Отражение радиоизлучения от поверхности нейтронной звезды

V.M. Kontorovich[1,3], S.V. Trofymenko[2,3]

[1]Institute of Radio Astronomy of NAS of Ukraine, [2]Kharkiv Institute of Physics and Technology, [3]Karazin Kharkiv National University

Рассмотрено возникновение нового типа излучения в полярном зазоре пульсара. Механизм основан на отражении от поверхности пульсара излучения кривизны, которое испускается возвратными позитронами, движущимися к поверхности нейтронной звезды вдоль магнитных силовых линий. Позитроны ускоряются продольным электрическим полем, частично проникающим в магнитосферу. Этот механизм в присутствии наклонного магнитного поля объясняет возникновение сдвига интеримпульса и появление дополнительных ВЧ-компонент в сантиметровом излучении пульсара Краба, обнаруженных Моффеттом и Хэнкинсом двадцать лет назад (ApJ 468, 779, 1996). Дана оценка потока энергии и спектра отраженного когерентного излучения, согласующаяся с наблюдениями. Объясняется появление и исчезновение сдвига положения интеримпульса в определённом частотном окне с увеличением частоты. Показано, что в виде ВЧ-компонент возможно наблюдается нелинейное отражение излучения возвратных позитронов от поверхности нейтронной звезды (вынужденное рассеяние на поверхностных волнах). Нелинейное отражение определяется «аномалией Вуда» на дифрагированных волнах, скользящих вдоль поверхности нейтронной звезды. В рамках данного механизма объяснён частотный дрейф этих компонент, открытый Хэнкинсом, Джонсом и Эйлек (ApJ, 802, 130, 2015). Два компонента могут возникать из-за медленных и быстрых волн, которые присутствуют в магнитосферной плазме. Данный механизм является общим для пульсаров и его вклад должен учитываться при построении теории их радиоизлучения.

Kontorovich V M and Trofymenko S V, Journal of Physical Science and Application (JPSA) 7, 11 (2017); arXiv:1707.01584.

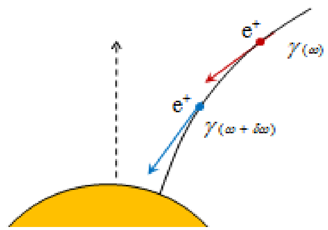
HEA - 2017

Kontorovich and Trofymenko (2016, 2017):

The radiation of a pulsar in the Crab nebula contains a signal reflected from the surface of the neutron star in the form of shifted IP.

That signal is associated with radiation of the

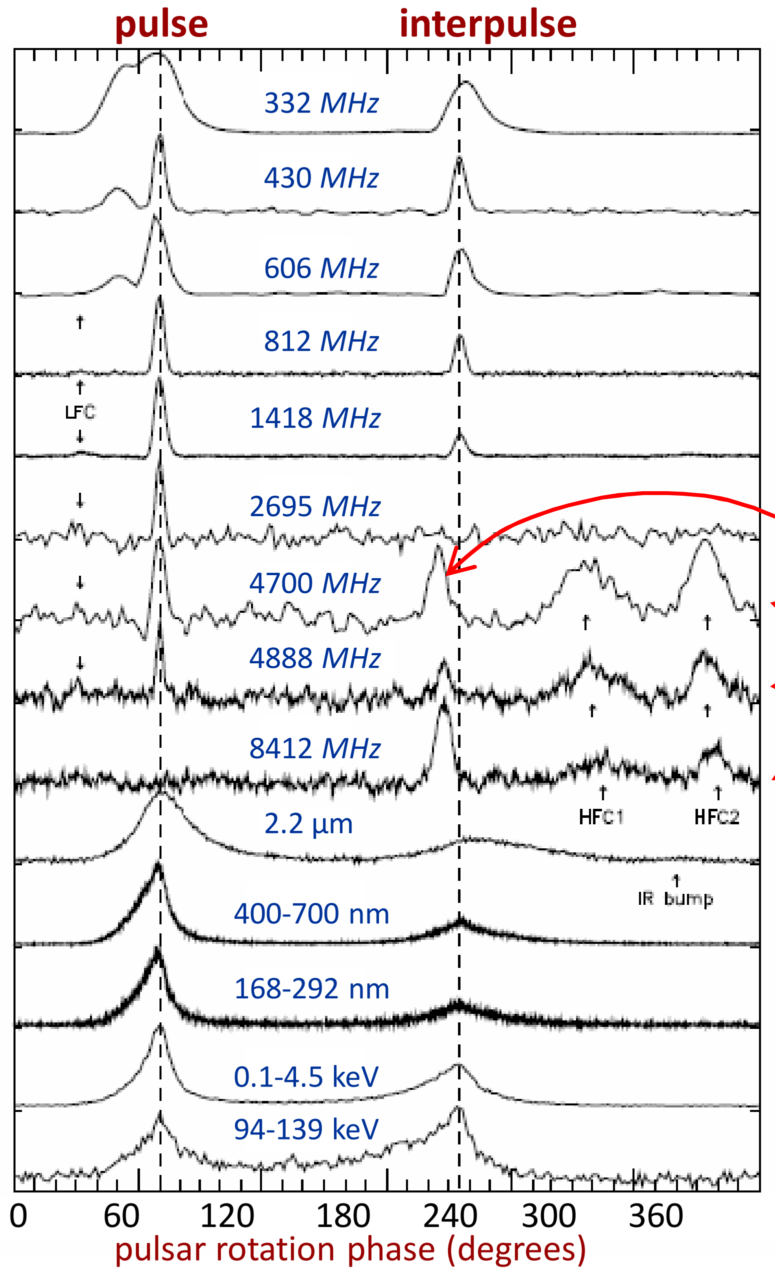
returning positrons



LTP 2016 & this report:

It is possible that in this case also a stimulated scattering from the star surface is observed in the form of HF components

Mysteries of pulsar radiation in the Crab

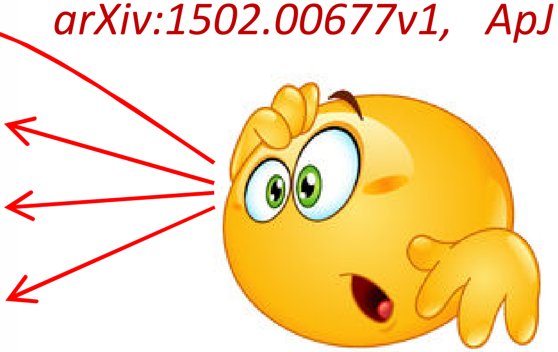


D. Moffett,T. Hankins // Astrophys. J., 1996

By Courtesy of the Authors

20 years later:

T.H. Hankins, G. Jones, J.A. Eilek // arXiv:1502.00677v1, ApJ ***802****, 130 (2015)*



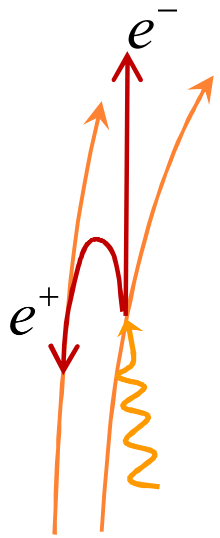
HEA - 2017

Shift of the interpulse as a result of mirror reflection from the pulsar surface of the radiation by relativistic positrons flying to a star from the magnetosphere

