Stimulated scattering on surface waves and pulsar radiation

V.M. Kontorovich

Institute of Radio Astronomy of NAS of Ukraine,

Karazin Kharkiv National University,

Kharkiv, Ukraine

e VIII-th International Conference "SOLITONS, COLLAPSES AND TURBULENCE" Chernogolvka, May 2
in honor of Evgenii KUZNETSOV's 70th birthday

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V.M. Kontorovich

E-mail: vkont@rian.kharkov.ua
vkont1001@yahoo.com

Institute of Radio Astronomy NAS of Ukraine,
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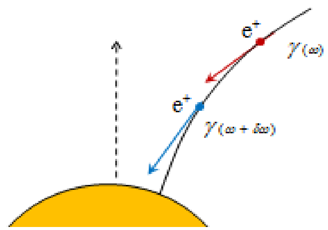
S.Trofymenko and author (2016):

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



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

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Stimulated scattering (SS) and anomalous radiation of the Crab pulsar

We point out that the SS phenomenon is possibly responsible for some types of radiation in pulsars. The source of radiation in this case is the powerful radiation by relativistic positrons extracted from the pair plasma magnetosphere by an accelerating electric field and flying toward the star.

Mirror reflection of this radiation together with an inclined magnetic field lead to a shift of the pulse in the Crab pulsar in the centimeter range, discovered 20 years ago by Moffet and Hankins [1, 2] which had received no explanation other than that proposed by the author of this report with S.V. Trofymenko a year ago [3]

Simultaneously, two additional pulse components arise (which like the shift of the interpulse, can be associated with reflection)

in the direction of the diffraction peak on the periodic surface structure excited by stimulated scattering [4]. The same mechanism explains the frequency drift of the component (Hankins, Jones and Ailek [2]), which is analyzed in detail in this report.

Preamble: The Pulsars

Pulsars, discovered in 1967 by
Jocelyn Bell and Anthony Hewish,
these are rapidly rotating, highly magnetized **neutron stars**.

The beam of radio waves emitted by them, like the beam of a **beacon**, sweeps out the Earth, causing regular radio **pulses**.

