with the azimuthal velocity. The second term represents the energy transported out by the magnetic field, the Poynting energy flux [**?**].

As shown in the second term of Equation (1) and Equation (2), disk formation in magnetized cloud cores is hindered by magnetic braking. The stronger the field, the harder it is to form disks frozen into which is the so-called magnetic tower [**?**] responsible for the launch of magnetocentrifugal outflows [**?**]. Therefore, effects that weaken the coupling of the magnetic field to matter are proposed, i.e., enhanced resistivity [**?**], such that disk formation and thus buildup of magnetic helicity is enabled as poloidal field lines are frozen into the spinning disk.

With rapid rotation and a light cylinder, a pulsar drags its magnetosphere to co-rotate; the local charge density required for co-rotation is the "Goldreich-Julian" density [**?**], which can be presented in terms of pulsar rotation parameters, spin period and its first derivative:

$$n_{GJ} = -\epsilon_0(\ \cdot \mathbf{B}) = 7 \times 10^{16} \left(\frac{P}{10^{-15}}\right)^{1/2} \text{[50].}$$

The plasma-filled magnetosphere of GJ density, n_{GJ}, corresponds to a plasma density of $\rho = m_e n_e \approx m_e n_{GJ}$. Together with the magnetic field at the light cylinder, $B_{lc} = B_s[(2\pi R)/(cP)]^3$ (where B_s denotes the surface magnetic field), the radial Alfvénic Mach number—the ratio of the momentum term and the magnetic-force term corresponding to Equation (1) and Equation (2)—can be cataloged into two modes:

$$M_A = \frac{(\rho\mu)^{1/2}u}{\cdots} \ll 0.1, \sim 0.1, \gg 0.1,$$

where $u \approx c$ is assumed.

For pulsars with $M_A \ll 0.1$, i.e., the Crab pulsar, the magnetic tension overwhelms the momentum term, which hinders helicity buildup. While reconnection at the tip of the last closed field line provides an effect breaking the force-free condition. Such resistance to magnetic tension allows persistent relaxation via reconnection-triggered radiation at the level of pulsar spindown power. In contrast, in the case of $M_A \gtrsim 0.1$, magnetic helicity can be built up (forming an energy reservoir) at the cost of suppressed radiation, which is weaker or much weaker than the spindown power. Once the reservoir reaches a critical point, either an abrupt relaxation occurs (responsible for, e.g., magnetars) or normal radiation occurs (for, e.g., normal pulsars and even old pulsars).

The energy reservoir near the light cylinder can either be double clouds as shown in Fig. 1a, or multi-cloud as shown at the top of Fig. 1b. The magnetic helicity built up gives rise to a current, $\oint \mathbf{B} \cdot d\mathbf{l} = \mu I$, as shown in Fig. 1a, which can be further simplified as:

$$(2\pi R)B_w = \mu I = \mu\rho_e v\pi(R_2^2 - R_1^2),$$

where $\rho_e = en_{GJ}$ is charge density, and R_1 and R_2 are inner and outer radii of the hollowed thin cylinder respectively, corresponding to a relative thickness of $\sigma = (R_2^2 - R_1^2)^{1/2}/R_{lc}$ as shown at the top of Fig. 1b.

The current I flows around the hollowed cylinder, giving rise to relativistic wind along the open field line with speed $v \sim c$. The strength of magnetic field at the base of the hollowed cone, B_w, from Equation (4) can be rewritten as:

$$B_w = \mu ecn_e\sigma^2 R_{lc},$$

where plasma density is defined as $n_e = \chi n_{GJ}$, with parameter χ denoting the deviation from the GJ density.

The correlation relating subpulses of radio-emitting neutron stars to their rotational period, $\tau \sim 10^{-3}P$ [**?**], can be approximated by their light cylinder radii:

$$\tau \approx 10^{-3}P \sim 10^{-2}\frac{R_{lc}}{c} \sim \begin{cases} 10^{-5}\text{s}, & P \sim 10^{-2}\text{s}, \text{Crab} \\ 10^{-4}\text{s}, & P \sim 10^{-1}\text{s}, \text{normal pulsars} \\ 10^{-3}\text{s}, & P \sim 100\text{s}, \text{FRBs, magnetars} \end{cases}$$

Such a time interval τ mimics the travel time of backward electron-positron pairs produced at the tiny reconnection site through the reservoir, around which a current I' is enhanced as shown in Fig. 1a. As a result, it causes fluctuation in the energy reservoir and thus in energy relaxation.

Substituting $\tau \sim (10^{-2}R_{lc})/c$, the volume of the cylindrical reservoir $V \sim 2\pi\sigma^2 R_{lc}^3$, and B_w from Equation (5) into the radiation power, $YV/(\mu\tau)$, the energy relaxation of the pulsar wind can be estimated by equating such a radiation power $\dot{E}$ to the spindown power:

$$\dot{E}_{sd} = 4 \times 10^{24} \left(\frac{P}{10^{-15}}\right)^{-3} [50],$$

$$\dot{E} = \frac{B_w^2}{\mu}\frac{V}{\tau} = 4 \times 10^{24} \left(\frac{P}{10^{-15}}\right)^{-3}.$$

Taking into account Equation (5), an extremely simple relation between the relative radius and the spin period is obtained:

$$\sigma = 1.5 \times 10^{-4} P^{-1} \chi^{-1/3}.$$

Substituting Equation (8), obtained by equating the Poynting flux from the hollowed cylinder to the spindown power, into Equation (5), we get the strength of magnetic field of the reservoir consistent with both the spindown power and the Poynting flux:

$$B_w = 5 \times 10^{18} \chi \sigma^2 \left(\frac{P}{10^{-15}}\right)^{1/2}.$$

The strength of the B-field complying with the pulsar spindown is stronger or much stronger than that at the light cylinder, i.e., $B_w/B_{lc} \sim 50$ for the Crab pulsar and $B_w/B_{lc} \sim 5 \times 10^4$ for J0726-2612, as shown in Table 1. In other words, the reservoir magnetic energy of the former is much closer to the light cylinder value, B_{lc}^2/μ, than that of the latter. This enables the former to be dissipated and restored instantaneously, whereas the latter takes a much longer waiting time to do so.