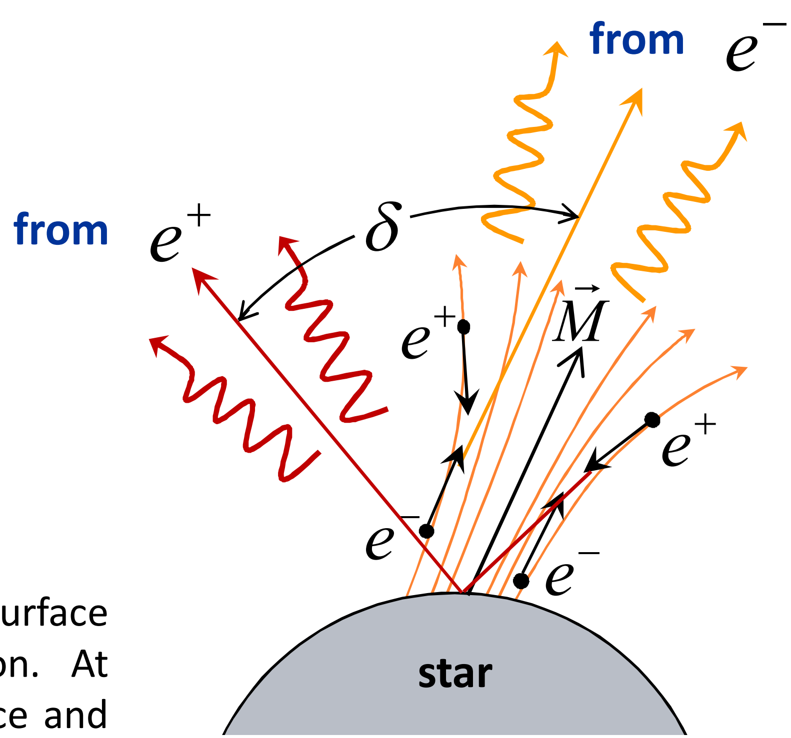
V.M. Kontorovich and S.V. Trofymenko, JPSA **7,** 11 (2017)

HEA - 2017

THE RIDDLE SOLUTION: RADIATION BY RETURNING POSITRONS MOVING IN THE INCLINED MAGNETIC FIELD



As the origin of the shifted high-frequency IP we consider the radiation by positrons moving towards the surface of the pulsar in the polar gap. Such positrons can be returned from the lower layers of the magnetospheric plasma by the same electric field which accelerates the electrons outward the star.



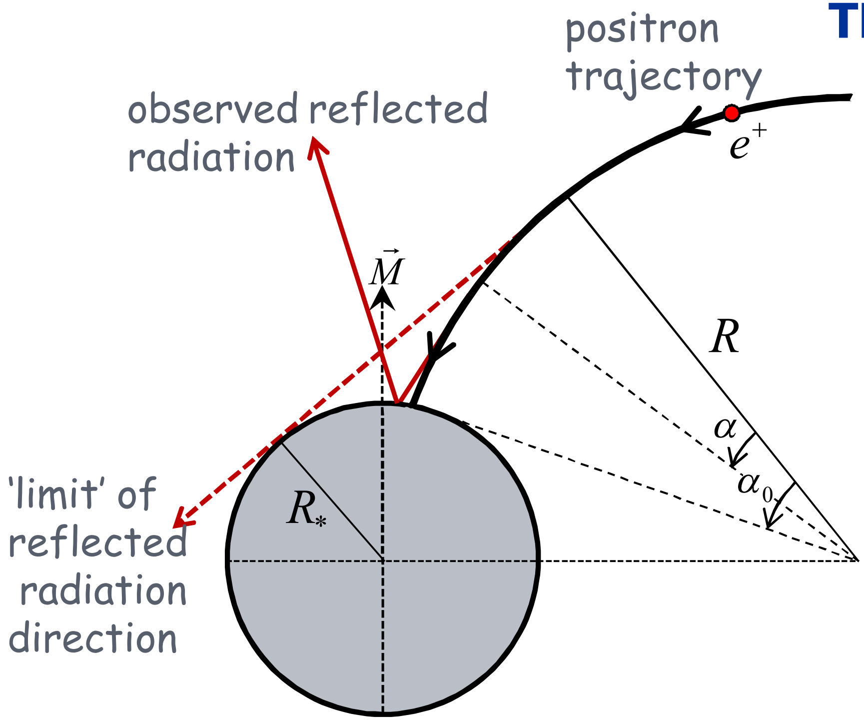
Moving along curved magnetic field lines towards the surface of the star the positrons emit curvature radiation. At sufficiently high frequencies it reflects from the surface and propagates outward the star. Moreover, when the positrons hit the surface the so-called transition radiation is generated in the direction outwards the surface as well.

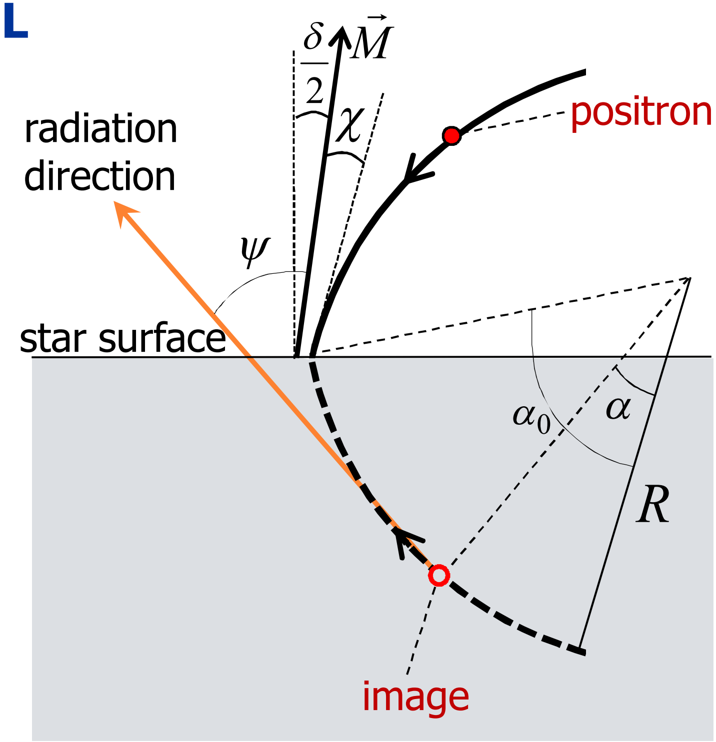
e^+ radiation = reflected curvature radiation + transition radiation

low-frequency interpulse – from e^- radiation

high-frequency (shifted) interpulse – from e^+ radiation

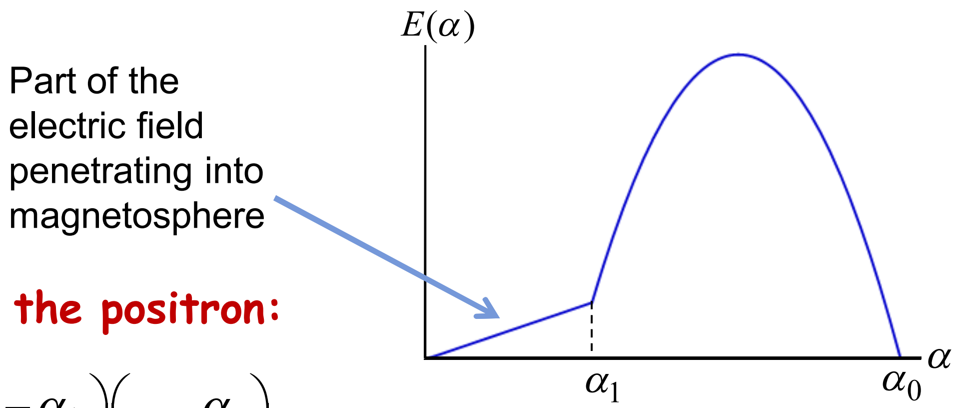
THE MODEL





angle corresponding to 'effective' part of positron trajectory:

$$\alpha_0 \sim \arccos\left(1-\frac{R_*}{R}\right)-\frac{R_*}{R}$$



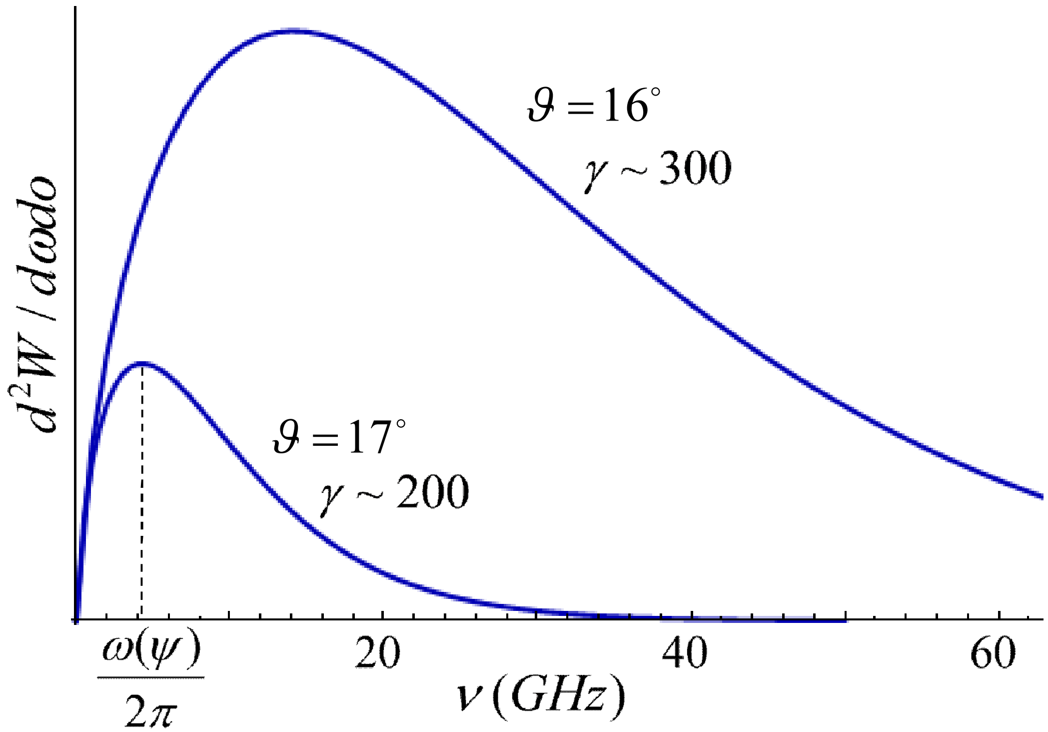
Model of the electric field accelerating the positron:

$$E(\alpha)=E_1\alpha\frac{(a_0-a_1)}{\alpha_0 a_1}\theta(\alpha_1-\alpha)+\left(E_1+E_2\frac{\alpha-\alpha_1}{\alpha_0}\right)\left(1-\frac{\alpha}{\alpha_0}\right)\theta(\alpha-\alpha_1)$$

Kontorovich and Trofymenko, JPSA **7**, 11 (2017); PNS-17

RADIATION SPECTRAL-ANGULAR DENSITY

Single positron radiation spectral distribution (smoothed) for different values of ψ:



In the direction of a certain angle with magnetic field

$$\psi = \vartheta + 2\chi$$

(see the picture on the previous page)

the radiation is emitted at certain characteristic frequency:

$$\omega(\psi) \sim c\gamma^3(\alpha)/R$$

depending of gamma

The reflection which directs radiation to the telescope begins at sufficiently high frequency $\omega_{\min}$ which is radiated by positrons having the Lorenz-factor: $\gamma_{\min} \sim (\omega_{\min} R/c)^{1/3}$

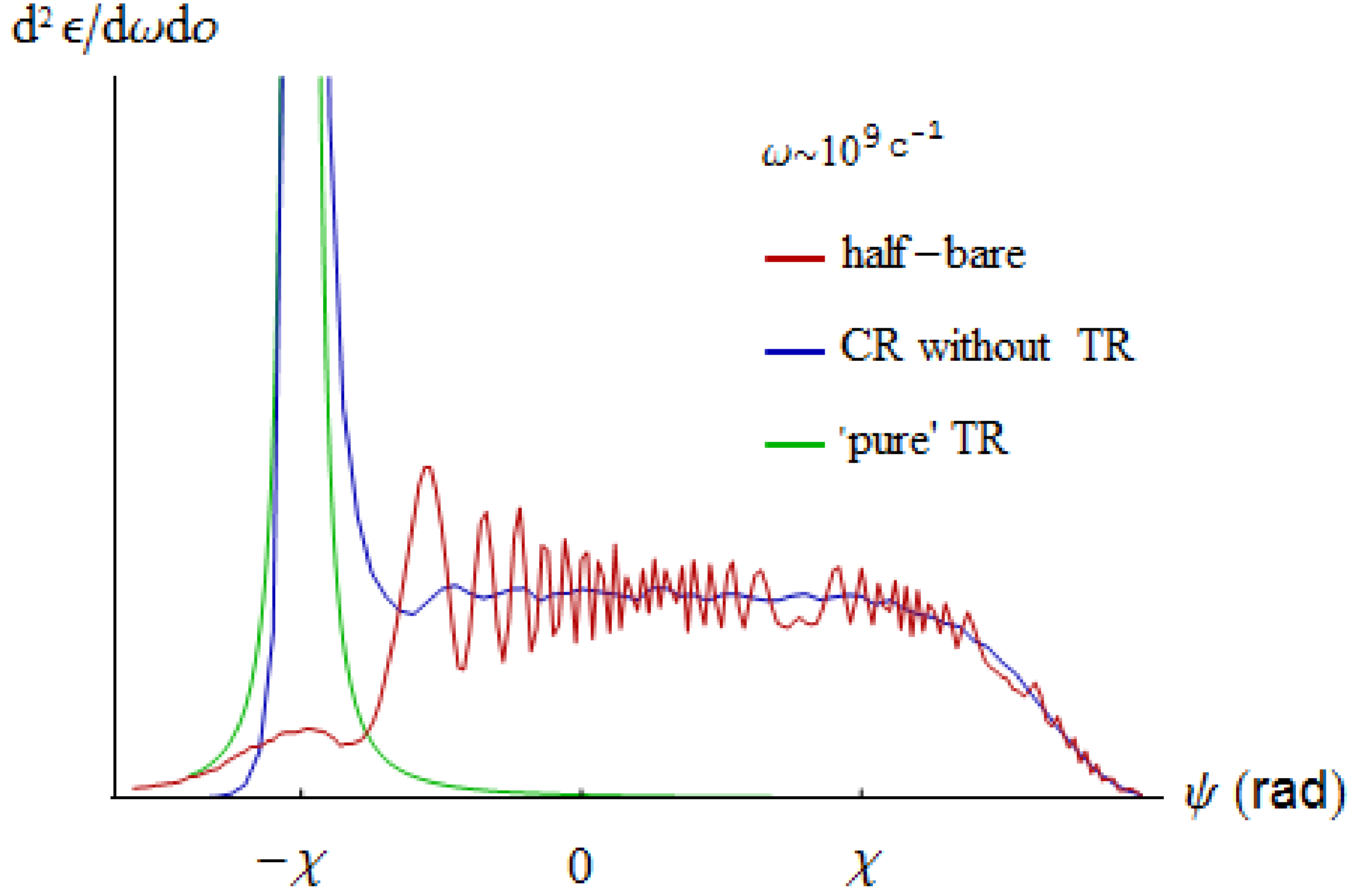
Distribution of radiation by positron (reflected curvature radiation + transition radiation) is calculated with the use of method of images (see the previous page) on the basis of the well-known expression of relativistic electrodynamics [5]:

$$\frac{d^2W}{d\omega\, do} = \frac{e^2\omega^2}{4\pi^2 c^3}\left|\int_{-\infty}^{+\infty} dt\, \vec{n}\times\vec{\mathrm{v}}(t)\exp\left\{i\omega\left(t - \frac{\vec{n}\vec{r}_0(t)}{c}\right)\right\}\right|^2$$

