Radio emission of the Crab and Crab-like pulsars

Yuri Lyubarsky

Ben-Gurion University

The Crab pulsar: Double-peaked light curve

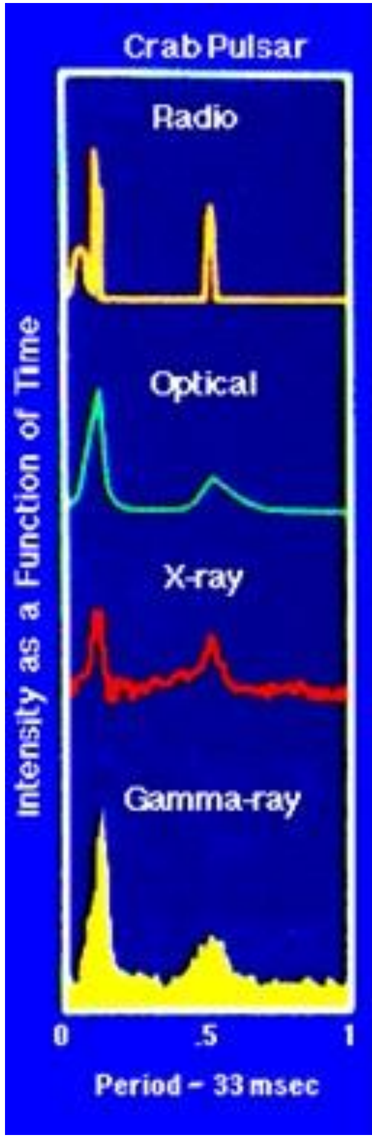
Giant pulses

High-energy emission; in phase with the main radio pulses

Millisecond pulsars: The abundance of double pulses in recycled pulsars is incompatible with the standard explanation of double-peaked pulsars as orthogonal rotators or nearly aligned rotators with a hollow cone beam.

Many of them are gamma-pulsars

In some of them, giant pulses are observed

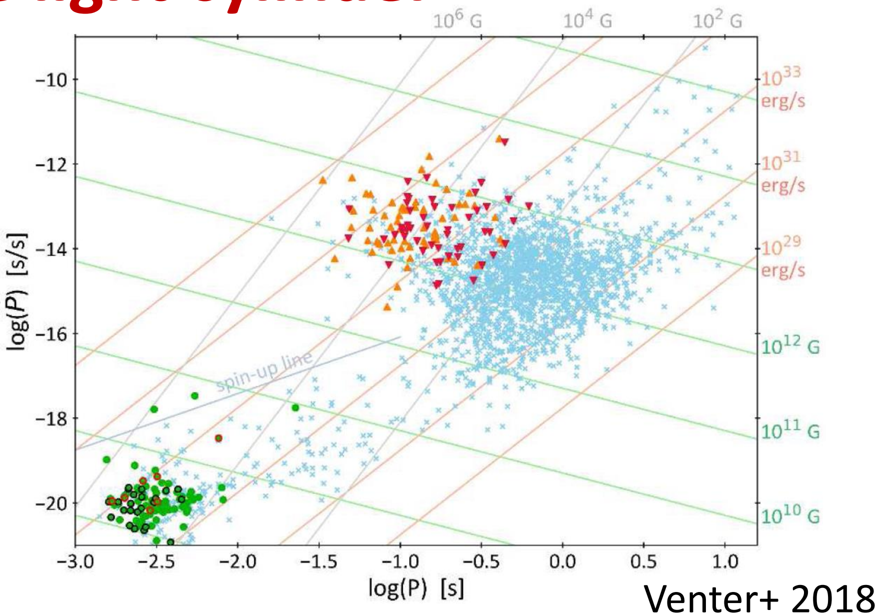


Pulsars with large magnetic fields at the light cylinder

In gamma pulsars $B \geq 1$ kG

In all ms pulsars that exhibit radio and gamma peaks aligned *B>100* kG (Johnson+ 2014; Ng+ 2014)

