On Pulsed Multi-Band Emission from TeV Gamma Rays to Radio Waves in the Crab and Velar Pulsar

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Abstract

Increasing observations of pulsed TeV γ-rays, i.e., in Vela[1] and Crab pulsar[2] [3] set unprece- dented constraints on mechanism and location of pulsar emission. In particular, how such ultra-high energy radiation (UHE) usually treated as incoherent be nearly in phased with coherent radio emis- sion, and thus achieving an approximately in phased multiband emission have not been understood. Here shows that fast spin velocity and strong strength of surface magnetic field of a pulsar result in accumulation of magnetic energy near the light cylinder. As a bundle of last closed field lines at such a energy reservoir is carried across the light cylinder by magnetocentrifugal, a forced reconnec- tion is triggered at the tip of the last closed field lines generating pair production. The resultant particle-wave resonance at the tiny reconnection site is analogous to the Free Electron Laser (FEL) process[4–6] where high-energy electrons are deflected, focused, and guided by magnetic fields, invok- ing coherent synchrotron emission responsible for pulsed TeV emission. Propagating of such a TeV γ-ray emission along the flux tube surrounding the tiny reconnection region leads to pair cascade responsible for multiband emission from 102MeV to radio. As each reconnection event corresponds to a microstructure with cone-core pattern, radiation of microstructure in multiband should exhibit similar morphology and polarization behavior. And a fluctuation in strength of magnetic field at the reconnection site can give rise to pulsed PeV γ-ray emission.

Full Text

Preamble

On Pulsed Multi-Band Emission from TeV Gamma Rays to Radio Waves in the Crab and Velar Pulsar Bi-Ping Gong∗ Increasing observations of pulsed TeV γ-rays, i.e., in Vela[1] and Crab pulsar[2] [3] set unprece- dented constraints on mechanism and location of pulsar emission. In particular, how such ultra-high energy radiation (UHE) usually treated as incoherent be nearly in phased with coherent radio emis- sion, and thus achieving an approximately in phased multiband emission have not been understood.

Here shows that fast spin velocity and strong strength of surface magnetic field of a pulsar result in accumulation of magnetic energy near the light cylinder. As a bundle of last closed field lines at such a energy reservoir is carried across the light cylinder by magnetocentrifugal, a forced reconnec- tion is triggered at the tip of the last closed field lines generating pair production. The resultant particle-wave resonance at the tiny reconnection site is analogous to the Free Electron Laser (FEL) process[4–6] where high-energy electrons are deflected, focused, and guided by magnetic fields, invok- ing coherent synchrotron emission responsible for pulsed TeV emission. Propagating of such a TeV γ-ray emission along the flux tube surrounding the tiny reconnection region leads to pair cascade responsible for multiband emission from 102MeV to radio. As each reconnection event corresponds to a microstructure with cone-core pattern, radiation of microstructure in multiband should exhibit similar morphology and polarization behavior. And a fluctuation in strength of magnetic field at the reconnection site can give rise to pulsed PeV γ-ray emission.

INTRODUCTION

The conversion of kinetic energy into magnetic energy thereby radiation is a fundamental astronomical process.

I.e., in the Solar Dynamo, the Sun’ s internal engine gen- erates cyclic magnetic fields responsible for Sun’ s observ- able activity.

For compact objects, i.e., neuron stars, such a conver- sion can be accomplished by induced electric field at po- lar cap with strength proportional to spin velocity and surface magnetic field in the context of the models of polar-cap gap. As a result, extracted electric beam can be accelerated at the cost of rotation energy, giving rise to high energy curvature radiation, pair production, and hence coherent emission along open field lines into the magnetosphere.

However, it is unlikely that the observed γ-ray emis- sion above 100 GeV[7]TeV can be explained by curvature radiation. Whereas, it is difficult for such γ-ray emission to get pulsed by emission originating in pulsar wind[1, 8] located outside pulsar magnetosphere.

