The Origin of Giant Pulses and Their Correlation with X-ray and PeV Emission from the Crab Pulsar

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Abstract

Increasing observations of microstructures, in particular giant pulses, require a pulsar emission mechanism with small size, high energy density, pair production, and Alfvén waves, which give rise to coherent trains responsible for subsequent pulsar emission. However, it remains difficult to reproduce these fundamental elements in polar-cap-based models. This paper proposes a reconnection process at the tip of the last closed field line region, with a current sheet of width $\sim 10^{-1}$m and length 10^{1}m, in the vicinity of the light cylinder. The resultant interaction of triple beams emanating from the X-line of the reconnection site leads to microstructures distributed in a cone-core pattern of pulsar emission. This new scenario can interpret not only the frequency and power of giant pulses, but also their correlation with X-ray and PeV emission exhibited in the Crab pulsar.

Full Text

Preamble

Increasing observations of microstructures, particularly giant pulses, require a pulsar emission mechanism characterized by small spatial scales, high energy density, pair production, and Alfvén waves, which generate coherent wave trains responsible for subsequent pulsar emission. However, reproducing these fundamental elements in polar-cap based models remains challenging. This paper proposes a magnetic reconnection process occurring at the tip of the last closed field line region, involving a current sheet of width 10^{-1} m and length 10^{1} m, in the vicinity of the light cylinder. The resulting interaction of triple beams emanating from the X-line of the reconnection site produces microstructures distributed in a cone-core emission pattern. This new scenario can interpret not only the frequency and power of giant pulses but also their correlation with X-ray and PeV emission observed in the Crab pulsar.

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Introduction

Microstructure has been known to exist almost since pulsars were discovered [**?**, **?**]. It has been shown that a pulse profile actually builds up from a large number of localized, transient events described as intermittency, fine structures, discrete emissions, short-lived emission centers, microstructure, and nanoshots [**?**].

Giant pulses (GPs) were first discovered in the Crab pulsar B0531+21, which turn out to be highly polarized and particularly much more powerful than the mean pulse of a pulsar, with equivalent brightness temperature T_b 10^{37} K, indicating coherent emission. A pulse of 1,000 Jy with a duration of 2 ns corresponds to an energy density of about 2×10^{14} erg cm^{-3} concentrated in a volume of one meter in size [**?**].

Typical models for GPs are as follows: (a) Direct emission mechanisms such as curvature radiation, with electrons trapped in bunches in the potential troughs of a large-amplitude plasma wave, resembling coherent curvature radiation (CCE) in studies of general pulsar emission [**?**]. (b) The model of relativistic plasma masers, which produces high brightness temperature transient pulses at the cost of a long coherence path length, analogous to beam-driven relativistic plasma emission (RPE) responsible for general radio emission, where plasma emission is generated by an electron beam causing Langmuir waves to grow and then convert into escaping radiation [**?**]. (c) The plasma turbulence model, where GPs originate from the conversion of electrostatic turbulence in the pulsar magnetosphere through the mechanism of spatial collapse of nonlinear wavepackets [**?**]. This short-duration process responsible for GPs differs from the Anomalous Doppler emission (ADE) responsible for general pulsar radiation [**?**], in which all electrons (and positrons) quickly radiate away the perpendicular component of their energy.

Nevertheless, these polar-cap based models populated by relativistically outflowing pair plasma encounter overwhelming difficulties in beam formation and beam-driven wave growth, which have been found to be unviable [**?**]. On the other hand, it has recently been suggested that a current sheet trapped in opening field lines beyond the light cylinder for 2–3 light cylinder radii can account for high-energy or radio emission from young pulsars [**?**, **?**, **?**]. However, how to produce radio emission for normal pulsars and how to create the cone-core pattern of radio emission in such an extended radiation region have not been addressed.

If the very short nanobursts are the fundamental elements of pulsar emission, then they require a process of small size with high energy density and pair production with Alfvén waves (AW), so that coherent trains responsible for subsequent emission can be generated. This paper demonstrates that these requirements can be achieved automatically by a tiny reconnection site with high plasma number density and strong magnetic field (B-field) located at the tip of the last closed field line region in the vicinity of the light cylinder, which provides a simple and unified model responsible for emission from the Crab pulsar ranging from radio to PeV energies.