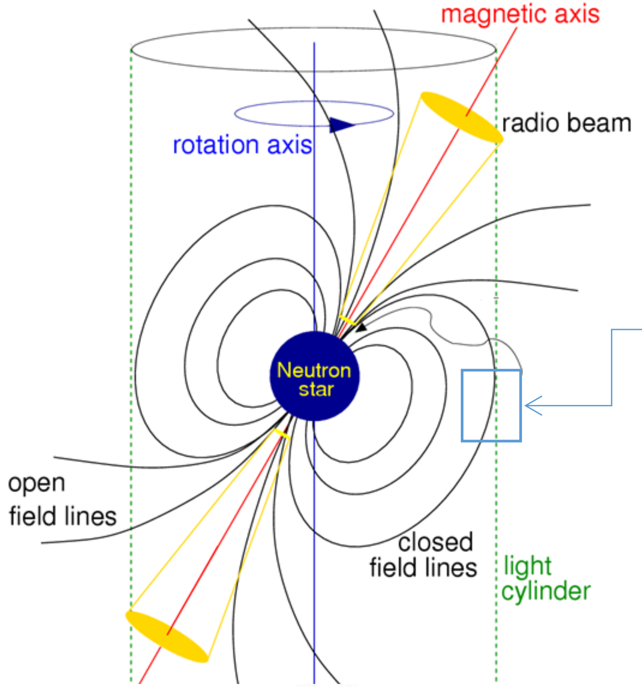
Giant pulses are observed only from ms pulsars with *B>100* kG (Bilous+2015)

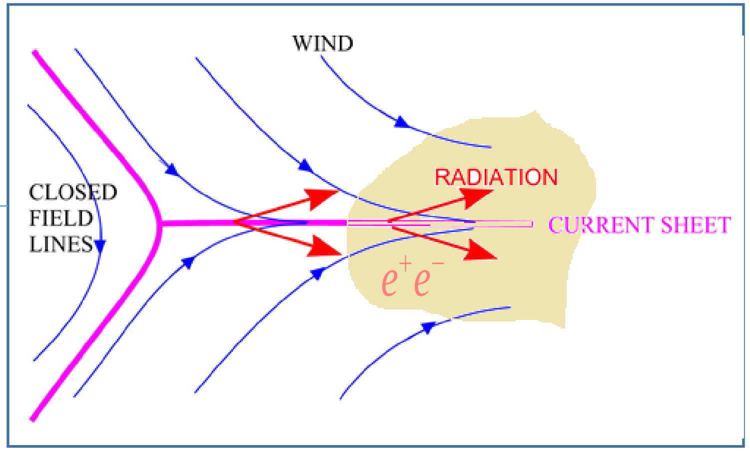


Venter+ 2018

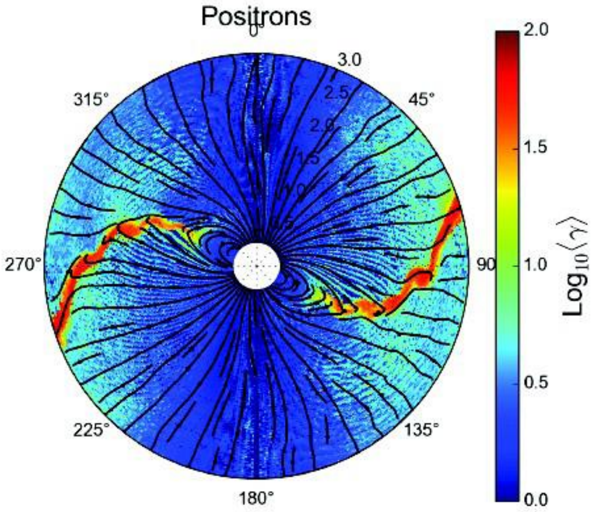
In pulsars with the highest magnetic field at the light cylinder, a special radio emission mechanism works associated with the high-energy emission region.

High-energy radiation from the relativistically hot plasma in the current sheet just beyond the light cylinder