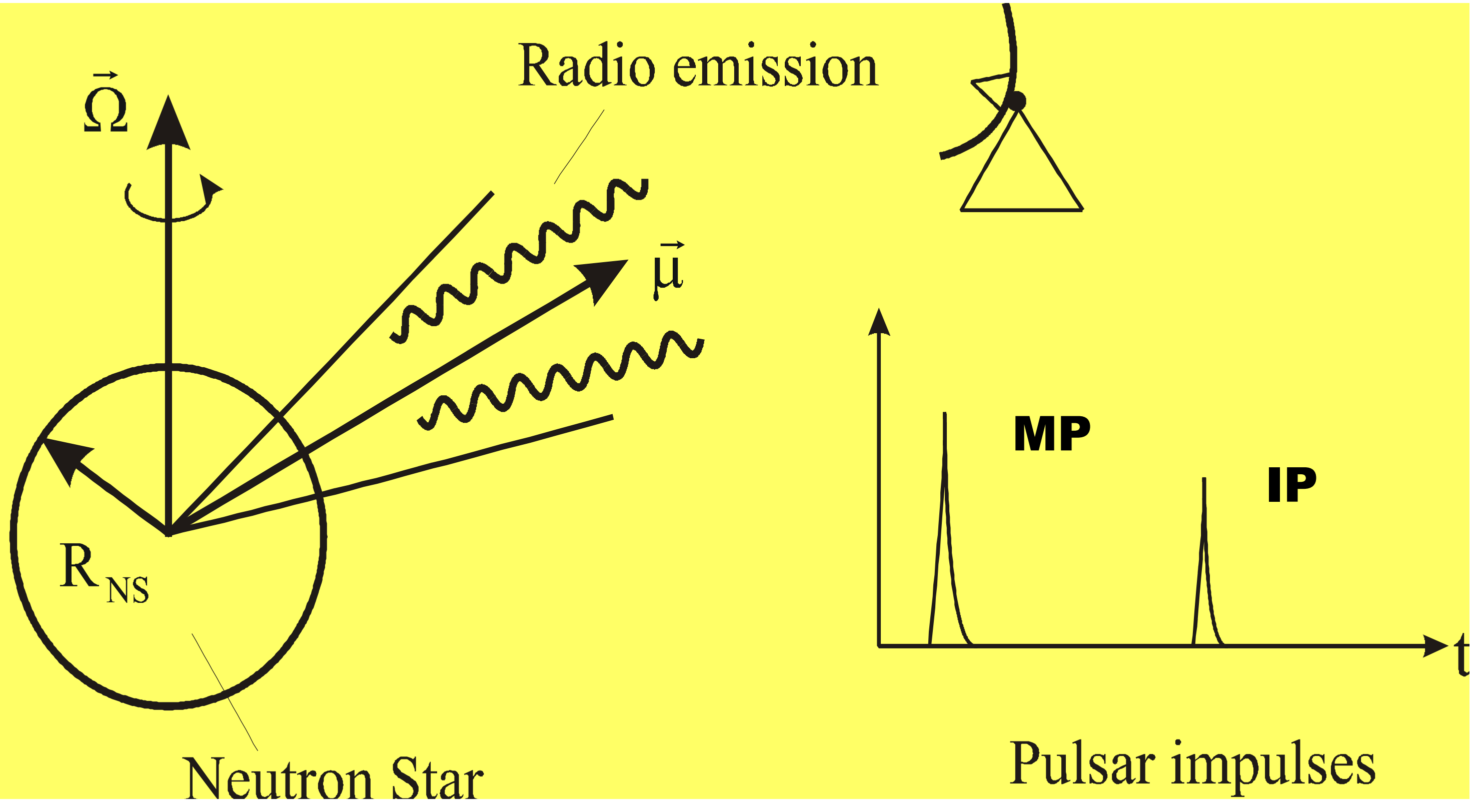
$\Omega \sim 1/s \quad R_{NS} = 10\,km$

$M_{NS} \sim M_{SUN},$

$B_s \sim 10^{12} G,$

$E \sim \Omega R B_s / c \sim 10^6 G,$

$\Gamma = \varepsilon / mc^2 \geq 10^7$



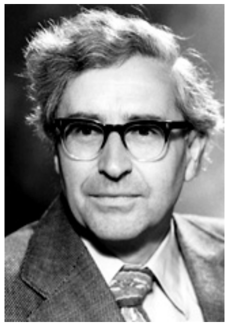
Л. Д. Ландау (1908 - 1968)

L. D. Landau was one of the first (1932), who has stated idea about existence in a nature of neutron stars – giant macroscopic atomic nuclei

W. Baade (1893-1960)

F. Zwicky (1898-1974)

W. Baade and F. Zwicky independently came to a conclusion about existence of neutron stars and associated them with super nova star explosions (1934)



A. Hewish (b. 1924)

A.Hewish received the Nobel prize for detection of pulsars through periodic radio radiation (1967)

Pulsars were identified with rotating neutron stars

Neutron stars as ones of the most compact objects in Universe

Neutron stars and black holes are the most compact objects known in nature and have the strongest gravitational fields. They are formed by the collapse of the burned-out core of a massive star, accompanied by a supernova star explosion in which the envelope of the star is violently ejected.

With a mass some 400,000 times that of the Earth and a diameter not larger than that of the city, a neutron star is essentially a giant atomic nucleus, held together by gravity. The gravitational attraction at its surface is some 11 orders of magnitude greater than on the surface of the Earth.

(By E. van den Heuvel, Science)

Pulsar in the Crab

is the most studied object and belongs to a small group of pulsars, which along with the main pulse (MP) also have an interpulse (IP) located between the neighboring main pulses. Usually, the interpulse is associated with the signal from the second (conditionally "Southern") magnetic pole.

As is known, the average pulse profiles as "fingerprints" characterize the pulsar, and their "phase" - the moment of appearance on the period - is fixed with a high degree of accuracy.