Furthermore, multi-location radiation from both elec- tron–positron pairs produced in polar cap cascades and from primary particles accelerated in the separatrix and current sheet [9, 10] can not explain why UHE usually thought as incoherent be nearly in phased with coherent radio emission, and thus achieving an approximately in phased multiband emission.

On the other hand, a correlation relating subpulses in pulsed emission of radio-emitting neutron stars to their rotational period (τ 10−3P), is not only seen in mag- netars but in members of all classes of radio-emitting ro- ∗ Also at Department of Physics, Huazhong University of Science and Technology tating neutron stars, regardless of their evolutionary his- tory, their power source or their inferred magnetic field strength[11].

Moreover, such microstructures, i.e., Giant Radio Pulses (GRP) are not only correlate with UHE[12], X- ray emission[13], but also exhibiting a conal-core pat- tern indicated by their the polarization behavior[14, 15].

Consequently, it requires multiband microstructures with conal-core morphology.

To confront with these challenging problems, a new model is proposed with three processes: (a) magnetic en- ergy accumulation in the vicinity of light cylinder; and (b) the forced reconnection at the tip of the last closed field lines in the vicinity of light cylinder. (c) the FEL process[4, 5] triggered by such a reconnection causes a coherent multiband emission which well accounts for approximately in phased emission from TeV γ-ray[1, 2, 16] to radio.

Interestingly, the resonance condition of particle-wave operating in such FEL resembles that of anomalous Doppler emission (ADE), applying to radio emission[17–19]. However, the natural frequency of such emission has been thought too high to account for pulsar radio emission[20].

Here shows that such a resonance can leads to an insta- bility required in coherent emission thereby responsible for multiband emission from UHE TeV to radio, which is arranged by as follows. Section II: Generation of forced reconnection by the tiny site of magnetic reconnection near the light cylinder of a pulsar triggering pair produc- tion, accelerating them to relativistic speed, and produc- ing Magnetohydrodynamic (MHD) waves. Section III:

Resultant particle-wave resonance resembling FEL gives rise to coherent synchrotron radiation accounting for TeV γ-ray emission. And subsequent interaction of of such UHE photons with magnetic field surrounding the recon- nection site invokes pair cascades leading to enhanced coherent emission in X-ray, optic and radio bands ap- proximately in phase with UHE ones. Section IV: Pre- dictions of pulsed PeV γ-ray emission by solar dynamo like fluctuation in energy density at the reconnection site. at a tiny reconnection site, Sin = F · vin = −v · (J × B) − II. FORCED RECONNECTION OCCURRING NEAR LIGHT CYLINDER Pulsars with much faster spin speed and much stronger strength of surface magnetic field than that of the Sun, their magnetic energy accumulation and relaxation un- dergo more rapidly and radiate more coherently.

Analogous to the solar dynamo, the rotation energy of the star, −IsΩ ˙Ω (where Is is the moment of initial of the star) is converted into Poynting flux originating in magnetic energy reservoir, · S, and relaxed at the dissipation site, −J · E, −IsΩ ˙Ω + · S = −J · E = −J E − J E Notice that the dissipation term is composed of the par- allel component with the Poynting flux along the open field lines, J E ; and vertical component with coher- ent emission in the equatorial plane, J E respectively.

The former directly contributes to the incoherent wind, and the latter gives rise to coherent pulsed radiation in multi-frequency from UHE γ-ray to radio. The orthog- onal phase between coherent and incoherent emission as shown in bottom left of Fig1 well accounts for the correla- tion of coherent multiband emission with incoherent high energy emission exhibited in the Crab like pulsars[21].

Once an episodic ejection from the reservoir occurs near the light cylinder, such a plasma cloud is carried to a height, Δh σRlc (where σ 1 and σRlc corresponds to the size of 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, t0 (at phase, \$ \$0), to a height of, Δh.