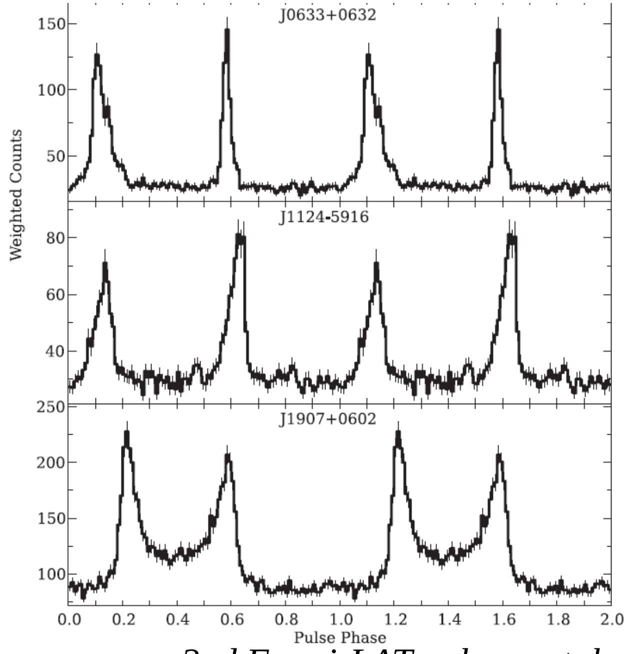


Beyond the closed part of the magnetosphere, the current sheet separates oppositely directed magnetic fields. The natural place for the energy release and high energy emission (Lyubarsky 1996; Bai&Spitkovsky2010; Kalapotharakos+2012,2018; Cerutti+2016)