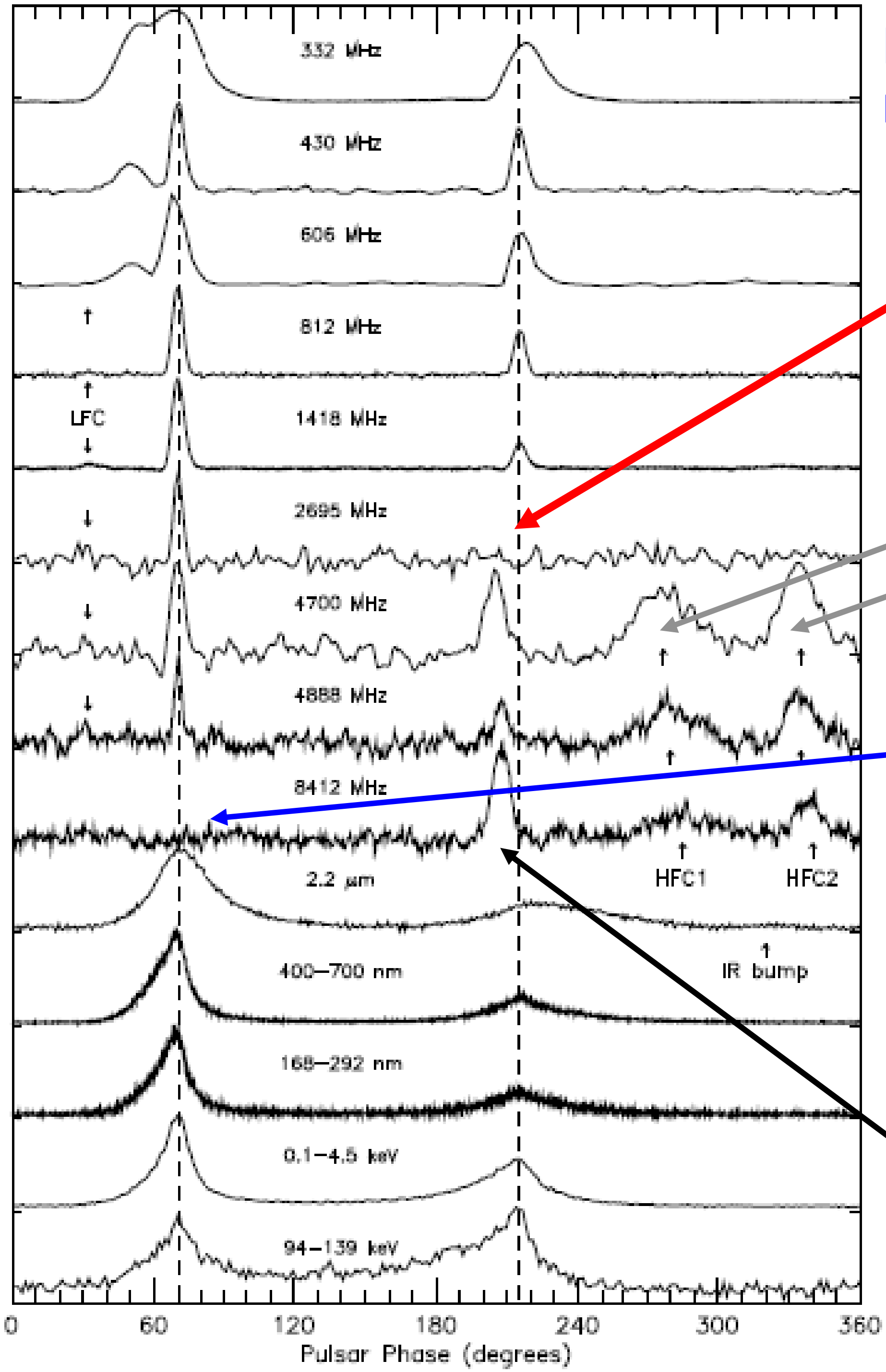
The more surprising was the discovery by Moffet and Hankins of the pulsar in the Crab Nebula of a very unusual phenomenon - a shift in the position of the IP in the transition to a centimeter wavelength range.

Along with this shift in the same range Moffett and Hankins found two additional pulses: HF components HFC1 and HFC2.