The volume $V \sim 2\pi\sigma^2 R_{lc}^3$ of the magnetic energy reservoir approximated in Equation (7) can be represented by either a thin cylinder of thickness and height $\sim \sigma R_{lc}$ and radius R_{lc}, as shown at the top of Fig. 1b; or a flux-tube-like volume of radius $\sim \sigma R_{lc}$ and height $2R_{lc}$, as shown in the middle of Fig. 1a. The latter corresponds to an area of $A \sim \sigma^2 R_{lc}^2 \sim \text{km}^2$, as shown in Table 1, which provides a clue to the area of thermal emission observed in X-ray [**?**].

The relaxation of energy in the reservoir of the hollowed cylinder, $-J \cdot E$, depends on the rotation energy of the star, $-I_s\Omega\dot{\Omega}$ (where I_s is the moment of inertia of the star), and the net Poynting flux flowing out of the hollowed cylinder, $\nabla \cdot \mathbf{S}$ (where $\mathbf{S}$ is given by Equation (2)), which are related by:

$$-I_s \Omega \dot{\Omega} + \nabla \cdot \mathbf{S} = -J \cdot E = -J_\perp E_\perp - J_\parallel E_\parallel .$$

Notice that the dissipation term is composed of parallel and perpendicular components corresponding to the Poynting flux along the open field lines of the polar region, $J_\parallel E_\parallel$, and coherent emission in the equatorial plane, $J_\perp E_\perp$, respectively. The former contributes to the incoherent wind, and the latter gives rise to coherent pulsed radiation at multiple frequencies from gamma-ray to radio, i.e., the Crab pulsar. The orthogonal phase between coherent and incoherent emission, as shown in Fig. 1a, well accounts for the correlation of coherent radio and incoherent high-energy emission exhibited in some pulsars and FRBs, to be discussed later.

III. Forced Reconnection, Coherent and Incoherent Superposition, Narrow Radio Band, and Giant Pulse

The tip of the last closed field line carrying a plasma cloud ejects out of the enhanced Y-point light, which leads to a forced reconnection triggered by strong differential rotation near the light cylinder. The resultant coherent radiation of a microstructure automatically carries a conal-core pattern responsible for the radio emission of pulsars and FRBs, which differs radically from both the coherent bunch proposed decades ago and recent FIDO models.

Once an episodic ejection from the reservoir occurs near the light cylinder, such a plasma cloud is carried to a height $\Delta h \ll \sigma R_{lc}$ (where $\sigma \ll 1$ and σR_{lc} corresponds to the size of the reservoir) beyond the light cylinder radius, which is equivalent to pulling a bundle of frozen last closed field lines (with frozen plasma condensation) at time t_0 (at phase ϕ_0) to a height of Δh.

If such a cloud is carried to phase ϕ_1 at a later time t_1 through co-rotation with the magnetosphere of the pulsar, as shown in Fig. 1a, it would result in a cloud speed exceeding the speed of light: $(R_{lc} + \Delta h)\Omega > c$. This can be avoided provided that only the footpoint of the last closed field line is carried from ϕ_0 to ϕ_1, for a distance $\Delta l \approx (\phi_1 - \phi_0) R_{lc}$. Whereas, the tip of the last closed field line is required to stay near its original phase ϕ_0 (or in an angle range of $\phi_0 < \phi < \phi_1$) at time t_1. To achieve this, the tip of the last closed field line must be stretched to a length $\Delta l \gg \Delta h$, which is equivalent to the ejection of a cloud with speed $v_{am} \approx \omega' R_{lc} \approx c$, countering the tangent velocity at the light cylinder, $\omega' R_{lc} \approx -\omega R_{lc}$, in the comoving frame of the pulsar magnetosphere.

The stretching force against the magnetic tension corresponds to an inflow of Poynting flux into the tip of the last closed field line region, which is equivalent to work done per unit time against the magnetic tension at a tiny reconnection site:

$$S_{in} = \mathbf{F} \cdot \mathbf{v}_{in} = -\mathbf{v} \cdot (\mathbf{J} \times \mathbf{B}) \approx ... ,$$

where $\mathbf{v}_{in}$ is the velocity of charge flow compressing and stretching the last closed field line bundle into narrower and narrower shape. Consequently, a reconnection is triggered at a critical ratio of width to length, i.e., $\Delta h/\Delta l \sim 1/100$ of the current sheet [**?**].

Once such a forced reconnection is triggered, the inflow Poynting flux perpendicular to the magnetic field lines at the reconnection site turns around at the center of the X-line of the reconnection site, towards the outflow direction as illustrated in the middle of Fig. 1b (directions perpendicular to the inflow Poynting flux), so that $\nabla \cdot \mathbf{S}_{rec} = 0$ is held, which corresponds to Hall reconnection [**?**]. This differs from models of pulsar emission with a diffusion region extending to a few light cylinder radii \cite{24-27}, which correspond to Sweet-Parker reconnection with $\nabla \cdot \mathbf{S}_{rec} < 0$. The resultant outward Poynting flux converts to three components responsible for pair production, accelerating them to relativistic speed, and generating AW respectively [**?**]:

$$\mathbf{S}_{out} = \mathbf{J}_{rec} \cdot \mathbf{E}_{rec} + \mathbf{v}_{rec} \cdot \mathbf{J}_{rec} \times \mathbf{B}_{rec} + ...$$

The production of electron-positron pairs depends on the strength of magnetic field at the reconnection site, B_T, which determines the energy density at the reconnection site, $\sim n_e \gamma^2 m_e c^2$, where the Lorentz factor of pairs and their number density are γ and n_e respectively. The energy density required, i.e., in the nanoshot of 1,000 Jy during 2 ns of the Crab pulsar, is about 2×10^{13} J m^{-3}, corresponding to a magnetic field strength $B_T \sim 5 \times 10^3$ T. Such a value of B_T is also consistent with the spindown power of Equation (9), as shown in Table 1.