The arrangement is as follows. Section (II) shows that the radial force exerted on the Y-point, the junction of the last closed field line and equatorial current sheet, is determined by the toroidal B-field. As the Y-point approaches the light cylinder, the last closed field line must be stretched by an equivalent differential rotation which triggers forced reconnection at the tip of the last closed field region. Section (III) demonstrates that the resulting relativistic reconnection invokes electron-positron pairs and AW leading to relativistic particles in phase with AW. Drifting along the flux tube of open field lines, these coherent beams give rise to radio emission responsible for observations. Section (IV) addresses superposition of microstructures, and Section (V) relates GPs with X-ray and PeV emission.

II. Effective Differential Rotation Above the Y-Point

Analogous to the solar dynamo, the oscillation of the toroidal field of the pulsar magnetosphere can shift the position of the Y-point in the vicinity of the light cylinder. As a result, the last closed field line is stretched by strong differential rotation which automatically triggers forced reconnection, releasing magnetic energy via pulsar emission. For simplicity, an aligned rotator is assumed in this paper.

The force on the Y-point can be analyzed by the equation of magnetohydrostatic equilibrium, where the forces are balanced by J × B + _{eE}, with J being the current density,   the mass density, _e = en_e the charge density, and E and B the electric and magnetic fields at the Y-point respectively. In the spherical coordinate system (r, ,) shown at the top of [Figure 1: see original paper]a, the azimuthal component of the Lorentz force experienced by the Y-point is given by [**?**]:

F_ = |(J × B) + {eE} | = J_r · B_

where J_r is the component of the electric current perpendicular to the magnetic flux surfaces at the Y-point. The term _{eE} is neglected since it completely vanishes in a true steady state [**?**]. The force component F_ = F_ corresponds to a torque per unit volume at the Y-point,   = r sin F_ , which accelerates charges of both signs along the positive -direction and vanishes in the case of force-free electrodynamics [**?**].

The current crossing the magnetic flux surfaces requires a strong force component F_r = F_ , which can be obtained via the radial component of the force equation:

F_r = |(J × B)r + {eE}r| J_ · B_

where B_ and J_ are the toroidal field and meridional current density at the Y-point respectively. The first term on the right-hand side is dominated by (J × B)r = $J\_$ · $B\_$. *For the term* {eE}r = J_ B_ + J_ B_ , the first component J_ B_ contributes to the right-hand side of Equation (3), while the second component J_ B_ = 0 due to J_ = 0 at the Y-point [?].

Consequently, the radial force from Equation (3) drives the Y-point towards the light cylinder, resulting in relaxation of the magnetic energy piled up at the Y-point, / , analogous to the buoyancy of piled-up toroidal field B_ triggering solar activities. The energy relaxation from the Y-point proceeds through a number of intermittent reconnections. Once an intermittent ejection of plasma is driven away from the Y-point by F_ from Equation (3) to a height Δh beyond the light cylinder radius, it is equivalent to dragging a bundle of frozen closed field lines at time t_0 (at phase _0) to the height Δh. When such a cloud rotates to phase _1 at a later time t_1 through co-rotation with the pulsar spin, as shown in [Figure 1: see original paper]a, it would result in a cloud speed exceeding the speed of light: (R_{lc} + Δh)Ω > c.

In fact, this can be prevented. Firstly, only the foot-point of the last closed field line is carried from _0 to _1, for a distance Δl (_1 - _0)R_{lc}. Secondly, the tip of the last closed field line is required to stay near its original phase _0 (or in an angular range of _0 < < _1) at time t_1. To achieve this, the last closed field line must be stretched to a length Δl, which is equivalent to the ejection of a cloud with speed v_{am} ω'R_{lc} c, countering the tangent speed corresponding to the rotation speed at the light cylinder, where ω' -ω, equivalent to a counter-rotation velocity with respect to the comoving frame of the pulsar magnetosphere. The trajectory of v_{am} beyond the Y-point forms a section of an Archimedean spiral, as depicted by the thick red curve at the top of [Figure 1: see original paper]a, which is determined by ΔR = β (where β is a constant), much shorter than the light cylinder radius, ΔR R_{lc}.

The motion of the ejected cloud along the Archimedean spiral is resisted by the magnetic force composed of magnetic tension and magnetic pressure respectively [?]. As soon as the cloud moves beyond the light cylinder, the dominant force resisting the magnetic force from Equation (4) is replaced by the differential rotation between the tip and footpoint of the last closed field line bundle, which corresponds to an inflow of Poynting flux S towards the stretching last closed field line bundle:

· S = -v · (j × B) -

where v_{in} is the velocity compressing the last closed field line bundle into an increasingly narrow shape, which ends up with a minimum curvature radius of R_c δ. The left-hand side inflowing Poynting flux, at the cost of rotational energy and magnetic energy of the magnetosphere, is thus transferred to the reconnection site on the right-hand side of Equation (5). Consequently, a significant enhancement of field strength and number density of the frozen plasma cloud at the tip of the last closed field line results, which triggers reconnection at the critical ratio of length to width ($L/\delta = 100/1$) of the current sheet [?] formed by the driven-out last closed field line bundle.