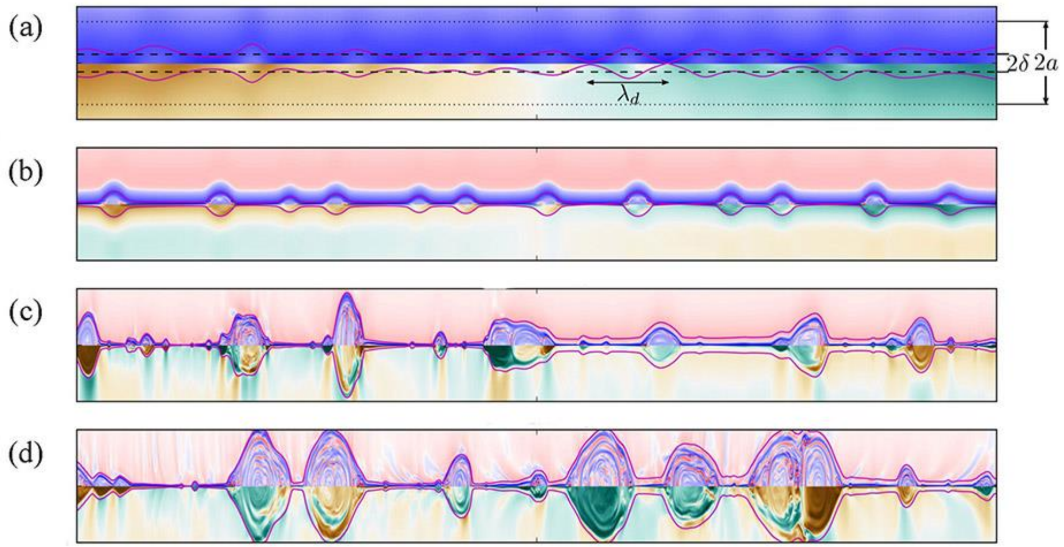
Cerutti+ 2016

Two-peaked lightcurves are generic: one peak per crossing of the current sheet

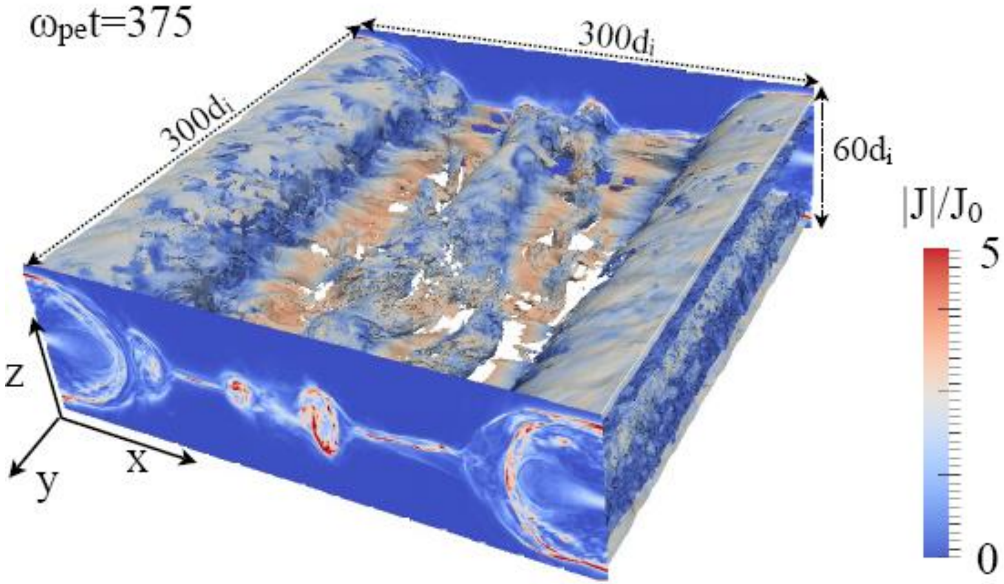


2nd Fermi-LAT pulsar catalog

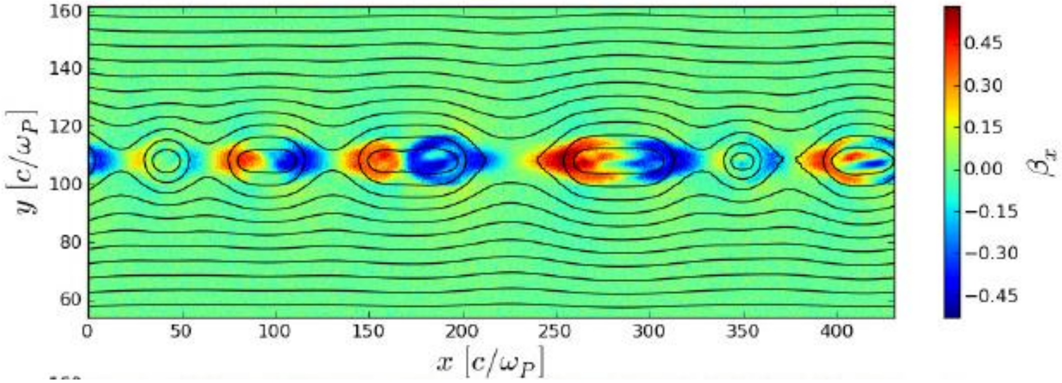
Magnetic dissipation in the current sheet via formation and coalescence of current ropes (aka magnetic islands)



Huang+ 2017



Guo+ 2015



Kagan+ 2015

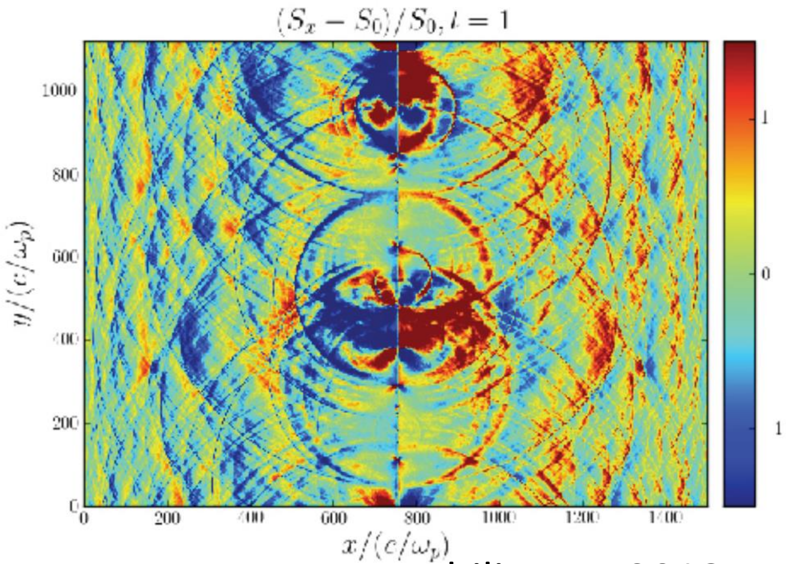
Electro-magnetic pulses from coalescencing magnetic islands

Coalescence of two magnetic islands produces a magnetic perturbation in the vicinity of the coalescence region. MHD waves are generated around the current sheet.