Both effects for a long time did not receive any physical explanation, which Dr. Hankins and colleagues wrote about in 2015.

D. Moffett & T. Hankins, ApJ. **468,** 779 (1996); astro/ph 9604163 3

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



Pulsar in the Crab. Average pulses

D. Moffett, T. Hankins, 1996

The disappearance of the interpulse
Pulsar B0531 + 21

Change of low-frequency radiation mechanism in the gap.

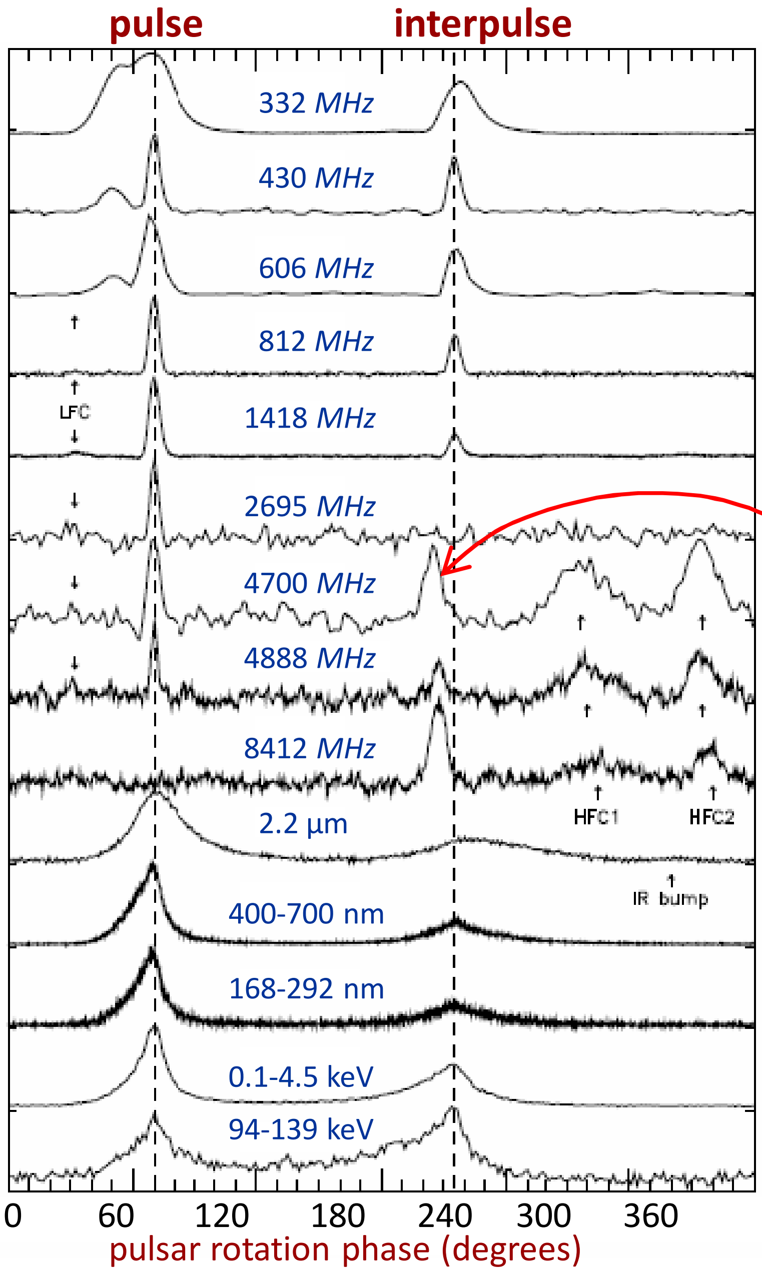
High-frequency components of Moffet-Hankins (1996)

Disappearance of the main pulse of the pulsar B0531 + 21
(Explanation: Kontorovich and Flanchik, 2013)

Shift of high frequency IP relative to low frequency IP

(Explanation:
Kontorovich and Trofymenko, 2015)