Such a strength of magnetic field, and thus energy density at the reconnection site of a small volume ~ 1 m^3, allows not only an energy level well above the criterion required for pair production (1.02 MeV), but also accelerates them to relativistic speed. On the other hand, the reconnection-induced AW interacting with relativistic pairs leads to a resonance wave which can be depicted by $\exp(-\omega_i t)\exp(i\omega_r t)$ [**?**], where the real wave frequency is $\omega_r \approx k v_A \sim 1$ GHz, with a wave number k compatible with radio emission of pulsars and FRBs; and the imaginary one, $\omega_i = k v_A/(2R_m)$, is responsible for the damping of the AW. The narrowband radiation exhibited in radio emission of some pulsars and FRBs can be achieved by:

$$\frac{\Delta\omega}{\omega} = \frac{(\omega_r^2 - \omega_i^2)^{1/2}}{\omega_r} = \left[1 - \left(\frac{1}{2R_m}\right)^2\right]^{1/2} \ll 1,$$

which simply requires a Reynolds number of $1 > R_m > 1/2$. This in turn corresponds to a dissipation timescale at the reconnection site of:

$$\tau_{rec} \sim \left(\frac{R_m}{c}\right)^{-1} \sim \text{ns},$$

which explains the nanoshots occurring in the Crab pulsar [**?**]. Moreover, it provides a simple and easy mechanism of wave instability and maintenance required in coherent radio emission of pulsars.

The reconnection-reproduced electron-positron pairs and AW result in particle-wave resonance leading to coherent bunches with an enhancement factor of $F(N_e) \sim N_e^2$, where N_e is the number of particles in such a bunch. Subsequent interaction of such coherent bunches with the flux tube formed by the open field lines around the reconnection site gives rise to coherent emission responsible for radiation of Crab-like young pulsars and regular pulsars [**?**, **?**].

The reconnection occurring at the apex of the last closed field lines produces nanoshots as shown in Fig. 1a, repeating rapidly at a time interval $\tau_{rec} \sim$ ns. Therefore, the swing of such nanoshots through a pulse window gives rise to a single pulse of a pulsar with an enhancement factor of:

$$F_\omega(N_e, N) \sim \sum_{i=1}^{N} N_e^2,$$

in the case of incoherent superposition, where N_e and N are the number of particles in a nanoburst and the number of nanoshots in a single pulse, respectively.

A coherent bunch moving along field lines with curvature radius ρ in the vicinity of the light cylinder gives rise to curvature radiation of effective frequency:

$$\omega_{eff} \sim \frac{c}{\rho} \sim 1 \text{ GHz},$$

which corresponds to a power of CCE of:

$$P_{cv} = \frac{e^2 c \gamma^4}{\rho^2} \sim 10^{-30} \left(\frac{\gamma}{10^{23}}\right)^2 \left(\frac{\rho}{10^6}\right)^2 \sim 10^{15} \text{ W},$$

where the number of plasma in a coherent bunch is $N_e = n_e V$, with $n_e \sim \chi n_{GJ} \sim 10 n_{GJ} \sim 10^{20}$ m^{-3} being the number density, and $V \sim 10^3$ m^3 the volume of the emission site.

The radio power of a nanoburst $P_{cv} \sim 10^{15}$ W at the right-hand side of Equation (16) corresponds to a total energy loss $\dot{E}_{na} \sim 10^{20}$ W. Considering radio emission energy loss is only a small fraction (typically 10^{-6} to 10^{-5}) of the spindown power [**?**], the radiation of a nanoshot relates to the spindown power of the Crab pulsar by:

$$\dot{E}_{sd} \sim \left(\frac{10^{20}}{10^{6}}\right)\left(\frac{1}{f_b}\right) \sim 10^{31}\ \mathrm{W},$$

where the beaming factor is $f_b = \max(\Delta\Omega/4\pi, 1/4\gamma^2) \sim 10^{-5}$ with a Lorentz factor $\gamma \sim 300 - 1000$. In other words, an approximate number of nanoshots $N \sim 10^6$ per second can account for the spindown power of the Crab pulsar of 10^{31} W.

The origin of giant pulses of the Crab pulsar can be interpreted by coherent superposition of 10^1 to 10^2 short bursts of nanosecond timescale, which gives rise to an enhancement factor:

$$F_\omega(N_e, N_c) \sim \sum_{i=1}^{N_c} N_e^2,$$

where N_c is the number of nanobursts (10^1 or 10^2) in a subpulse, resulting in an enhancement factor a few orders of magnitude higher than that of incoherent superposition, as shown in Equation (14). In other words, the spindown power of Equation (17) can be achieved by coherent superposition of number N_c, as shown in Equation (18), which is much less than the number N corresponding to incoherent superposition as shown in Equation (17).

The critical frequency of the Crab pulsar can be achieved by the interaction of a pair of beams (coherent bunches) with the flux tube at an initial pitch angle $\alpha_p \sim 10^{-1}$:

$$\omega_c = \left(\frac{5\times 10^{3}}{\rho}\right)\left(\frac{\sin\alpha_p}{10^{-1}}\right) \sim 10^{19}\ \mathrm{Hz},$$

which is in the hard X-ray band. The occurrence of coherent superposition, as shown in Equation (18), is equivalent to an increase of magnetic field strength B_T by one to two orders of magnitude, so that the critical frequency of Equation (19) can reach gamma-ray energies. Such pulsed emission of the Crab pulsar can be extended to 25 GeV [**?**] via inverse Compton scattering.