Alfven wave: $$\mathrm{v}_{\mathrm{ph}} = \sqrt{\frac{\sigma}{1+\sigma}}\, c\cos\theta \quad \mathbf{v}_{\mathrm{gr}} = \sqrt{\frac{\sigma}{1+\sigma}}\, c\,\frac{\mathbf{B}}{B}$$

Fast magnetosonic wave: $$\mathrm{v}_{\mathrm{ph}} = \sqrt{\frac{\sigma}{1+\sigma}}\, c \qquad \mathrm{v}_{\mathrm{gr}} = \sqrt{\frac{\sigma}{1+\sigma}}\, c$$

$$\sigma = \frac{B^2}{4\pi\rho c^2}$$

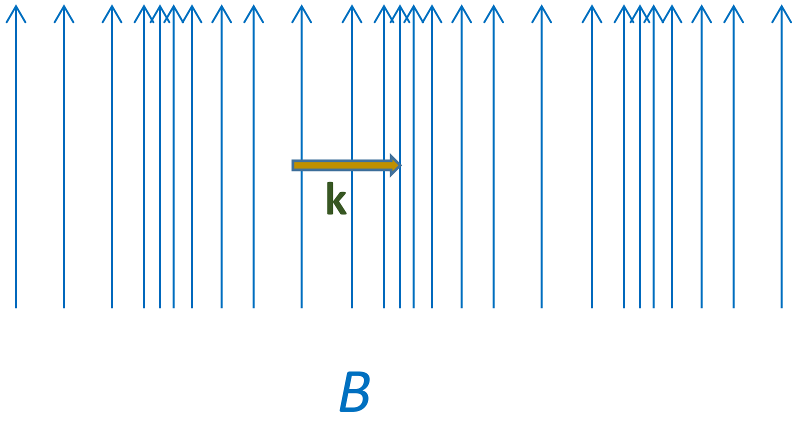


Philippov+2018

The group velocity of the Alfven waves is directed along the magnetic field lines therefore, they do not transfer the energy away from the current sheet.

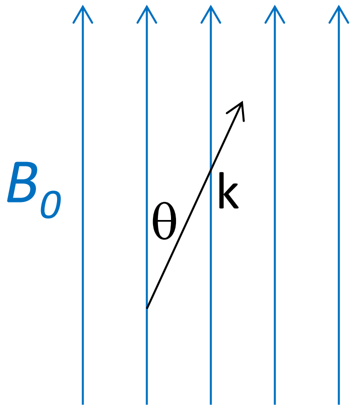
Fast magnetosonic waves do propagate across the magnetic field lines therefore any coalescence event produces a quasi-spherical, in the frame of the plasma in the sheet, fms pulse of the duration ~*a*/*c*, where *a* is the transverse size of the island.

FMS waves in a highly magnetized plasma



Fast magnetosonic wave: longitudinal oscillations, transverse electric field

$$\mathrm{v_{ph}} = \sqrt{\frac{B^2}{4\pi\rho + B^2}}\,c$$



$$\propto \exp\left(-i\omega t + i\mathbf{k}\cdot\mathbf{r}\right)$$

$$-\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E} \qquad \nabla \times \mathbf{B} = \tfrac{4\pi}{c}\mathbf{j} + \tfrac{1}{c}\tfrac{\partial \mathbf{E}}{\partial t} \quad \Rightarrow \quad i\mathbf{k}\times(\mathbf{k}\times\mathbf{E}) = \tfrac{4\pi}{c}\mathbf{j} - i\omega\mathbf{E}$$

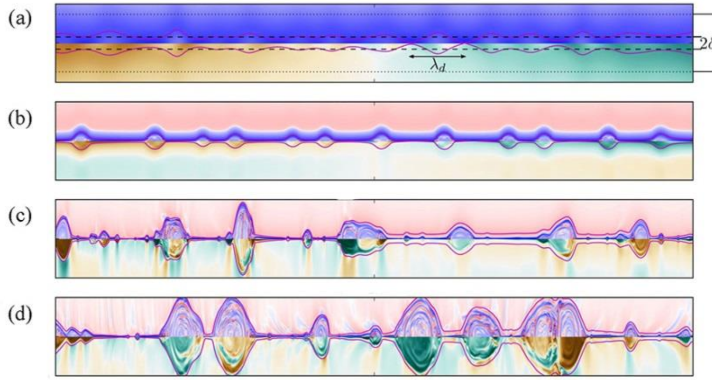
$$\mathbf{k}\cdot\mathbf{E} = 0; \qquad \mathbf{E}\cdot\mathbf{B}_0 = 0 \qquad \omega = \sqrt{\frac{\sigma}{1+\sigma}}\,ck \quad \Rightarrow \quad \frac{j}{i\omega E} = -\frac{1}{4\pi\sigma}$$

At $\sigma \to \infty$, the conductivity current vanishes. Therefore the wave smoothly transforms to a vacuum electro-magnetic wave when plasma density goes to zero.