III. Forced Reconnection

Once such forced reconnection occurs, the inflowing Poynting flux (along the -axis) turns around at the center of the X-line of the reconnection site towards the -axis, so that $\cdot S = 0$ is satisfied, which corresponds to Hall reconnection [?] as shown at the top of [Figure 1: see original paper]b. The resulting outward Poynting flux converts to:

$$S \cdot ds = J^2 \quad v \cdot J \times B \, dV + \quad B^2$$

The three terms on the right-hand side of the above equation are responsible for pair production, accelerating them to relativistic speeds, and generating AW respectively.

Such forced reconnection with high energy density, T/ , results in relativistic reconnection and hence pair production, c^2 n_eσm_{ec}^{2}. The reconnection becomes relativistic when the so-called magnetization parameter $\sigma = \gamma^2 > 1$, where γ is the Lorentz factor of the plasma. In the case of σ 1, the Alfvén speed in the cold plasma limit approaches the speed of light [?]:

$$v\_A = c\sqrt{}(\sigma/(1 + \sigma))$$

The particles and AW stemming from such magnetic reconnection at the critical field B_T can undergo resonant wave-particle interaction because it allows the growth or damping of waves and the scattering and acceleration of particles, so that the particle sees the electric field of the wave as a static field in its rest frame [?].

The resulting coherent bunch moving along field lines with curvature radius gives rise to curvature radiation with effective frequency γ^3( )c 1 GHz, which corresponds to a power of CCE:

$$P\_\{cv\} = e \, e^2 c\gamma^4 \quad 10^{-30} N\_e^2\gamma^4(\ )^2 \quad 10^{18} \text{ W}$$

where N_e = n_{{{eV}}*{{rec}}} = n'V' (superscript denoting values at the emission site) is the number of plasma particles contained in a bunch. The radio power P*{cv} 10^{18} W on the right-hand side of Equation (8) should be 10^{-6} times the inflow energy from Equation (5) responsible for all-band radiation of the Crab pulsar. With a curvature radius of R_{lc}, we have four equations (Equation (5)–Equation (8)) containing six variables: B_T, γ, V_{in}, δ, and n_e. Although an exact solution to these four equations is not available, they still set strong constraints on the six parameters, allowing the best parameter estimation to be obtained: B_T $10^{4.5}$ T, γ 10^2, V_{in} 10^7 m/s, δ 10^{-1} m, n_e 10^{24} m^{-3}, and N_e 10^{25}.

These parameters are conceivable. For instance, the Goldreich-Julian density at the Y-point is n_Y $_0\Omega B\_$ 10^{12} m^{-3} for the Crab pulsar, and a much smaller volume of the reconnection site V_{rec} corresponds to a much larger number density of n_e $n_{YV}Y/V_{rec}$ 10^{24} m^{-3}, where V_Y is the volume of the Y-point. The B-field at the Y-point can be ten times that at the light cylinder [?], B_Y $10B_{lc}$ 10^3 T, and the reconnection site of much smaller volume than that of the Y-point can further enhance B_Y to B_T $10^{4.5}$ T.

IV. Superposition of Microstructures

A pulse window of a pulsar must compose numerous coherent emission bunches as shown in Equation (8). Their superposition can be investigated by the energy radiated per unit solid angle per unit frequency interval from a bunch with volume V and number of particles N_e drifting along a curved field line [?]:

$$dI_{tot}/d\omega d\Omega = (e^2\omega^{4\ 2}/8\pi^2c^3)\ |\ n \times (n \times \beta)\ e^{i\omega(t - n \cdot r(t)/c)}\ dt|^2$$

The coherent emission power is enhanced by a factor of $F_\omega(N_e)$, where $F_\omega(N_e)$ is a dimensionless parameter denoting the enhancement factor defined as:

$$F_\omega(N_e) = |\Sigma_{j=1}^{N_e} e^{-i\omega(n \cdot \Delta r_j/c)}|^2$$

where n is the unit vector to the observer and Δr_j is a section of a bunch of length L_{bc}.