Kontorovich and Trofymenko, JPSA **7**, 11 (2017)

Radiation angular distribution of a positron image

calculated with (red curve) and without (blue curve) taking into account the interference of the **reflected curvature radiation** with the **transition radiation** (the effect of the positron 'half-bareness')



HEA - 2017

Trofymenko and Kontorovich, AASP, **7** (2017)

ESTIMATION OF THE COHERENT RADIATION FLUX

The observations indicate the necessity of coherent character of radiation emission by charged particles in the pulsar magnetosphere. For the estimation of the positron radiation intensity and derivation of the radiation **energy spectrum** at first it is enough to accept the very fact of the existence of inhomogeneous (clamped) positron flow in the gap. In this case the main contribution to radiation is made by coherently radiating volumes, which size V_{coh} depends on the wavelength and Lorenz-factor, depending on the curvature of the positrons trajectories. **The number of such volumes can be rather roughly estimated through "division" of the total radiating volume by V_{coh}.**

$$\left.\begin{aligned} r_{\parallel} &\sim \lambda \\ r_{\perp} &\sim \gamma\lambda \end{aligned}\right\} V_{coh} = r_{\parallel} r_{\perp}^2 \sim \gamma^2 \lambda^3$$

r and $r_{\perp}$ are the linear sizes of the coherently radiating volume in the directions along and perpendicular to the positrons velocity

$$J(\omega) \sim \frac{\kappa^2 n_{GJ}^2 e^2 \lambda^{3-1/3}}{2^{5/3} \pi^{14/3} d^2 R_*^{4/3}} \sqrt{\frac{mc^2 \bar{h}}{2eE_0}} \int_0^{R_{PC}} \frac{dr r^{5/3}}{\sqrt{1 - r^2 / R_{PC}^2}} \int_{\gamma_{\min}(r,\omega)}^{\gamma_{\max}} d\gamma \gamma^{7/2} \sim \kappa^2 \lambda^{3-1/3} \bar{\gamma}_{\max}^{-9/2} \cdot 10^{-40} \frac{W}{Hz \cdot m^2}$$

For $\lambda / l << 1 \quad J(\omega) \rightarrow J(\omega) \cdot (\lambda / l) \sim \lambda^{4-1/3}$

Kontorovich and Trofymenko, JPSA **7,** 11 (2017); PNS-17

We use linear accelerating field growth on positron trajectory contributing to the radiation flux

$\lambda = 2\pi c / \omega$ – radiation wavelength

$n_{GJ} \sim \vec{\Omega}\vec{B} / 2\pi ce$ – is the Goldreich-Julian number density; $\kappa \cdot n_{GJ}$ – is the number density of positrons;

$\bar{\gamma}_{\max}$ – is the average value of the positron Lorenz-factor at which its radiation ceases to hit the telescope

R_* – is the pulsar radius; R_{PC} –is the polar cap radius; d – is the distance from the pulsar to the Earth;

E_0 – is the accelerating electric field on the magnetic axis; l – is the inhomogeneity scale;

$\bar{h}$ – is some average length of the positron trajectory interval which contributes to radiation flux

LARGE LORENZ-FACTOR CONTRIBUTION

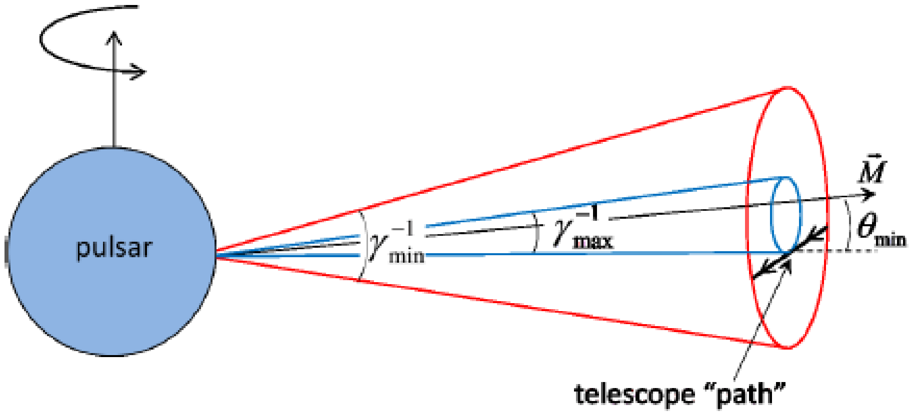


Fig. 7 Schematic picture of angular regions (cones) of concentration of the reflected radiation by positrons at two extreme values of the considered Lorenz-factors. At $\gamma = \gamma_{max}$ radiation ceases to hit the telescope. The magnetic axis does not coincide with the ones of the cones due to its assumed inclination with respect to the surface normal

Here we assume that the initial angular width of the positron radiation diagram $1/\gamma_{min}$, when the particle moves at the beginning of the effective path, exceeds the value of the minimal angle θ_{min} between the magnetic axis and the direction to the telescope. With the increase of the positron Lorenz-factor at lower altitudes the characteristic angle of its radiation diagram becomes less than θ_{min} (at γ_{max}) and radiation ceases to be caught by the telescope.

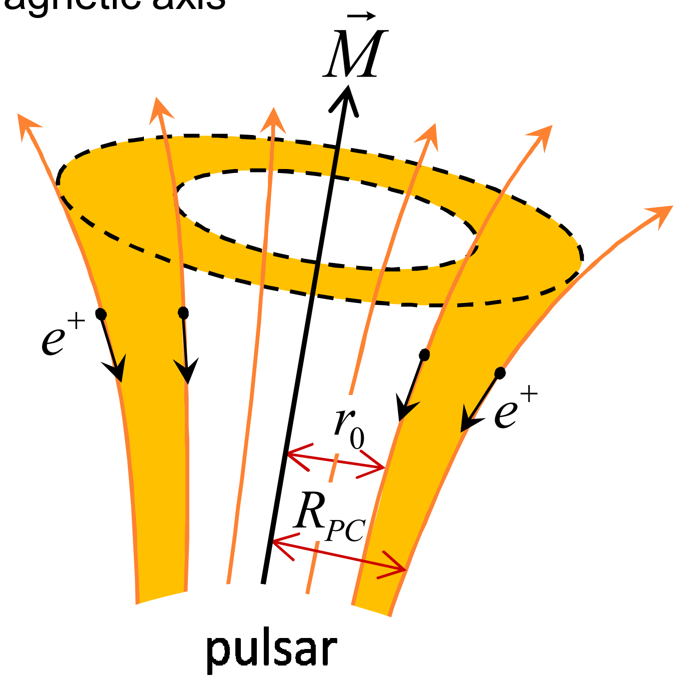
Kontorovich and Trofymenko, JPSA **7,** 11 (2017)

As the expression on the previous page shows, the contribution to the radiation flux in our case grows with the increase of γ. Due to this fact the value of the integral with respect to γ is mostly defined by the upper limit γ_{max} while the exact value of γ_{min} is not very significant in general position. Let us note that such situation is different from the well known case of synchrotron radiation of the electron component of cosmic rays with the decreasing energy spectrum. Due to such spectrum of the electron energies the integral with respect to γ in this case is merely defined by the lower limit and the contribution to the radiation flux is associated only with γ_{min}. It leads to the well known relation between spectral indices of such cosmic radio emission sources as radio galaxies, quasars, supernova remnants, etc. in the case of synchrotron radiation.