Parameters of the emitted pulses

The width of the current sheet is determined by the balance between the dissipative heating and the synchrotron cooling (Lyubarskii 1996; Uzdensky &Spitkovsky 2014)

$$\Delta \sim 1 B_6^{-3/2}\ \mathrm{m}$$



Huang+ 2017

Width of ropes, $a=10^3\, a_3$ cm; length $l=10\zeta a$.

$\Gamma=10\,\Gamma_1$ – Lorentz factor of the flow within the sheet

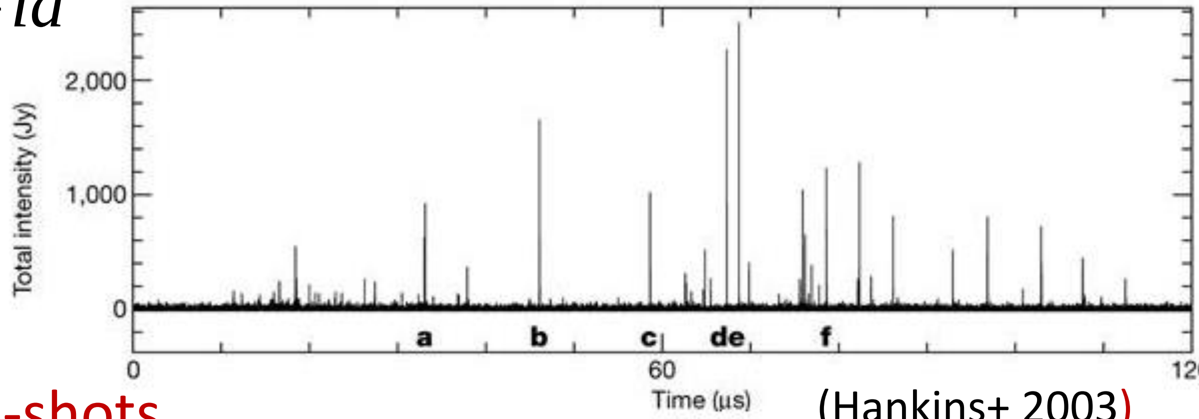
Observed duration of the pulse $\tau = 3\dfrac{a_3}{\Gamma_1}$ ns

Frequency $f \sim \tau^{-1}$ ~300 MHz

Energy of the pulse in the comoving frame $U' \sim \frac{B^2}{8\pi} l a^2$

Spectral flux at the distance D

$$S \sim \frac{U'\Gamma^3}{\pi f \tau D^2} = 350\ \varsigma a_3^3 \Gamma_1^3 B_6^2 \left(\frac{2\ \mathrm{kpc}}{D}\right)^2 \mathrm{Jy}$$



(Hankins+ 2003)

Compatible with the observed parameters of nano-shots

Non-linear interaction of pulses

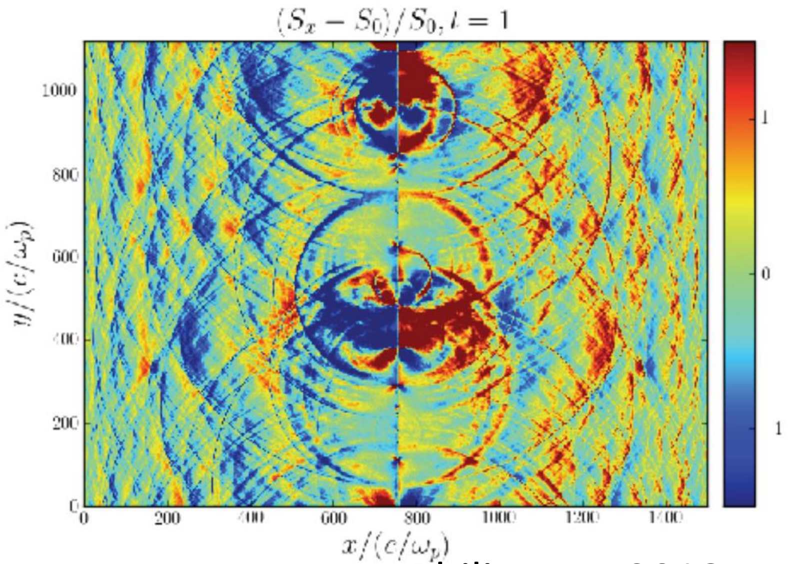
An fms pulse produced by a coalescence event passes through other pulses.
The non -linear interaction between the pulses should be generally taken into account.
The simplest is the interaction of three waves

$$\omega = \omega_1 + \omega_2; \qquad \mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2$$