If such a cloud is carried to the phase \$ \$1 at a later time, t1, through co-rotation with the magnetosphere of the pulsar, as shown in bottom left of Fig1, it would result in a speed of cloud exceeding the speed of light, (Rlc + Δh)$\Omega > c$.

This can be avoided, provided that only the footpoint of the last closed field line is carried from \$ \$0 to \$ \$1, for a distance Δl (\$ \$1 − \$ \$0)Rlc. Whereas, the tip of the last closed field line stays near its original phase \$ \$0 (or in an angle range of \$ \$0 < ϕ < \$ \$1) at time t1. To achieve this, the tip of the last closed field line must be stretched to a length, Δl Δh, which is equivalent to the ejection of a cloud with a speed of, vam ω'Rlc c, countering the tangent velocity at the light cylinder, ω'Rlc $-\omega$Rlc, in the comoving frame of the pulsar magnetosphere.

The stretching force against the magnetic tension cor- responds to an inflowing of Poynting flux into the tip of the last closed field line region, which is equivalent to a work done per unite time against the magnetic tension where vin is the velocity of charge flow compressing and stretching the last closed field line bundle into nar- rower and narrower shape. Consequently a reconnection is triggered at a critical ratio of width to length, i.e., Δh/Δl 1/100 of current sheet[22].

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 outflow direction as illustrated in the bottom of Fig1 (directions perpen- dicular to the inflow Poynting flux), so that $\nabla \cdot$ Srec = 0 is held, which corresponds the Hall reconnection[23]. This differs from models of pulsar emission with a diffusion region extending to a few light cylinder radius [22, 24], which corresponds to the Sweet-Parker reconnection with $\nabla \cdot$ Srec < 0. The resultant outward Poynting flux con- verts to three components responsible for pair produc- tion, accelerating them to relativistic speed, and gener- ating MHD respectively [25], Sout = Jrec $\cdot$ Erec + vrec $\cdot$ Jrec $\times$ Brec + which invokes particle-wave resonance thereby coherent bunches responsible for coherent emission in multiband.

III. RECONNECTION TRIGGERED RESONANCE AND COHERENT

> SYNCHROTRON EMISSION The stretching of the tip of the last closed field line bundle triggers the magnetic reconnection allowing not only an energy relaxation at a level well above the crite- rion required in the pair-production, 1.02 MeV, but also accelerating pairs of density number of ne to relativis- tic speed of the Lorentz factor γ, which relate with the energy density at the reconnection site by,   ne$ $2mec2. where me is the electron mass and c is the speed of light.

By Equation (3), a strength of magnetic field at the re- connection site, BT   104T , corresponds to an accelera- tion electric field of, E   cBT   1012V /m, comparable to that of the pulsar surface, although the strength of mag- netic field at the reconnection site is much weaker than that of the surface one, BT   Bs. Once the magnetic field, BT , is given, a constant ne$ $2   const is expected.

A fast plasma speed, i.e., γ 106 corresponds to a small number density ne   1015m−3 in the case of BT   104T.

Pair production and their acceleration at the tiny reconnection site naturally leads to a wave instability, and thus resonance of wave-particle, obeying the gy- roresonance condition, which has been denoted as the anomalous Doppler condition in the context of pulsar emission[20], ω − sΩe/γ − k v = 0 , In above equa- where Ωe is the cyclotron frequency. tion, s = 0, denotes the Cerenkov resonance, requiring an equivalence of wave and particle speed, $\gamma\phi = \gamma$, and the ADE resonance condition with s = −1, correspond- ing to a faster particle speed, $ $2 $ $2 ϕ, can be depicted as[20], $ $2 − $ 2 ≈ 2 $2 Assuming that all particles are in their ground (Landau) state, the anomalous Doppler transition to an excited state can, in principle, drive wave growth for all values of γ [20]. The reconnection triggered resonance frequency can be obtained by rewriting the cyclotron frequency in Equation (5), ω = 2 × 1011(103)2( )   1015Hz , Such a resonance frequency corresponds to an observa- tional frequency of, $\omega$$ $2   1027Hz, which accounts for both TeV γ-ray emission and multi-frequency emission to be addressed later.