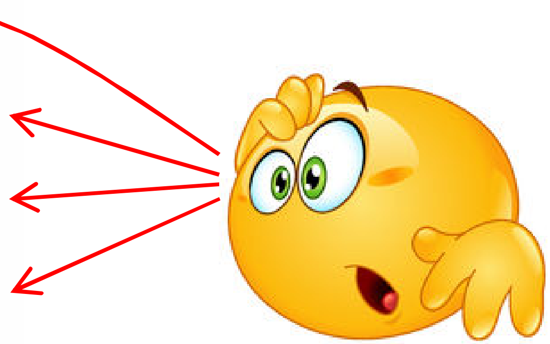
Mysteries of pulsar radiation in the Crab



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

By Courtesy of the Authors

T.H. Hankins, G. Jones, J.A. Eilek // arXiv:1502.00677v1, 2015



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…dramatic changes in the pulsar's radio emission between low and high radio frequencies…

By Hankins, Jones & Eilek, 2015

We do not, unfortunately, have a ready explanation for the geometrical or physical origin of the multiple radio components we see in the Crab pulsar.

We present detailed observational characteristics of these different components which future models of the pulsar's magnetosphere must explain.

…above about 5 GHz the Main Pulse disappears, the mean profile of the Crab pulsar is dominated by the High-Frequency Interpulse (which is quite different from its low-frequency counterpart) and the two High-Frequency Components…

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

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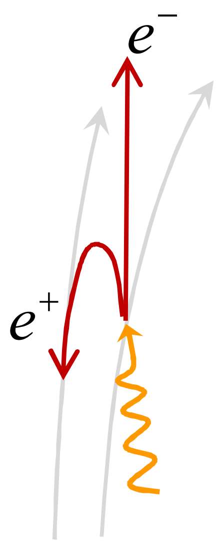
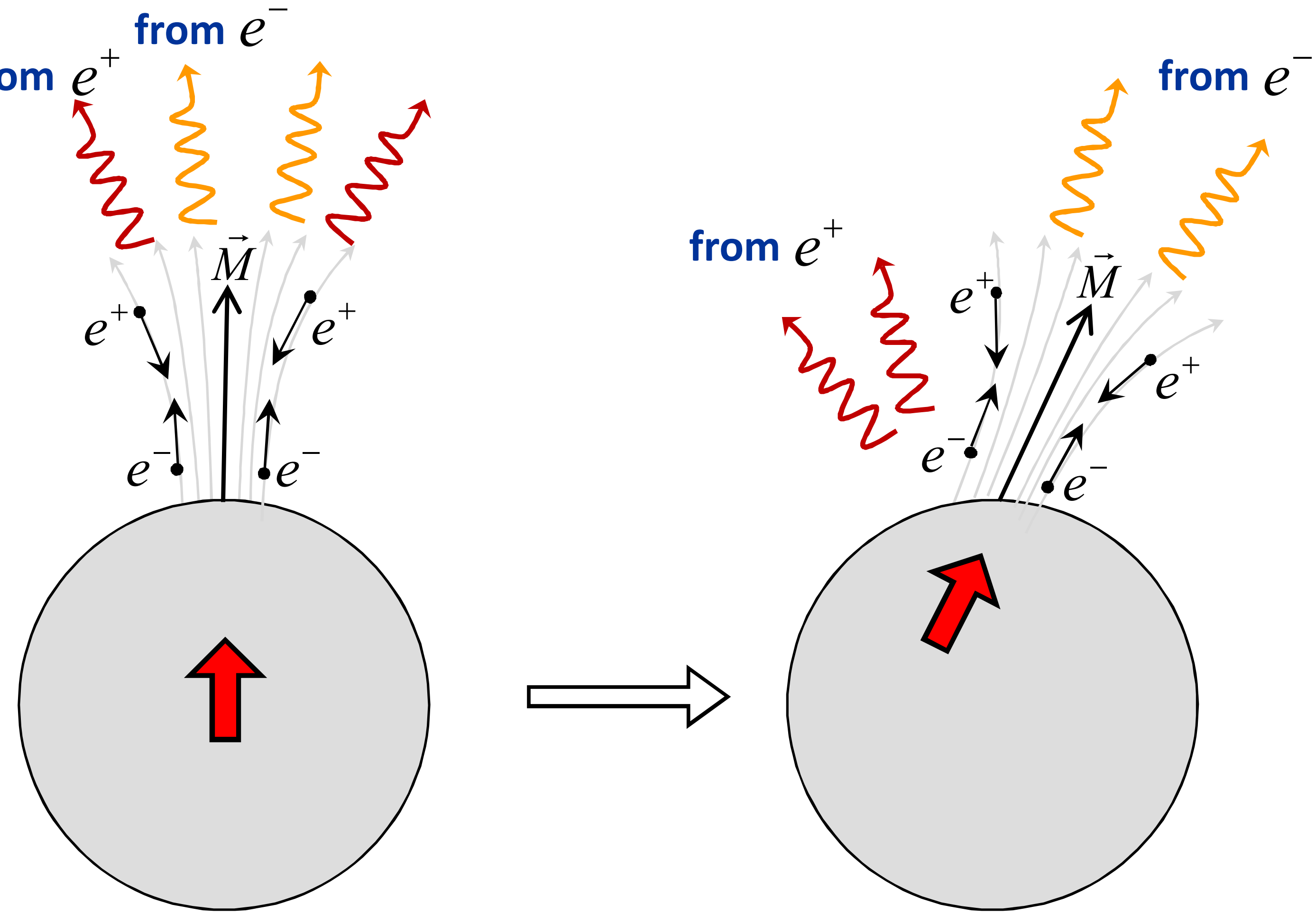
Solving the puzzle of the IP shift: emission by **POSITRONS** and **reflection** of radiation from the surface of the star in an **inclined** magnetic field