THE HIGHEST FREQUENCY FOR THE SHIFTED INTERPULSE

In the framework of our model the minimum value $\gamma_{\min}$ of the positron Lorenz-factor, at which the radiation begins reflecting from the surface and gets to the telescope, defines the minimal frequency ω of radiation which can reflect from the surface and hit the telescope. The relation between these values is the following: $\omega \sim c\gamma_{\min}^3 / R$, where $R = 4R_*^2 / 3r$ is the positron trajectory radius and r is the distance from the magnetic axis

Therefore : $$\gamma_{\min}(\omega, r) \sim \left(\frac{4R_*^2\omega}{3cr}\right)^{1/3}$$



For certain ω the reflected radiation mechanism must disappear for $r = r_0$, at which $\gamma_{\min}(\omega, r_0) = \overline{\gamma}_{\max}$

The shift of IP has to disappear too.

Thus in the considered model the coherence leads to formation of a hollow cone (in accordance with [6]), restricted from the inner and outer sides by the magnetic field lines situated respectively on distances r_0 and R_{PC}) from the magnetic axis (in the vicinity of the star surface. The particles moving in the specified region make the main contribution to the radiation flux.

Taking $r_0 = R_{PC}$ for the maximum frequency at which the reflected radiation mechanism is still possible we obtain: $$\omega_{\max} \sim \frac{3cR_{PC}\overline{\gamma}_{\max}^3}{4R_*^2}$$

To accurately estimate this frequency it is necessary to use self-consistent models

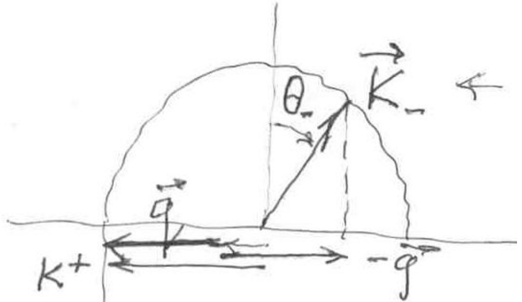
High-frequency components as a result of stimulated scattering on surface waves of the radiation of returning relativistic positrons

There is an alternative model of HF components not linked with reflection and IP shift
(S.A.Petrova, Radio Physics and Radio Astronomy, 1, 27 (2010))

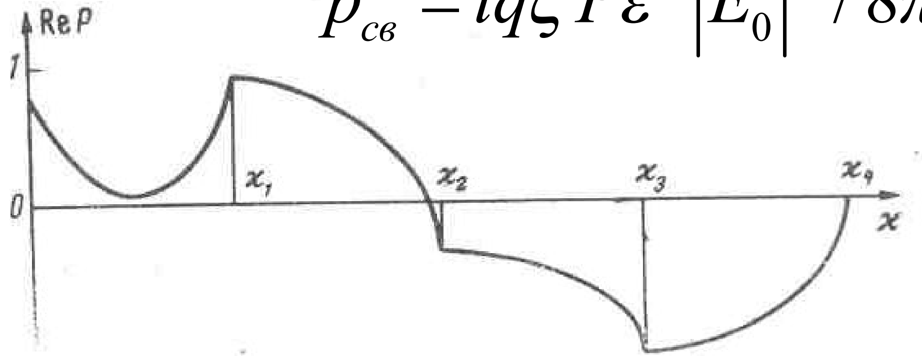
HEA - 2017

Excited surface waves and Wood's anomalies

Gavrikov, Kats & Kontorovich
Soviet Doklady, 1969; JETP, 1971



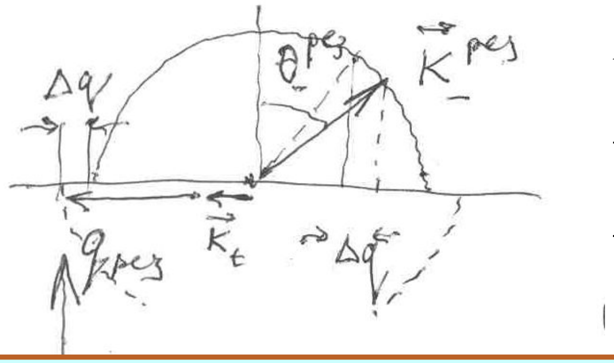
$$p_{cв} = iq\zeta P \varepsilon^I \left|E_0^i\right|^2 / 8\pi$$



This (Wood's) wave has

For Wood's wave maximum Is expected of ReP

The Light Pressure **P** as function of wave number q/k, where **q** belongs to SW and **k** to EM wave. Maxima correspond to generation of grazing waves



$$P = \frac{(\varepsilon-1)}{4q}\Big\{T_s^2\cos^2\varphi\cdot(C_{1y}^T - C_{-1y}^{T*}) + $$
$$+\varepsilon^I T_p^2\sin^2\varphi\left[Z_x(B_{1x}^T - B_{-1x}^{T*}) + \varepsilon Z_z(B_{1x}^T - B_{-1x}^{T*}) + 2q_x(\varepsilon-1)Z_xZ_z\right] -$$
$$-\sqrt{\varepsilon^I}\,\frac{T_sT_p}{2}\left[B_{1y}^T - B_{-1y}^{T*} + Z_x(C_{1x}^T - C_{-1x}^{T*}) + \varepsilon Z_z(C_{1z}^T - C_{-1z}^{T*}) + 2q(\varepsilon-1)Z_z\right]\sin 2\varphi\Big\}$$

T=E/Ei , H/Hi are the Fresnel coefficients,
Z=E/H are wave impedances , phi – is the angle with i-plane

We may expect also the Resonance with surface EM H-wave

$$\Omega(q) = \pm\Omega_0(q) - 2iq^2\frac{\eta^I + \eta^{II}}{\rho^I + \rho^{II}} \mp \frac{iq^2 P\varepsilon^I\left|E_0^i\right|^2}{16\pi(\rho^I + \rho^{II})\Omega_0(q)}.$$

Kats & Maslov, JETP, 1972

The Wood's anomaly
and estimates for the scattered fields

$$E_{\pm} \approx (k\varsigma) E_{0y} \quad \mathrm{kz} \neq 0 \qquad (1) \qquad E_{\pm} \approx \sqrt{\varepsilon} \cdot (k\varsigma) E_{0y} \quad \mathrm{Kz} = 0 \qquad (2)$$

We will be interested in the case of large moduli of ε. In the coefficients for combinational fields, this factor enters in the numerator as a nonlinear element (ε -1) and in the denominator (the coefficients "a”) in the form of multipliers at k_z. Therefore, for ε>>1, they cancel each other and do not affect the evaluation of the combinational fields, unless k_z is small. For the grazing components (k_z = 0), the amplitudes increase significantly.

Indeed, under the condition k_z = 0, "a“ becomes 1/kε^1/2.