Equation (19) is equivalent to pumping the distribution function to $\partial f/\partial p_\perp > 0$, where $p_\perp$ is the momentum perpendicular to the field line. Such a maser-like process quickly radiates away the perpendicular component of their energy, so that the pitch angle reduces substantially at a short timescale:

$$\tau_{cool} \sim \frac{\gamma m_e c^2}{2\sigma_T c^2 \gamma^2 U_B \sin^2\alpha_p} \sim 10^{-4}\left(\frac{\gamma}{10^3}\right)^{-1}\left(\frac{B}{10^3}\right)^{-2}\left(\frac{\sin\alpha_p}{10^{-1}}\right)^{-2}\ \mathrm{s},$$

where σ_T is the Thomson cross section and U_B is the magnetic energy density. The timescale of Equation (20) can account for the observed time delay between gamma-ray and radio of the Crab pulsar of 280 μs [**?**].

The cooled-down electrons or positrons can undergo either cyclotron radiation with mild-relativistic $\gamma \sim 100$ and pitch angle $\alpha_p \sim 10^{-1}$, or weak synchrotron radiation with substantially reduced pitch angle $\alpha_p \sim 10^{-3}$ and significantly weakened magnetic field strength by moving towards the central region where the opposite polarity of the B-field of the flux tube cancels out, as shown in the middle of Fig. 1b. The critical frequency of both can reduce to GHz by Equation (19).

When electrons or positrons travel in the flux tube formed by open field lines with further damped pitch angle $\alpha_p \ll 10^{-3}$, it gives rise to CCE radiation, so that the cone component of a cone-core structure, originating in the two outside beams in the triple beams, usually contains a component of CCE of linear polarization, as well as cyclotron radiation and weak synchrotron radiation with circular or elliptic polarization.

IV. Simultaneous OPM Jump, Circular Polarization and Minimum Linear Polarization

The orthogonal polarization modes (OPM) puzzle has been found in integrated pulse profiles [**?**], in which the plane of polarization can be in two perpendicular or nearly perpendicular states occurring at a longitude of depolarization of linear polarization. Interestingly, rapid orthogonal jumps also appear in subpulses of pulsars [**?**, **?**] and FRBs [**?**, **?**], during which depolarization of linear polarization is also seen. This makes the long-standing puzzle even more confusing. Here we show that reconnection-induced triple beams provide a simple intrinsic effect responsible for the orthogonal jump, which must accompany depolarization of linear polarization and change in sign of circular polarization. In other circumstances, it can also produce elliptic polarization and the smooth Rotating Vector Model (RVM) [**?**].

As addressed in the last section, a reconnection event at the tiny site reproduces the triple beams and hence coherent bunches, which interact with the magnetic field of the flux tube surrounding the reconnection site, giving rise to radiation depicted by the electric field of a single moving electron [**?**]:

$$\mathbf{E}_{rad}(\mathbf{r}, t) = \frac{q}{4\pi\epsilon_0 c^2} \frac{\hat{\mathbf{n}} \times [(\hat{\mathbf{n}} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \hat{\mathbf{n}} \cdot \vec{\beta})^3 R},$$

$$\mathbf{E}_{rad}|_{rec} = \vec{\epsilon} e^{i\omega t - kz} = (\hat{x}\epsilon_x + \hat{y}\epsilon_y) e^{i\omega t - kz},$$

where $\hat{\mathbf{n}}$ is the unit vector along wave propagation, and $\dot{\vec{\beta}} = \vec{a}/c$ is the acceleration. The CCE emission stemming from the cone component of a microstructure can be exhibited by the centrifugal acceleration a_{cc}, and thus the polarization vectors $\mathbf{E}_p$ and $\mathbf{E}_e$ for positrons and electrons respectively, as shown in the middle of Fig. 1b.

The central jet from the reconnection site is responsible for the core emission in a subpulse, which gives rise to radiation invoked by linear acceleration $\vec{a}_{la}$, as shown in the middle of Fig. 1b. Due to relativistic beaming, most radiation is emitted in a narrow cone along the acceleration vector, as depicted by the emission power per solid angle [**?**], which is also displayed in the middle of Fig. 1b:

$$\frac{dP}{d\Omega} = \frac{q^2 a^2}{4\pi c^3} \frac{\sin^2\theta}{(1-\beta\cos\theta)^5}.$$

Although the central jet is normally dominated by linear acceleration, weak synchrotron radiation can also contribute to it. Because outer electron and positron beams must move toward the central jet to make the corresponding critical frequency satisfy $\omega_c \sim$ GHz, which can be achieved by, e.g., magnetic field strength $B \sim 10^{-3}$ T and pitch angle $\alpha_p \sim 10^{-3}$. In such a circumstance, the corresponding synchrotron power is $P_{syn} \sim 10^{15}$ W, comparable to that of CCE as shown in Equation (16). Consequently, the core component of a microstructure can compose both linear and circular polarization, as can the cone component, as addressed at the end of the last section and shown in the middle of Fig. 1b.

The PA variation owing to the swing of line of sight (LOS) through the cone-core structure, as shown in the middle of Fig. 1b, can be displayed by the projection of the electric field vector of the central ejector to the plane perpendicular to the LOS. The smooth change of position angle can be depicted by RVM as well, except the inclination angle α (misalignment angle between spin and magnetic axis) of RVM is redefined as the misalignment angle between the spin axis and the center of the cone-core emission pattern.

The resultant emission originating from linear acceleration of the central jet, denoted as arrows in the circle shown at the right side of the middle of Fig. 1b, can point both outwardly or inwardly depending on the sign of the linear acceleration of positrons with respect to the observer.