Possible for $S \leftrightarrow S + A$ and $S \leftrightarrow A + A$

For monochromatic waves

$$\frac{da_{\mathbf{k}}}{dt} = V_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} a_{\mathbf{k}_1} a_{\mathbf{k}_2}; \qquad \frac{da_{\mathbf{k}_1}}{dt} = -V^*_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} a_{\mathbf{k}} a_{\mathbf{k}_2}; \qquad \frac{da_{\mathbf{k}_2}}{dt} = -V^*_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} a_{\mathbf{k}_1} a_{\mathbf{k}}$$



Philippov+ 2018

$$\left|V_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}}\right| \sim \frac{\omega^{3/2}}{B_0}$$

$$V^{S\to S+A}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} = -\left(\frac{\pi\left|\cos\theta_1\right|}{2k_2}\right)^{1/2}\left(\frac{k_1 c}{k}\right)^{3/2}\frac{\sin\theta_1\left[1-\mathrm{sgn}\left(\cos\theta_1\right)\cos\theta_2\right]\left[\left(\mathbf{k}_2\times\mathbf{k}\right)\cdot\hat{\mathbf{z}}\right]}{B_0\sin\theta_2\sin\theta}$$

$$V^{S\to A+A}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} = \left(\frac{2\pi\omega_1\omega_2 c}{k}\right)^{1/2}\frac{k_1\sin\theta_1\cos\phi_2 + k_2\sin\theta_2\cos\phi_1}{B_0}$$

Non-linear interaction of pulses (cont)

For wide spectra and random phases

$$\frac{\partial n_{\mathbf{k}}}{\partial t} = \int W_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} \left[n_{\mathbf{k}_1} n_{\mathbf{k}_2} - n_{\mathbf{k}_1} n_{\mathbf{k}} - n_{\mathbf{k}_2} n_{\mathbf{k}} \right] \delta\left(\omega_{\mathbf{k}} - \omega_{\mathbf{k}_1} - \omega_{\mathbf{k}_2} \right) d^3\mathbf{k} \qquad W_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} = 2\pi \left| V_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} \right|^2$$

The characteristic interaction time $t \sim \left(W_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}} n_{\mathbf{k}} k^2 \right)^{-1} \sim \left(\frac{u}{u_0} \omega \right)^{-1}$ $\qquad u_0 = \frac{B_0^2}{8\pi}; \qquad u = \omega n_{\mathbf{k}} k^3$

Radiation escapes if $t \sim \frac{R_L}{c} = \frac{P}{2\pi}$ ⇒ Radio luminosity $L \sim \frac{1}{Pf} L_{\rm sd}$

The Crab: *P*=33 ms, *f*~100 MHz; L_{sd} =5 10^{38} erg/s

Estimated $L \sim 3\ 10^{-7}\ L_{sd} \sim 10^{32}$ erg/s; observed L=7 10^{31} erg/s

Polarization

General: a) e-m waves propagate within a medium in the form of normal modes;

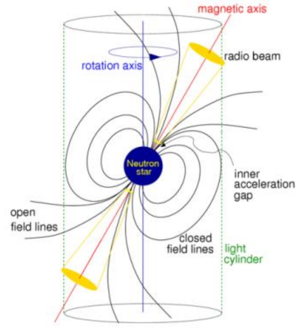
b) in the electron-positron plasma, the normal modes are linearly polarized;

c) if the scale of beating between the modes is less than the inhomogeneity scale, the polarization of the modes is adjusted to the local direction of the magnetic field

$$\Delta n \frac{L}{\bar{\lambda}} \begin{cases} >> 1, & \text{adiabatic walking} \\ \sim 1, & \text{polarization limiting zone} \\ << 1, & \text{vacuum propagation} \end{cases}$$