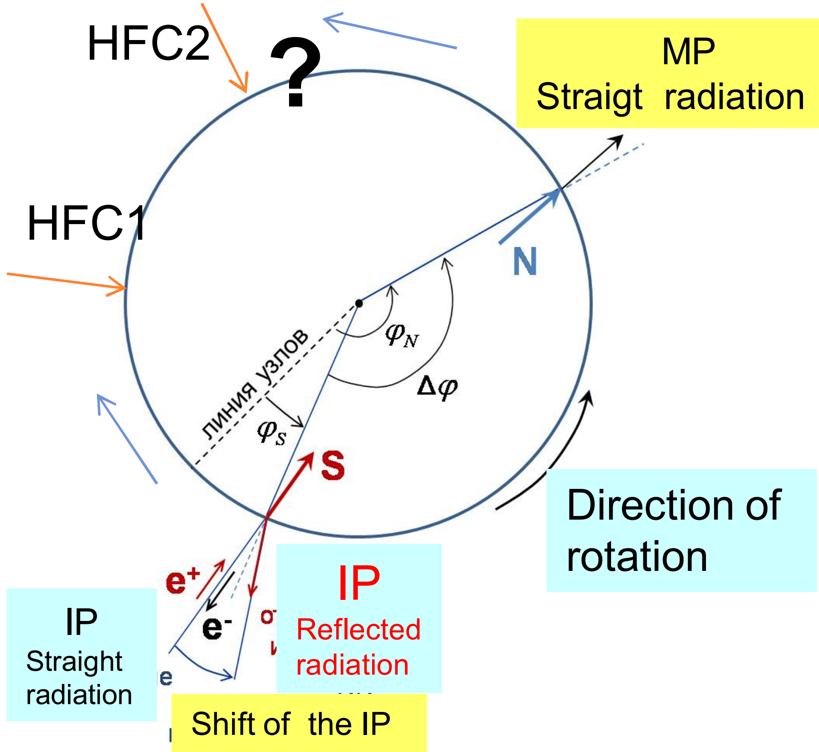
Instead of ε, denominators of Raman fields now has ε^1/2.

Therefore, if the estimate for the combinational fields far from the Wood's anomaly has the form (1), then in the Wood's anomaly it goes over into (2).

The combinational fields increase in ε^1/2 times.

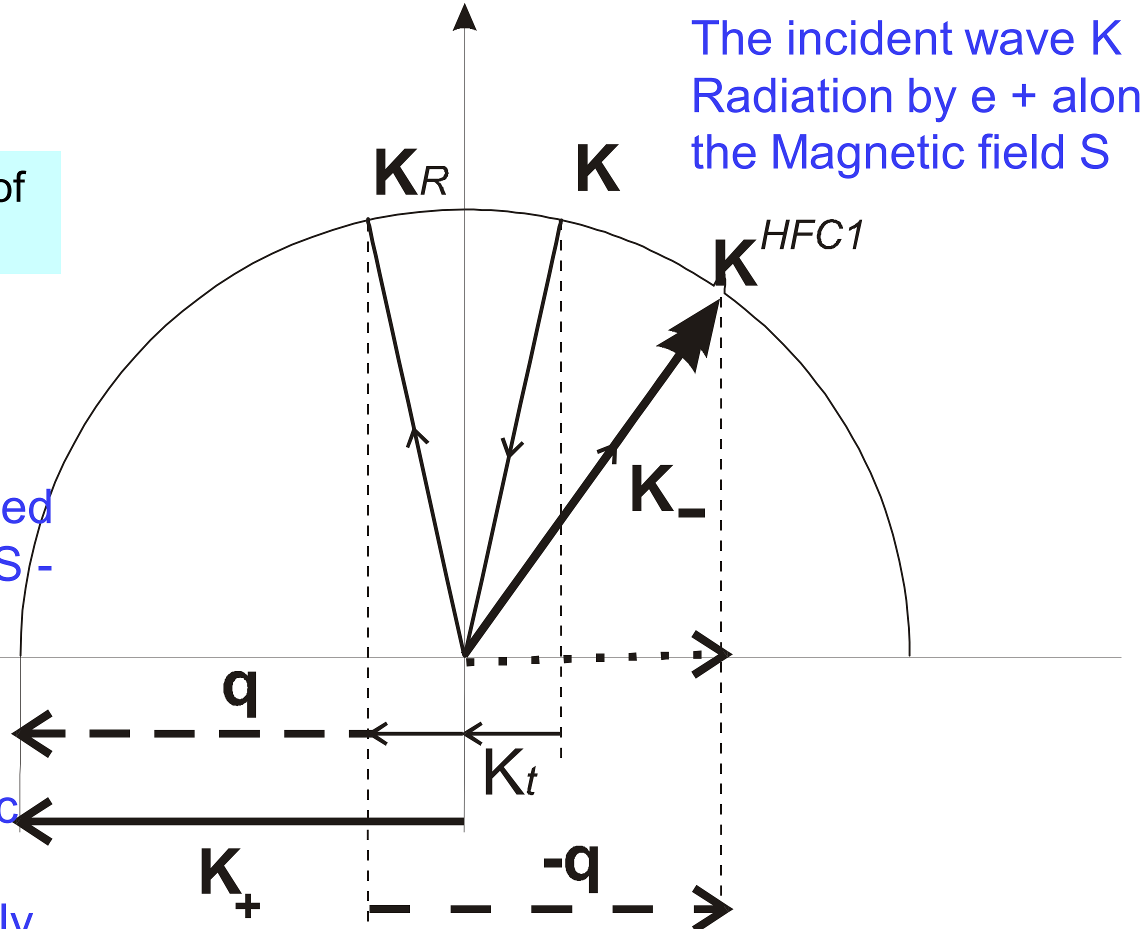
Therefore, in what follows we shall consider the Wood-Rayleigh conditions k_z = 0 as necessary for stimulated scattering.

The stimulated scattering scheme at the S pole of a pulsar



Amplified with Wood's anomaly Stokes wave K_ generates high-frequency Moffett-Hankins' component ----------- HFC1

The incident wave K
Radiation by e + along the Magnetic field S



The angle of incidence is determined by the Slope of the magnetic field S - (By the shift of the interpulse)