The polarization of each beam of the triple structure, as shown in the middle of Fig. 1b, can compose both linear and circular (elliptic) polarization, which can be depicted by two orthogonal plane waves [**?**, **?**]:

$$\epsilon_{xk} = \epsilon_k \cos\alpha_k e^{i\beta_{xk}}; \quad \epsilon_{yk} = \epsilon_k \sin\alpha_k e^{i\beta_{yk}},$$

where $k = 0$ denotes the core, and $k = 1$ and $k = 2$ represent the double cone respectively; α_k denotes the angle between the global electric field of each wave, and β_{xk}, β_{yk} represent the phase for each electric field component. Usually when

$\alpha_k = 0$ or $\pm\pi/2$, the wave is linearly polarized; and $\alpha_k = \pm\pi/4$ corresponds to right- and left-handed circular polarization respectively.

The Stokes parameters of a wave, as shown in Equation (23), are read [?]:

$$\begin{aligned} I_k &= \epsilon_k^2, \\ Q_k &= \epsilon_k^2(\cos^2\alpha_k - \sin^2\alpha_k), \\ U_k &= \epsilon_k^2 \sin\alpha_k \cos\alpha_k \cos\delta\beta_k, \\ V_k &= \epsilon_k^2 \sin\alpha_k \cos\alpha_k \sin\delta\beta_k, \end{aligned}$$

where $\delta\beta_k = \beta_{yk} - \beta_{xk}$ is the phase deviation between two orthogonal electric field components. Therefore, circular and linear polarization can be distinguished by $\delta\beta_k \neq 0$ or $\delta\beta_k = 0$ respectively. In other words, linear polarization requires $\delta\beta_k = 0$, while the angle α_k is arbitrary, each value of which has its own PA. Let us examine what happens to the PA when a specific angle $\alpha_k = \pm\pi/4$ is chosen:

$$\tan\psi_k = \frac{U_k}{Q_k} = \tan^{-1}\left[\frac{2\sin\alpha_k\cos\alpha_k\cos\delta\beta_k}{\cos^2\alpha_k - \sin^2\alpha_k}\right] = \pm\infty.$$

In such a case, a swing of LOS from, e.g., the cone ($k = 1$) to the core ($k = 0$) results in three different PA changes corresponding to Equation (25):

$$\psi_{1,0} = \psi_1 - \psi_0 = \begin{cases} 0, & \alpha_1 = \alpha_0 = \pm\pi/4 \\ \pm\pi/2, & \alpha_1 = -\alpha_0 = \pm\pi/4 \\ \text{RVM-like}, & \alpha_1 = \alpha_0 = \alpha_2 = \pm\pi/4 \end{cases}.$$

By Equation (26), as long as $\alpha_1 = \alpha_0 = \alpha_2 = \pm\pi/4$, an RVM-like smooth PA variation is expected. In this situation, the radiation intensity of linear and circular components are peaked either at the same phase or separated phases, while the signs of α_0, α_1 and α_2 remain unchanged as LOS swings from cone 1 through the core 0 to cone 2. This is widely exhibited in both subpulses and single pulses and in both pulsars and FRBs \cite{4-6, 40, 55, 59}.

In contrast, the orthogonal jump occurs whenever $\alpha_1 = -\alpha_0$ and $|\alpha_1| = |\alpha_0| = \pi/4$, as indicated by Equation (26). Such a sign change of $\alpha_1 = -\alpha_0$ can be achieved either by changing the sign of the dominant charge (electrons or positrons) in the cone beams, which is controlled by the guide field at the reconnection site that has been studied extensively in reconnection occurring in the solar wind and near-Earth magnetotail [?, ?], or by changing the sign of linear acceleration of the central jet responsible for core emission.

Moreover, by Equation (24), the sign change of $\alpha_1 = -\alpha_0$ inevitably leads to a sign change of circular polarization, $V_1 = -V_0$, which automatically explains the OPM occurrence accompanying a sign change of circular polarization as exhibited in observations \cite{3-6, 59}, also shown at the bottom of Fig. 1b. Furthermore, such a sign change of $\alpha_1 = -\alpha_0$ automatically leads to cancellation of linear polarization intensity at, e.g., the joint of cone 1 and core 0 by incoherent superposition of the Stokes parameters as shown in Equation (24):

$$L_{1,2} = \sqrt{(Q_1 + Q_0)^2 + (U_1 + U_0)^2} \approx 0,$$

which well explains the depolarization of linear polarization intensity during the PA jump. Such a prediction of simultaneous change of three observational values is strongly supported by observations from microstructure to single pulses and integrated pulse profiles, and from pulsars to FRBs \cite{4-6, 40, 55, 59, 60}.

The amplitude of PA jump less than $\pi/2$, i.e., approximately 60°, occurs [**?**]. This can be explained by $\alpha_1 \neq \pi/4$ or $\alpha_0 \neq -\pi/4$ in Equation (25), corresponding to elliptical polarization rather than circular polarization, which can be tested by further observations.

Therefore, the polarization of each beam composes a circular component with $\delta\beta_k \neq 0$ and $\alpha_k = \pm\pi/4$, and a linear component with $\delta\beta_k = 0$, not necessarily requiring $\alpha_k = \pm\pi/4$, but in the case of orthogonal jump it does. One of the triple beams, i.e., the cone, can be 100% linearly polarized when such a beam is dominated by CCE or linear acceleration with $\delta\beta_k = 0$.

The polarization can vary rapidly from one burst to another depending on different guide fields at the reconnection site, which can change from one reconnection event to another [**?**, **?**]. An incoherent superposition of PA of a large number of such microstructures results in the PA of the integrated pulse profile, the latter of which usually appears more complicated than that of the former. Nevertheless, the imprint of the former is obvious, which also varies from one single pulse to another as shown in observation [**?**].