With the AW depicted by $\exp(-\omega_i t)\exp(i\omega_r t)$ [?], one gets a real wave frequency ω_r kv_A 1 GHz, where k is the wave number, and an imaginary one $\omega_i = -kv_A/(2R_m)$ respectively. The damping of the AW is determined by the magnetic Reynolds number R_m $_0Lv_A/$, where L is the length of the current sheet of the reconnection site. In the case of R_m 10^1, the two frequencies are comparable, ω_i ω_r, corresponding to a short frequency range $\Delta\omega/\omega = (\omega_r^2 - \omega_i^2)^{1/2}/\omega_r$ 1, responsible for those of GPs.

In such a case, an AW of wavelength λ δ and coherent length $c\tau i$ *$10^1\lambda$ corresponds to a coherent bunch of length comparable to that of a wave train, L*{bc} $\Sigma\Delta r_j$ $10^1\lambda$. Then simply applying half-wave superposition, the enhancement factor of such an in-phase bunch becomes $F_\omega(N_e)$ N_e^2, which results in coherent emission of nanobursts.

The reconnection occurring at the apex of the last closed field lines produces a nanoburst as shown in [Figure 1: see original paper]a, which repeats rapidly with a short time interval Δt $2\pi/\omega_i$. Therefore, the swing of those nanobursts through a pulse window results in the single pulse of a pulsar with an enhancement factor:

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

where N_e and N are the number of particles in a nanoburst and the number of nanoshots in a single pulse respectively, with $N \quad 10^4$ inferred from observation [?]. This provides a concrete mechanism for microbursts, contrary to speculation [?] about incoherent superpositions of short-lived narrowband nanoshots.

The incoherent superposition of coherent nanobursts from Equation (8) gives rise to the power responsible for observational radio emission of the Crab pulsar, $NP_{cv} \quad 10^{22}$ W [?], with a number of nanobursts $N \quad 10^4$. Moreover, such incoherent superposition can also widen the frequency range of the microbursts [?]. Consequently, forced magnetic reconnection at the critical B-field B_T can well account for the coherency, microstructure, and characteristic GHz frequency of radio emission from pulsars.

GPs from the Crab pulsar exhibit power-law statistics at large flux F, proportional to the electric field squared $F \quad E^2$. The distribution (binning linearly in F) is well depicted by $P(F) \quad F^{-\Gamma}$ with $\Gamma = 3.3 \pm 0.3$ at 800 MHz [?, ?], which can be rewritten by taking into account $B_T^2 \quad \gamma^2$ from Equation (6):

$$P(F) \quad F^{-\Gamma} \quad [(cB_T)^2]^{-\Gamma} \quad \gamma^{-2\Gamma}$$

Therefore, a regular nanoburst with Lorentz factor $\gamma_0 \quad 100$ becomes a GP by increasing its Lorentz factor to $\gamma_1 \quad 20\gamma_0$, which corresponds to a five-order-of-magnitude power increase compared with a regular one given by Equation (8). In particular, this reduces the distribution rate by 8–9 orders of magnitude according to Equation (10), which well accounts for the occurrence rate of GPs from the Crab pulsar: 10^1 per hour [?]. This corresponds to one GP in 10^5 pulse periods, with each pulse period containing $N \quad 10^4$ nanobursts [?].

Interestingly, the parameters from Equation (5)–Equation (10) for the Crab pulsar are remarkably similar to those of the millisecond pulsar PSR B1937+21, which has an approximately equivalent light cylinder B-field.

As addressed in Section (III) and shown in [Figure 1: see original paper]b, the reconnection zone is responsible for both pair production and their acceleration to relativistic speeds. 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 [?], which have been studied extensively in the context of substorms in Earth's magnetosphere and solar flare events in the solar corona [?]. Consequently, once a reconnection event occurs at the tip of the last closed field line, three coherent bunches are generated simultaneously in the X-line region. Interacting with the flux tube, three nanobursts are produced simultaneously in the core-cone region, with the central one corresponding to core emission and the outer ones responsible for cone emission respectively, as shown in [Figure 1: see original paper]a. In the case of weak central emission, only double-peaked cone components are observable. The observation of triple or double distributions of nanobursts during each reconnection event in the emission pattern may test the validity of the new model.