With the cyclotron frequency, Ωe   1011(BT 104)   1015Hz and the electron plasma frequency, ωp = 1015)1/2   1 × 109Hz (e is electron charge, $ $0, the permittivity of free space), the cyclotron, plasma, and resonance frequencies are related by,)1/2(ne Ωe ω ωp Ωe/γ .

The characteristic length of the diffusion region, le, where reconnection takes place can be estimated by the electron inertial length le   de = c/ωp   3$×$10−1m, with ne   1015m−3 in the case of γ 106 by Equation (3).

Correspondingly the length of a coherent bunch of   le is much longer than the radiation wavelength, de/(c/ω)   106 for TeV γ-ray emission resembling that of an efficient undulator of FEL. The critical frequency (for isotropic pitch angle distribution) originating reconnection of the Crab and Vela pulsar can reach, ωc = (106)2   1027Hz, which is vastly higher than the fundamental cyclotron frequency, Ωe/γ. This provides a natural mechanism for pulsed emission at level of ω TeV γ-ray in the Crab and Vela pulsar. The single particle synchrotron radia- tion corresponding to Equation (7) is read, Esyn = 106)mec2 100W .

In contrast, the condition of particle-wave resonance as shown in Equation (6) guarantees that the total syn- chrotron emission by a coherent bunch with Lorentz fac- tor, γ 106 and number density, ne 1015m−3, radiate e)2 9 × 1026, in an equivalent number of, N 2 as the length of the reconnection site equals the initial length, le de, ei (nel3 Etot = (1015m−3)2(3 × 10−1)6Esyn 1027W .

The reconnection generated TeV photons travel along a cone-core pattern, as shown in bottom of Fig1. The cone component with larger pitch angle with respect to the field lines surrounding the reconnection site, produces electron-positron pairs via the single-photon conversion process, γ + B → e+ + e− resembling that of polar cap models[26]. Such pairs have nonzero pitch angles and very quickly lose all of the transverse component of their momentum owing to synchrotron radiation, which con- tributes further to the creation of new e± pairs. These new particles are then again accelerated and produce more photons and pairs. Such a copious pair creation occurring in open field line region is called a pair cascade or a pair "discharge" , with λ 103 − 105, denoting the cascade multiplicity parameter[26].

In contrast, the core component propagates along the central jet where the surrounding magnetic field cancel out, as shown in bottom of Fig1, which radiates in linear acceleration, with better chance escaping the absorption by cascade, especially in the leading phase of a pulse window[16, 27].

The first generation post reconnection radiation corre- sponds to a resonance and critical frequency of, ω' = 2 × 1011(102.5)2( ) 1013Hz, c = (105)2 1023Hz, where Bem Blc is the strength of magnetic field of the flux tube surrounding the tiny reconnection site, which is approximately the magnetic field at the light cylinder.

Correspondingly, the first generation cascade gives rise to 102MeV γ-ray emission of powers of a single particle and a coherent bunch similar to Equation (8) and Equation (9) respectively, syn = 105)mec2 10−5W , tot = (3 × 1015)2E′ syn 1026W .

The emission power of E′ tot 1026W at 102MeV at the cost absorption of TeV photons requires a cascade multiplicity parameter of $ 0 $\sim$ 102, *whichrelateswiththeinitialplasmanumberasshowninEquation*(9), *e* $\sim$ *Nei* $0.

Subsequent emission power of X-ray and radio emission are produced by further generations of cascade, EX (1018Hz 1023Hz 1026W 101)2 1023W .

Eradio (1026W 1023Hz ωradio 108Hz 104)2 1019W .

Therefore, a number of reconnection events of 105−6 result in power of radio emission which is 5-6 order of magnitudes lower than that of the spindown power[26].