V. Offset High Energy Components, States of Radiation, Absence of Spin & Gamma-Ray Radiation

After investigating coherent radio emission and its contemporaneous high-energy radiation, we now move on to their non-contemporaneous high-energy emission, which imposes further constraints on the magnetosphere and emission site of pulsars and FRBs.

The superb angular resolution of the Chandra X-Ray Observatory of the Crab pulsar [**?**] exhibits spectral variations consistent with a sinusoidal variation of the gamma-ray spectral index, in which the hardest one is between the main pulses $\phi = 0$ and interpulses $\phi = 0.4$, and the softest index lies between $\phi = 0.4$ and $\phi = 1.0$ [**?**], also shown in the middle of Fig. 1b. Such measurements challenge models of pair cascade processes in pulsar magnetospheres [**?**].

In the new scenario, the two phases $\phi = 0.0$ and $\phi = 0.4$ correspond to two reconnection sites (bipolar) dissipating with $J_\perp E_\perp$, which gives rise to multi-frequency coherent emission as shown in Equations (14)-(20) and in Fig. 1a. As the line of sight (LOS) swings through the phase between these bipolar coherent radiation regions, the radiation is dominated by incoherent emission composed of both thermal radiation by hot spots originating from bombarding of return plasma to the stellar surface, as shown in Fig. 1b (blue flux tubes), and non-thermal Poynting flux (up and down cone) produced by $J_\parallel E_\parallel$.

Since Hall reconnection produces inward electrons and positrons streaming separately along the separatrix to the stellar surface, the inward positrons can be accelerated by gaps existing in vacuum regions and bombard the stellar surface, reproducing hot spots. In contrast, the return electrons cannot reach the stellar surface at high speed and thus cannot produce observable thermal emission like those of positrons. Consequently, only one hemisphere of the star radiates observable thermal emission. This explains why the softest spectral index occurs in the phase interval $\Delta\phi = 0.4 - 1.0$, and the hardest spectral index of gamma-ray radiation appears in the phase interval $\Delta\phi = 0.0 - 0.4$, which provides a simple qualitative interpretation for the correlation of spectral index and multi-frequency coherent emission of the Crab pulsar [**?**], as shown at the bottom of Fig. 1a. Similarly, PSR J1119-6127 also exhibits in-phase radio and X-ray emission, while its gamma-ray profile peaks at a different phase $\phi \approx 0.2$ [**?**, **?**].

On the other hand, the huge discrepancy in luminosity between pulsars and FRBs can be explained simply by taking into account coherence effects. A coherent bunch of particle number N radiates coherently with power $N^2\dot{E}$, where $\dot{E}$ is the emission power of a single particle via, e.g., CCE. Consequently, the ratio of radiation power between the microstructure of a pulsar, i.e., the nanoshot of the Crab pulsar, and that of an FRB is:

$$\frac{P_{pulsar}}{P_{FRB}} \sim \left(\frac{N_{pulsar}}{N_{FRB}}\right)^2 \sim \left(\frac{10^{23}}{10^{25}}\right)^6 \sim 10^{-12}.$$

Therefore, a difference in size of the emission site of 2 orders of magnitude results in, e.g., 12 orders of magnitude deviation in luminosity, in the case of the nanoshot of the Crab pulsar and an FRB with approximately equal energy density, curvature radius ρ outside the light cylinder, and Lorentz factor γ, as shown in Equation (27).

The huge deviation in luminosity between a magnetar flare and the spindown luminosity of a pulsar (normal or old pulsar) can be attributed to their different energy accumulation in the magnetosphere, which can be understood by rewriting Equation (10) into three states:

$$\begin{cases} \dot{E}_{sd} + \dot{E}_{pl} = \dot{E}_{em}, & \text{normal, spindown} \\ |\dot{E}_{sd}| \sim |\dot{E}_{pl}|, & \text{low, nulling, quiescent .} \\ |\dot{E}_{sd}| \ll |\dot{E}_{em}|, & \text{high, flare} \end{cases}$$

The first and second terms on the left-hand side denote the power injection into the energy reservoir at the cost of kinetic energy loss of a pulsar, $\dot{E}_{sd}$, and the power of in-falling magnetic energy via twisting field lines into the energy reservoir, $\dot{E}_{pl}$. The term on the right-hand side is the power output from the reservoir, $\dot{E}_{em}$.

Normal pulsars with $M_A \ll 0.1$ correspond to extremely strong magnetic tension against the twist of field lines. It is the reconnection at the tiny end of the reservoir (the tip of the last closed field line) that provides a non-ideal MHD effect resisting such strong magnetic tension, which allows electromagnetic radiation releasing the kinetic energy of the pulsar rotation at a stable spindown power as shown in Equation (28). The quiescent state, as shown in the middle of Equation (28), denotes that the spindown power is transferred to helicity buildup, with $B_w \gg B_{lc}$, rather than radiation.

The relaxation of such piled-up energy occurs in two ways. Firstly, release of accumulated energy at the level of spindown power, i.e., in RRATs (Rotating RAdio Transients), a subclass of neutron stars emitting sporadic, short-lived radio bursts with intervals of silence lasting minutes to hours, like RRAT J1819-1458 [**?**], as shown in Table 1. Secondly, energy dissipation of piled-up energy for, e.g., hundreds of days for SGR J1935+2154, corresponds to a luminosity much larger than the spindown power [**?**, **?**].

The magnetar SGR J1935+2154 is not only one of the most active magnetars detected so far, but also the unique confirmed source of FRBs. FRB 20200428 bursts are distributed in a wide phase range, i.e., the Westerbork bursts and the CHIME 8 October bursts (vertical dashed) differ considerably from that of FAST [**?**], appearing to be anti-aligned with the persistent pulse profile in X-ray detected by NICER or XMM-Newton [**?**], as shown (vertical solid black) at the bottom of Fig. 1a. Interestingly, five months after its X-ray outburst associated with FRB 20200428, a radio pulsar phase emerged associated with X-ray spectral hardening [**?**]. Furthermore, the double peaks of such a radio pulsar phase are also anti-aligned with the persistent pulse profile in X-ray detected by NICER or XMM-Newton [**?**, **?**], which resembles the correlation of radio emission and offset gamma-ray emission exhibited in the Crab pulsar.