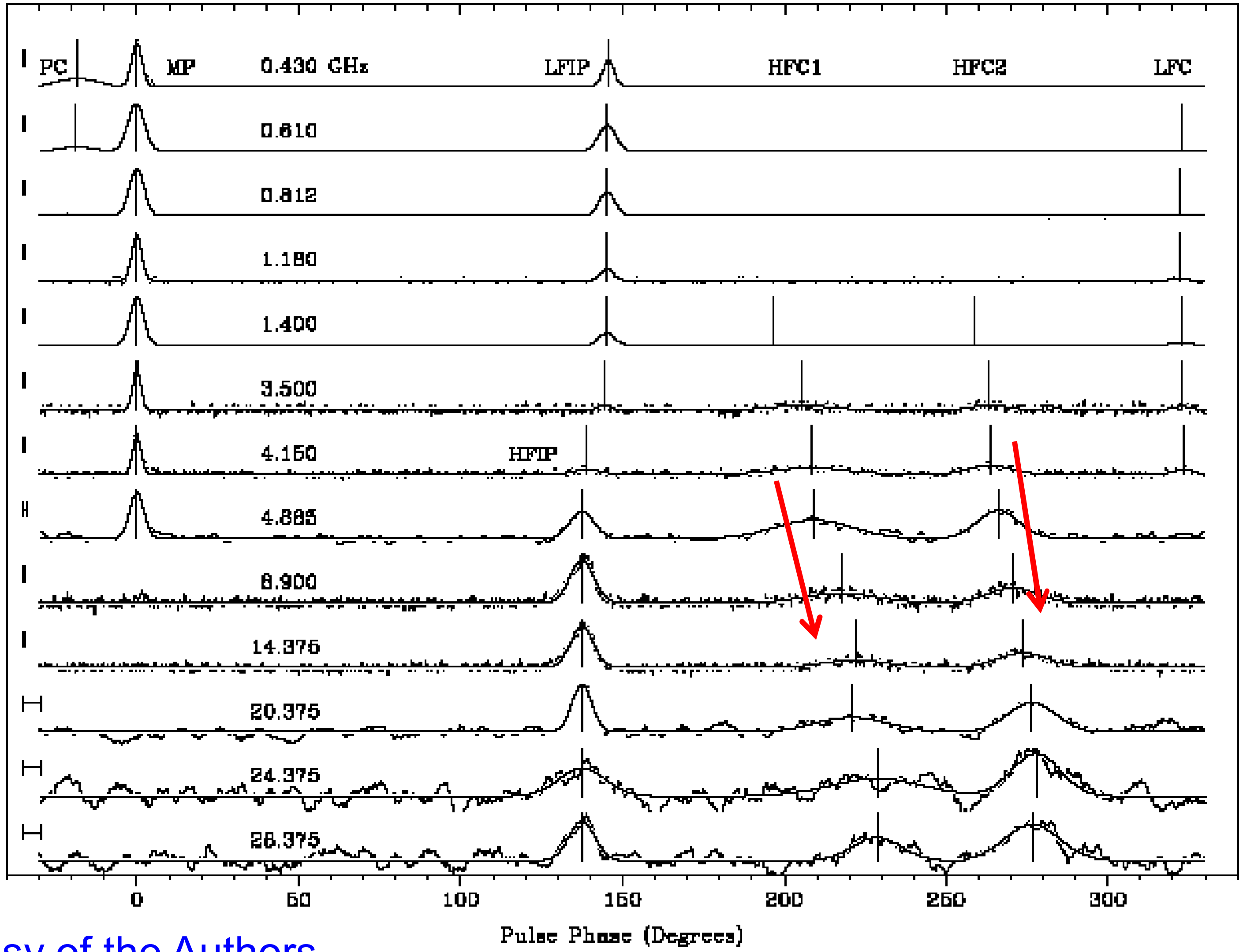
q is the wave vector of the surface wave, anti-Stokes electro-magnetic surface wave K +
corresponds to the Wood's anomaly,
the angle of incidence is the Rayleigh's angle.

Drift of the HF component in the Stimulated Scattering model

HEA - 2017

Drift of the HF component with increasing of frequency

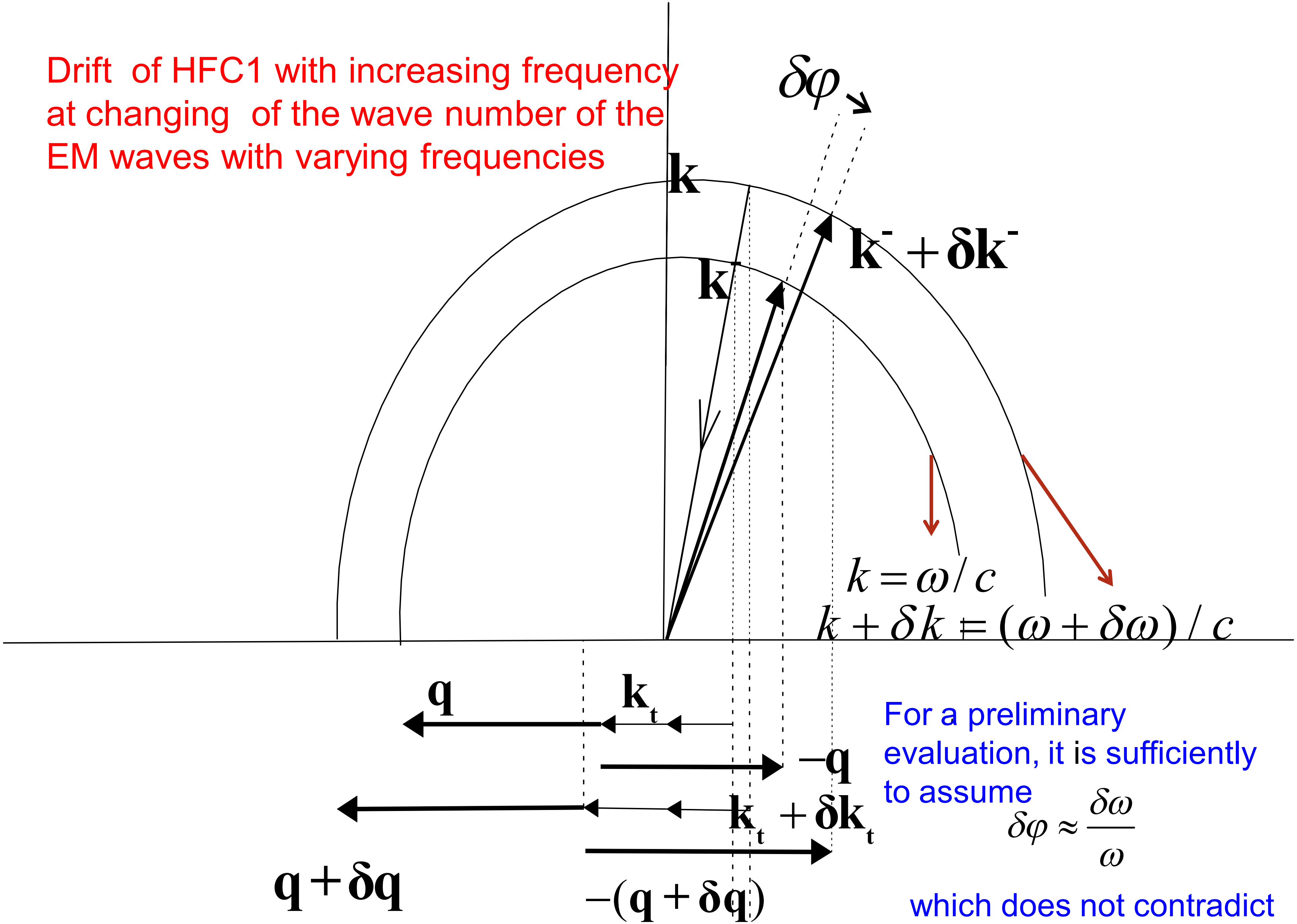
4 Hankins, Jones & Eilek



By Courtesy of the Authors

Hankins, Jones & Eilek, 2015 ApJ. 802 130 arXiv:1503.00677

Drift of HFC1 with increasing frequency at changing of the wave number of the EM waves with varying frequencies