V. Correlation of GP with X-ray and PeV Emission

The interaction of a pair of beams (coherent bunches) with an initial pitch angle αp *10*$^{-1}$ *with the flux tube is equivalent to pumping the distribution function to* f/p > 0, where p_ 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 to α_p 10^{-1} on a short timescale:

τ γm_{ec}^{2} / (2σ_{Tc}$^2\gamma^2$U_B sin$^2\alpha$_p)

where σT *is the Thomson cross-section and U_B is the magnetic energy density. Thus, a damping timescale of* τ *10*$^{-4}$ *s responsible for gamma-ray emission leading the radio emission by 280 s in the Crab [?] can be achieved with a B-field at the emission site of* B{em} 10^{-1}B_{lc}, a Lorentz factor γ 10^2, and a final pitch angle αp *10*$^{-5}$*. With these parameters, such damped synchrotron emission automatically radiates at a radio frequency* ω{em} = 3γ^2eB_{em} sinαp *1 GHz, which corresponds to a Larmor radius* R{syn} c/ω_c 10^{-1} m, comparable to the wavelength of AW.

It has been reported that both optical emission and X-ray emission are enhanced by 4% during the emergence of GPs [?], and it is further speculated that the GP-associated high-energy radiation has the same spectral energy distribution as that of regular pulses. Thus, the energy distribution of GP-emitting particles is similar to those of particles emitting regular pulses, which result from particle acceleration in the pulsar magnetosphere or a thin corrugated plasma flow at the equatorial current sheet [?]. Interestingly, these expectations can be well satisfied by Equation (10)–Equation (12) originating in forced reconnection near the Y-point of the pulsar magnetosphere.

A radio GP produced at pitch angle α_p 10^{-5} as shown in Equation (12), stemming from an ultrahigh-energy pulse with an initial pitch angle α_p 10^{-1} and Lorentz factor γ_1 $20\gamma_0$ from Equation (12), corresponds to a gyration frequency of 10^6 GHz. Putting such an enhanced frequency into energy E = ħγ^3 , where ħ is the Planck constant and $\omega/2\pi$, results in a ratio between initial energy (ultrahigh-energy) and final energy (radio) of E_i/E_r 10^{10}, which corresponds to an energy level of the initial pulse of 1 GeV. Taking into account dispersion of the initial pitch angle (10^{-1} α_p 10^{-1}) and fluctuations in γ, the initial energy E_i 1 GeV can be consistent with the pulsed emission in the range 100 MeV–300 GeV from the Crab pulsar [?].

As a result, synchrotron self-Compton (SSC) occurs. As synchrotron radiation of 1 GeV can be converted into electron-positron pairs of Lorentz factor γ 10^3, synchrotron photons that are upscattered once by the synchrotron-emitting electrons carry more energy than the unscattered synchrotron photons. The typical frequency of the upscattered photons is increased by a factor of γ^2. Multiple photon upscatterings are entirely suppressed by the Klein-Nishina cross-section [?]. Consequently, synchrotron photons of 1 GeV can be upscattered to an energy level of E $\gamma^2 \times 1$ GeV 1 PeV through suppressed SSC.

Interestingly, the spectral energy distribution of the Crab Nebula in the range keV–TeV displays a synchrotron component in the range keV–GeV and an inverse Compton component in the range GeV–PeV [?], which can be well interpreted by the occurrence of SSC at 1 GeV. Unlike pulsed X-ray emission that is in-phase with radio GPs [?], pulsed PeV emission has not been confirmed by observation yet [?]. Nevertheless, the correlation of PeV emission with GPs from the Crab pulsar can still be examined through their long-term occurrence, i.e., by comparing maximum (or minimum) occurrence rates in radio GPs and PeV emission at different timescales: hours, days, and months.

Consequently, the parameters interpreting radio GPs can be naturally extended to the high-energy emission of the Crab pulsar by changing the synchrotron radiation parameters from a final pitch angle of α_p 10^{-5} and Lorentz factor of γ_0 100 to an initial pitch angle of α_p 10^{-1} and Lorentz factor of γ_1 $20\gamma_0$, which is further responsible for ultrahigh energies of PeV via SSC. In other words, the new model provides a simple and unified scenario of pulsar emission from radio to PeV regime, which also suggests an alternative probe of the pulsar emission mechanism via ultrahigh-energy emission.

[Figure 1: see original paper] A schematic configuration of the forced reconnection. Panel a top: the stretched last closed field lines trigger reconnection, which produces outward beams resulting in emission with a core-cone pattern. Panel a bottom: a side view of the Y-point, which can be shifted radially along the r-direction by the toroidal field, and the magnetic pressure at the Y-point is along the -direction. The dashed ellipse depicts the pulsar magnetosphere. Panel b top: the forced reconnection at the tip of the last closed field line gives rise to Hall reconnection, with $\cdot$ S = 0. Panel b bottom: electron and positron beams separated by the guided field in the reconnection site.

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