Accelerating electric field returns pair's positrons to the surface of the star

V.M. Kontorovich and S.V. Trofymenko, arXiv:1606.02966

e^+ radiation = transition radiation + reflected curvature radiation

low-frequency interpulse – from e^- radiation

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

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)

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Stimulated Scattering

Stimulated scattering (SS) is an effect as common as a nonlinear frequency shift. In contrast to the frequency shift, at SS the coefficient at a squared module of the amplitude of strong incident wave contains an imaginary part, which is responsible for the arising instability.

Each type of stimulated scattering corresponds to its spontaneous analogue. What concerns scattering on surface waves, there has to be the stimulated scattering on them (SS on SW).

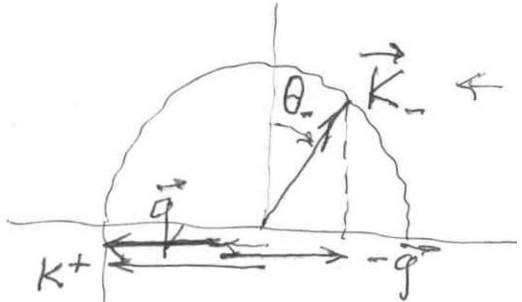
All kinds of SS had been observed in special experiments using powerful sources of radiation (lasers). SS on SW, unlike the rest of SS, has not been observed in its pure form, although it indirectly manifested itself in the appearance of the surface structures.

In nature, any type of SS of the natural origin is still nowhere to be registered.

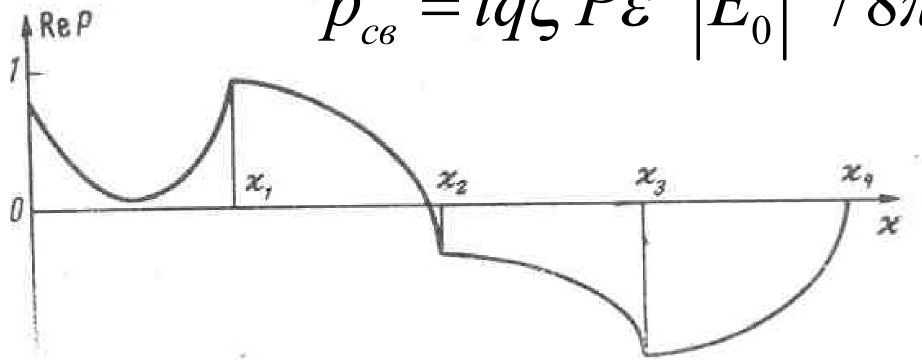
Excited surface waves and Wood's anomalies