For a preliminary evaluation, it is sufficiently to assume

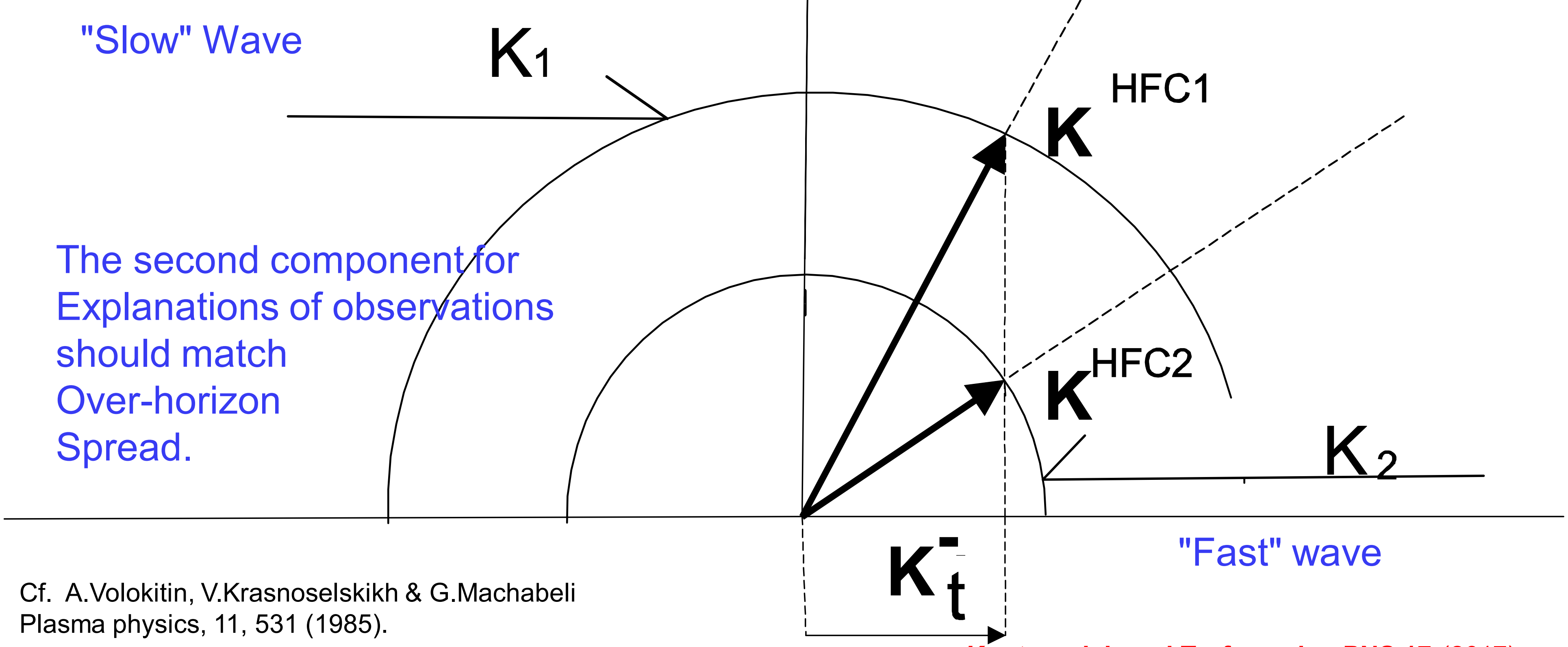
$$\delta\varphi \approx \frac{\delta\omega}{\omega}$$

which does not contradict the observational data.

Kontorovich and Trofymenko, PNS – 17 (2017)

Possible scheme of occurrence of two HF components due to birefringence in reflection

Two components can arise due to slow and fast waves, which are present in the magneto-spheric plasma. The scheme does not take into account the anisotropy of the medium.
Only the reflected Stokes waves are shown. In reality, the waves should, most likely, arise not directly at reflection, but in the propagation process of a reflected Stokes wave in a magnetospheric plasma.



The second component for
Explanations of observations
should match
Over-horizon
Spread.

Cf. A.Volokitin, V.Krasnoselskikh & G.Machabeli
Plasma physics, 11, 531 (1985).

Kontorovich and Trofymenko, **PNS 17-**(2017)

Implementation of stimulated scattering in nature

Thus, this is the first case that indicates at realization of the SS in the nature. With its help, one can hope to obtain information about the surface of a neutron star.

We note that the reciprocal motion of positrons, which arises when the accelerating electric field of a gap penetrates into a pair plasma, was considered in connection with the heating of the surface by the reverse current in a number of works, a detailed bibliography of which is given in the article by D. Barsukov et al. The difference between the magnetic field and the strictly dipole field, manifested in particular in its inclination, was also discussed in the literature [5], including the possibility of the toroidal component of the magnetic field, see [6].

However, the low-energy high-frequency radiation from the reverse positron flux, as well as radiation reflected from the surface of the neutron star, has not been considered anywhere before this our work.

Mon. Not. R. Astron. Soc. **395**, 1723–1732 (2009) doi:10.1111/j.1365-2966.2009.14663.x

Formation of the radio profile components of the Crab pulsar

S. A. Petrova★
Institute of Radio Astronomy, NAS of Ukraine, 4 Chervonopraporna Str., 61002 Kharkov, Ukraine

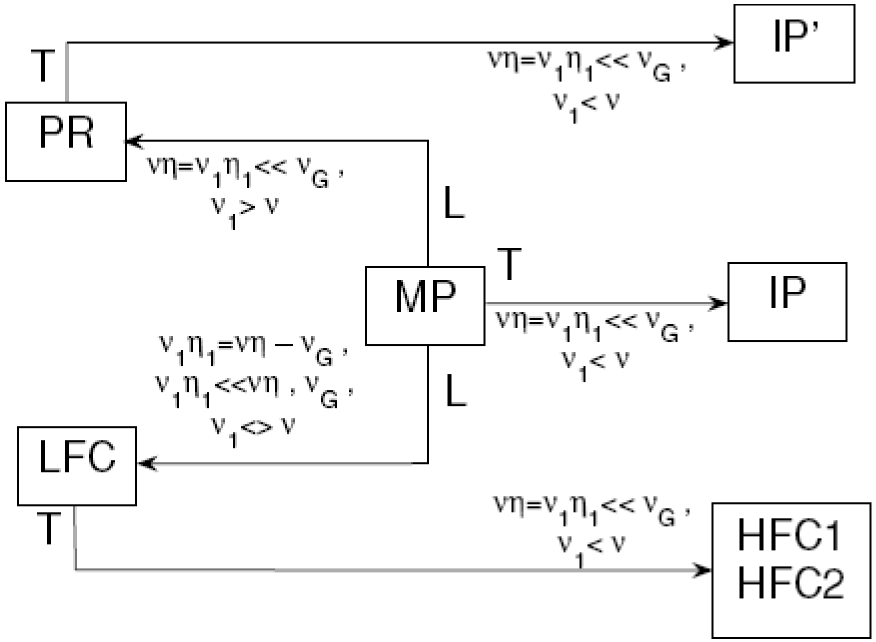


Figure 5. Summary of the component formation in the Crab pulsar. The marks L and T refer to the longitudinal and transverse regimes of induced scattering, respectively.

Альтернативная точка зрения
Светланы Петровой
на возникновение компонент:

Petrova S. RPRA, **1**, 19, 27 (2010)

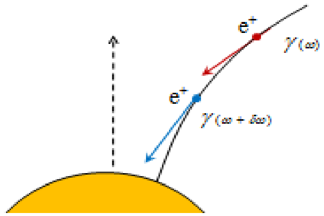
THE MECHANISM OF COMPONENT FORMATION OUT OF THE MAIN PULSE OF A RADIO PULSAR.

I. THE PRECURSOR

II. THE INTERPULSE

….It is suggested that the interpulse (IP), the high-frequency interpulse (IP′) and the pair of so-called high-frequency components (HFC1 and HFC2) result from the backward scattering of the main pulse (MP), precursor (PR) and low-frequency component (LFC), respectively. The ….

Благодарим за внимание!



1. **D. Moffett & T. Hankins**, ApJ. **468,** 779 (1996)
2. **T. Hankins, G. Jones & J. Eilek**, Ap J. **802**, 130 (2015)
3. **V. M. Kontorovich & S.V.Trofymenko,** *JPSA **7,** #4, 11 (2017)*
4. **V. M. Kontorovich**, Low Temperature Physics **42**, 2 (2016)
5. **J. Eilek & T. Hankins,** Journal of Plasma Physics 82, article ID 635820302 (2016)
6. **D.P.Barsukov, O.A.Goglachidze & A.I.Tsygan**, АЖ, **93,** 569 (2016); содержит библиографию по обратному току позитронов и отклонению от магнитного диполя в полюсе
7. **V. M. Kontorovich & S.V.Trofymenko,** Report on PNS-17, JPCS (2017), in press
8. **S.V. Trofymenko & V. M. Kontorovich,** AASP**, 7** (2017), in press