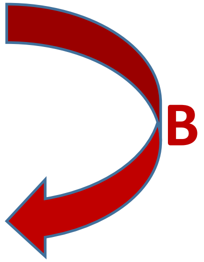
d) the observed polarization is formed at the polarization limiting zone;

e) in pulsars with a large B at the light cylinder, this occurs in the wind zone, well beyond the light cylinder



magnetosphere

Pulsar wind

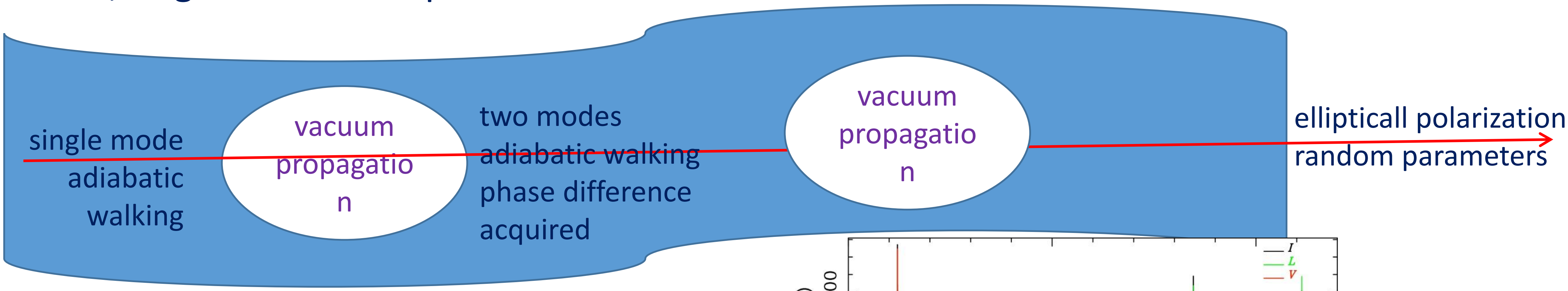


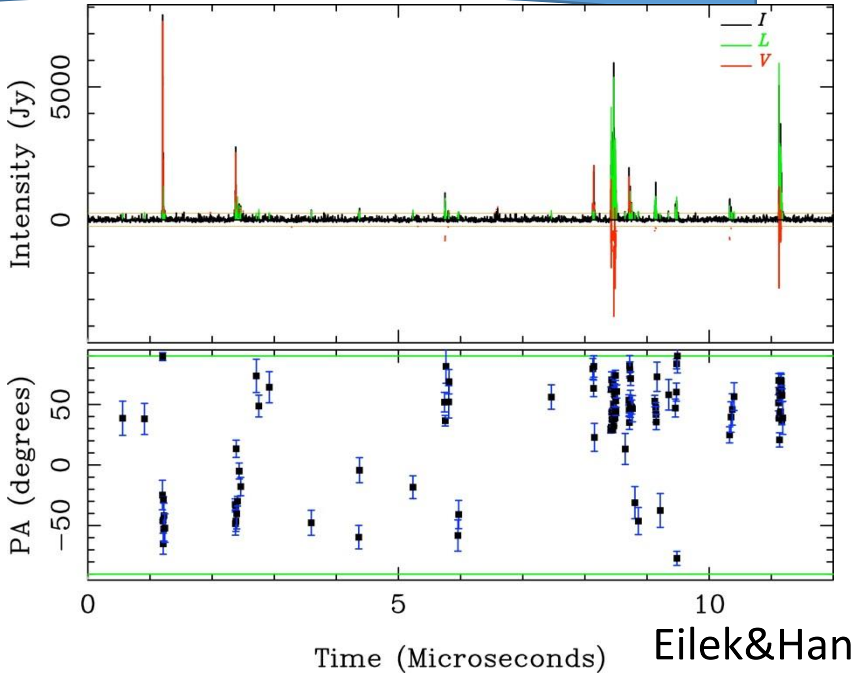
Polarization limiting zone

Polarization (cont)

If the magnetosphere and the wind were completely filled with plasma, one would observe 100% polarization along the pulsar axis.

However, large voids are expected in the outflow





Eilek&Hankins 2016

Conclusions

1. In pulsars with high magnetic fields at the light cylinder, both the high energy and the radio emission come from the same site.
2. The emission site is the current sheet separating, just beyond the light cylinder, the oppositely directed magnetic fields.
3. The emission is powered by the magnetic reconnection.
4. Coalescence of magnetic islands in the sheet produces magnetic perturbations that propagate away in the form of electro-magnetic nanoshots.
5. The estimated parameters of the radio emission are compatible with those observed. All scales (wavelength etc) are determined by the width of the current sheet

$$\Delta \sim 1 B_6^{-3/2} \text{ m}$$

Only pulsars with the highest B emit in the observed radio band