By Equation (3), the radial Alfvénic Mach number of magnetar SGR J1935+2154 is $M_A \approx 0.1$, which is much larger than that of the Crab pulsar as shown in Table 1. This allows a helicity buildup in magnetar SGR J1935+2154 approximately 3 orders of magnitude stronger than that of the Crab pulsar as shown in Table 1. Therefore, the X-ray outburst and FRB state of SGR J1935+2154 correspond to a high dissipation state, and the radio pulsar phase corresponds to a lower radiation state as shown in Equation (28), when the reservoir is sufficient only for spindown-level radiation.

The absence of spin exhibited in FRB 20200428, the high state of SGR J1935+2154, may stem from multi-reservoir buildup in the magnetosphere, and hence multi-reconnection sites which contaminate the Crab pulsar-like oblique radiation. Five months after such a high state of energy relaxation via X-ray outburst associated with FRB 20200428, it enters a low state dominated by oblique radio emission appearing as a radio pulsar [?].

No significant gamma-ray emission from any SGR or AXP has been detected by the Fermi LAT yet [?]. This can be well interpreted by Equation (19). The magnetic field of the reconnection region of the Crab pulsar, $B_w \sim 5 \times 10^3$ T, corresponds to a critical frequency of 10^{19} Hz. In comparison, the corresponding magnetic field is $B_w \sim 10^1$ T for typical magnetars, e.g., SGR J1935+2154, which expects a frequency in the X-ray band, $\omega_c \sim 10^{17}$ Hz, by Equation (19). Consequently, an enhanced magnetic field at the Y-point plus a tiny reconnection near the light cylinder provides a unified scenario as shown in Equation (28) responsible for ordinary pulsars, magnetars, RRATs, FRBs, and even pulsars located beyond the death valley.

VI. Association with Early Magnetosphere Models and Prediction

The main differences between the new model and FIDO models are: (a) helicity buildup in the case of non-ideal force-free conditions near the Y-point or energy reservoir; and (b) forced reconnection at the tip of the last closed field lines in the vicinity of the light cylinder (LC).

These two items themselves provide a new formation at the Y-point, by accumulated magnetic reservoir connecting with a tiny dissipation site undergoing rapid Hall reconnection. The superposition of a large number of such reconnection events automatically builds up a Y-shaped configuration. Furthermore, it provides a possible "physical solution" avoiding the singularity of the pulsar equation at the LC [?], because Hall reconnection occurring near the LC allows continuity in current and energy flux across the LC in the case of plasma speed not exceeding the speed of light.

In microphysics, such Hall reconnection gives rise to coherent radio emission, by which the problem of the disc-dome configuration believed unable to produce appreciable radiation [?] can be fixed. With assumptions of GJ-like force-free conditions, i.e., free escape of particles (both electrons and ions) from the neutron star surface and no pair creation [?], researchers have identified a ghost behind the elegant picture by discovering a completely different magnetospheric solution, in which electric field pulls electrons outward and the equatorial disk contains trapped ions, separated by large accelerating gaps existing in vacuum regions between the domes and the disk. These features are the consequence of the charge-separated nature of the solution [?]. The disk-dome configuration is believed to be the state of every neutron star below the death line (a "dead" pulsar), which produces no appreciable radiation [**?**, **?**].

As one possible "solution" to the tension between force-free magnetosphere and breaking-down dissipation, the model of this paper deviates from previous ones by a piled-up Y-point and a tiny dissipation site, which can be treated as adding a tiny dissipation site to the last closed field region of the disk-dome configuration. The resultant forced reconnection (in fact Hall reconnection) occurring near the LC leads to radiation enabling the disk-dome configuration to produce appreciable radiation for normal pulsars and even old pulsars.

Moreover, Hall reconnection produces: (i) inward electrons and positrons streaming separately along the separatrix to the stellar surface; and (ii) outward electron and positron beams interacting with surrounding open field lines responsible for cone emission of a microstructure. Furthermore, the trapped positrons piled up at the Y-point are also carried out by Hall reconnection as the central jet, which is responsible for the core component of the triple beams in the cone-core configuration. In other words, electrons drifting along open field lines are balanced by positrons escaping from the closed field line region across the LC via a large number of reconnections, so that circuit closure is automatically achieved. The reconnection occurring near the LC also corresponds to a continuous energy flux across the LC as shown in Equation (17), $\epsilon_{in} \sim \sum_{i=1}^{N} \epsilon_{out}$. Such energy relaxation from the piled-up Y-point is achieved by "persistent" emission of the triple beams triggered by Hall reconnection. On the other hand, such reconnection of tiny length scale in the vicinity of the LC automatically avoids plasma velocity exceeding the speed of light, $v > c$.

This paper for the first time directly confronts the most critical question raised by current observations: a microstructure with cone-core pattern, by an enhanced Y-point and tiny dissipation site, as shown in Fig. 2 [Figure 2: see original paper]. Firstly, the reconnection-triggered triple beams automatically give rise to a cone-core configuration responsible for polarization behavior of pulsars and FRBs. That is, an event of OPM jump must occur simultaneously with sign change of circular polarization and minimum linear polarization percentage. This is strongly supported by the huge number of polarization observations on both pulsars and FRBs and in both microstructures and integrated pulse profiles.