This also consists with pulsed spectrum of the Crab pulsar[1, 2, 7, 28] in which the X-ray peak dominates the spindown power.

On the other hand, according to the Spectral energy distribution (SED) of pulsed Crab pulsar [28], the power of TeV and MeV γ-ray emission are weaker than that of X-ray emission for one order of magnitude. This requires that the initial power of TeV and 102MeV γ-ray, which should be much stronger than that of X-ray emission as shown in Equation (11), to drop for 2-3 orders of magnitude. Therefore, an absorption of TeV and 102MeV emission by cascade is required, as indicated by Equa- tion (11), Equation (12) and Equation (13).

IV. PREDICTION OF PULSED PEV γ-RAY AND CONCLUSION The observational PeV emission of the Crab pulsar[29] can be achieved in the context of reconnection triggered FEL through fluctuation of the strength of magnetic field at the reconnection site, analogous to the oscillation of magnetic energy in solar dynamo. As a result, the emis- sion frequency and power corresponding to Equation (10) and Equation (11) are read, c = (104.5)(107)2 1029.5Hz , syn = 104.5)2(107)mec2 102W , 1014)2(tot = (syn 1030W . 1 × 100)6E” Such an emission power can well account for the obser- vational one of E” tot 0.5%Esd[29] , which is obtained again by simply a reconnection length of approximately the initial length, le de 1m.

The spin down power of a pulsar can be depicted by in- coherent sum of observational multiband coherent emis- sion, from, i.e., PeV γ-ray, 102MeV γ-ray, X-ray, optic to FIG. 1 [Figure 1: see original paper]. A schematic plot exhibiting the coherent synchrotron emission induced by a forced reconnection, not in scale. Top left: Multiband nonthermal spectrum triggered by reconnec- tion. The reconnection site of high energy density can produce pair production and accelerate them to relativistic speed, so that particle-wave resonance equivalent to that of FEL gen- erates coherent bunch equivalent to pump reconnection produced pairs to UHE. Top right: The resultant TeV γ-ray emis- sion triggers cascade leading to multiband emission equivalent to transitions from UHE to lower energy levels. Botton left:

Reconnection induced multiband emission with core-cone pat- tern. The neutron star locates at the center of the field lines.

The small red cylinder near the light cylinder depicts one of energy reservoirs by twisting of magnetic field, which give rises to Poynting flux parallel to the open field lines. While outward ejectors across the light cylinder invoke reconnection thereby coherent emission, with inward jet streaming along the separatrix bombarding the star surface causing thermal radiation along the open field lines. Bottom middle: The out- ward jet produces a triple beams. The two outside beams (re- sponsible for cone emission) interact with the magnetic field in the flux tube responsible for coherent synchrotron radia- tion at UHE, which induces multiband lower energy radiation via cascades. The central jet produces emission originating in linear acceleration. radio, Esd = (cid:88) κkEk .

A spatial superposition of a large number of such recon- nection events automatically build up a Y-shaped config- uration near the light cylinder[22].

The reconnection triggered FEL at the tip of last closed field line region corresponds to an extremely high en- ergy density, efficient wave growth and short distance of dispersion allowing pulsed coherent multiband emission from TeV γ-ray to radio emission. As each reconnection event triggers multiband emission with imprint of the triple beams, swing of the line of sight through such a cone-core structured multiband emission should exhibit similar morphology of pulse profile and polarization prop- erties in both integrated pulse profile and microstructure.

These can be tested by further multiband observation from UHE, X-ray, optic to radio.

MHD wavePulsed PeV?Pulsed TeV with core-coneopticKeVTeVradio100MeVCore by central jet, LAECone by synchrontronPair productionacceleration Coherent Synchrontron radiation, N2Coherent bunchby wave-particle resonance, FELLight cylinderNeutron starReconnection sitereservoiremission siteInteracting with B-field surrounding reconnection sitecascadeFlux tube around reconnection siteForced Reconnection at a tiny sitecascade

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