Secondly, the dissipation term is composed of parallel and perpendicular components corresponding to the Poynting flux along the open field lines of the polar region, $J_\parallel E_\parallel$, responsible for pulsar wind; and along the equatorial plane, $J_\perp E_\perp$, responsible for coherent pulsed radiation at multiple frequencies from high-energy emission respectively. The orthogonal phase between coherent and incoherent emission well accounts for the correlation of coherent radio and incoherent high-energy emission exhibited in some pulsars and FRBs.

The predictions are as follows:

1. The predicted correlation of PA jump with sign change of circular polarization and minimum linear polarization, as well as occurrence of elliptic polarization as shown under Equation (26), is expected to occur in: (a) shorter and shorter microstructures, i.e., nanoshots of the Crab pulsar and microshots of FRBs; and (b) microstructures of pulsars with 360-degree radiation.
2. The Hall reconnection triggered by enhanced magnetic field (much greater than that of the light cylinder) leads to radiation propagating in a "density cavity" along the flux tube formed by open field lines, which should leave imprints in both the rotation measure (RM) of the star and PA behavior in microstructures and single pulses.
3. The narrowband radiation occurs in radio emission of some young pulsars and FRBs with small Reynolds number $1 > R_m > 1/2$, as shown in Equation (13), corresponding to a very short timescale of microstructure. For pulsars and FRBs with $R_m \gg 1$ and much longer microstructure timescale, broadband emission is expected.
4. The energy budget responsible for pulsars, magnetars, RRATs, and FRBs depends on the radial Alfvénic Mach number, denoting the efficiency of helicity buildup of a star as shown in Equation (3).
5. Subpulses overlapped with each other along the rotation phase for most pulsars correspond to storms of beams radiating in a pulse profile [**?**]. In contrast, pulsars located beyond the death line like PSR J0250+5854 [**?**], which should be invisible in polar-cap gap models, can radiate in raindrops of weak subpulses as shown in Table 1 .
6. The predicted correlation of coherent radio with in-phase and offset incoherent high-energy emission should occur both in oblique rotators and approximately aligned rotators, which apparently deviates from that of polar cap models. Further multi-frequency observations of pulsars and FRBs together with their polarization behavior, i.e., OPM and RVM, will reveal unprecedented magnetosphere geometry and emission mechanisms of pulsars and FRBs.

FIG. 1 [Figure 1: see original paper]. A schematic plot exhibiting the coherent emission induced by forced reconnection, not to scale. Panel (a) top: The neutron star at the center of the light cylinder. The small red cylinders near the light cylinder are energy reservoirs created by twisting of magnetic field, which give rise to Poynting flux parallel to the open field lines. While magnetic reconnection triggers outward ejectors across the light cylinder invoking coherent emission, inward ejectors stream along the separatrix bombarding the stellar surface, causing thermal radiation along the open field lines. Panel (a) bottom: the correlation of radio and high-energy emission of SGR J1935+2154 [**?**] and the Crab pulsar [**?**]. Panel (b) top: an overview of the energy reservoirs (multi-site), which result in multi-ejectors across the light cylinder giving rise to coherent emission. The sum of dissipation of these ejectors is equivalent to a dissipation region approximated by a thin cylinder near the light cylinder. Panel (b) middle: the dissipation of an outward ejector operates via reconnection at the tip of the last closed field line, which produces triple beams. The two outside beams (responsible for cone emission) interact with the magnetic field in the flux tube by a pitch angle $\alpha_p \sim 10^{-1}$, giving rise to synchrotron radiation at high energy, which cools rapidly to the radio band with power comparable to that of CCE. The central jet produces emission originating from linear acceleration. The resultant linear polarization is denoted by arrows in the circle shown at the right side in the middle of Fig. 1b. Whether arrows point outwardly or inwardly depends on the sign of the linear acceleration of positrons with respect to the observer. Panel (b) bottom: the swing of LOS through such triple beams crosses the joint of the cone-core configuration, which leads to OPM jumps responsible for observations [**?**, **?**]. The left-hand side at the bottom of Fig. 1b denotes two different distributions of beams in the reconnection site controlled by different guide fields.

FIG. 2. [Figure 2: see original paper]. A schematic plot of the model with an enhanced Y-point and tiny dissipation site. In the plot, T, dt, and P denote waiting time between single pulses, the time duration of a microstructure, and the spin period respectively. E_B represents the magnetic energy piled up at the Y-point.

TABLE I. . Observational parameters and derived parameters of selected pulsars, magnetars and FRB.

Objects	P (s)	$\dot{P}$ (s s^{-1})	$\dot{E}_{sd}$ (W)	B_s (T)	B_{lc} (T)	R_{lc} (m)	B_w/B_{lc}	B_w (T)	σ
Crab pulsar	0.033	4.23×10^{-13}	4×10^{26}	4×10^{8}	1×10^{2}	2×10^{6}	5×10^{-3}	5×10^{1}	5×10^{3}
J1119-6127	0.41	3×10^{-25}	1×10^{10}	2×10^{-12}	1×10^{-3}	2×10^{8}	4×10^{-4}	6×10^{2}	3×10^{2}
J1819-1458	4.26	3×10^{25}	3×10^{9}	3×10^{-13}	2×10^{-3}	2×10^{8}	4×10^{-5}	4×10^{3}	4×10^{0}
J0726-2612	3.44	1.4×10^{-11}	4×10^{27}	2×10^{10}	7×10^{-4}	2×10^{8}	5×10^{-5}	5×10^{4}	3×10^{1}
J1935+2154	3.24	2.7×10^{-14}	8×10^{21}	3×10^{9}	2×10^{-6}	1×10^{9}	3×10^{-6}	5×10^{4}	1×10^{-1}
J0250+5854	23.5	6×10^{14}	6×10^{14}	6×10^{14}	6×10^{14}	6×10^{14}	6×10^{14}	6×10^{14}	6×10^{14}

Note: The table contains placeholders for missing values in the original text.

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