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

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

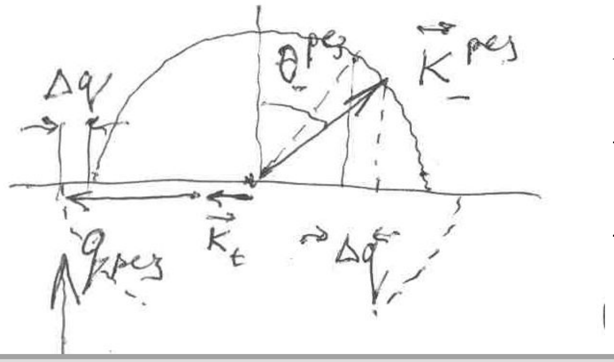


This (Wood's) wave has k_z=0



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



$$P = \frac{(\varepsilon-1)}{4q}\Big\{T_s^2\cos^2\varphi\cdot(C_{1y}^T - C_{-1y}^{T*}) +$$

$$+\varepsilon^I T_p^2\sin^2\varphi\left[Z_x(B_{1x}^T - B_{-1x}^{T*}) + \varepsilon Z_z(B_{1x}^T - B_{-1x}^{T*}) + 2q_x(\varepsilon-1)Z_xZ_z\right] -$$

$$-\sqrt{\varepsilon^I}\,\frac{T_sT_p}{2}\left[B_{1y}^T - B_{-1y}^{T*} + Z_x(C_{1x}^T - C_{-1x}^{T*}) + \varepsilon Z_z(C_{1z}^T - C_{-1z}^{T*}) + 2q(\varepsilon-1)Z_z\right]\sin 2\varphi\Big\}$$

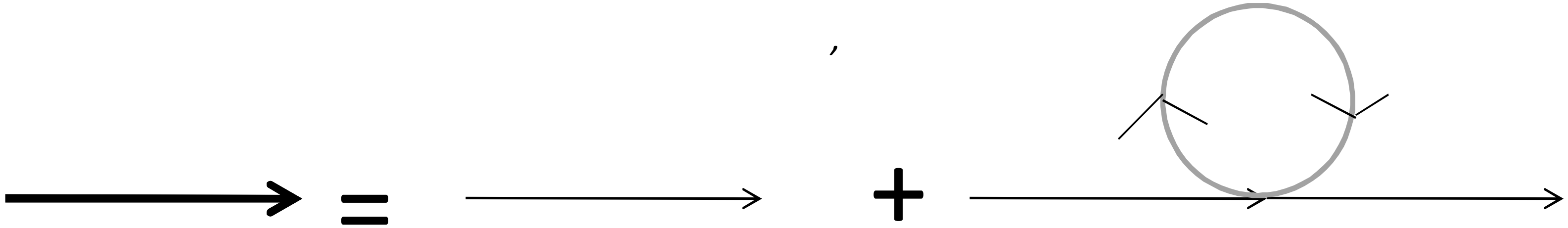
We may expect also the Resonance with surface EM H-wave

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

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

Kats & Maslov, JETP, 1972

Analogy of SS to the nonlinear frequency shift



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

$$\Omega^2(q) = gq + \frac{\alpha}{\rho}q^3$$

For the cm-wave region the main is the gravitational term

$$\Omega(q) = \sqrt{gq} << \omega = ck$$

The scattered field are found from the boundary conditions at the surface, $z = \zeta(x, y, t) = \zeta_{q\Omega} \exp(i\mathbf{qr} - i\Omega t)$, where $\zeta_{q\Omega}$ are the amplitudes of the SW,

$$\begin{aligned} [\mathbf{n}, \mathbf{E}^{I} - \mathbf{E}^{II}]_{z=\zeta(x,y,t)} &= 0, \\ [\mathbf{n}, \mathbf{H}^{I} - \mathbf{H}^{II}]_{z=\zeta(x,y,t)} &= 0. \end{aligned} \tag{1}$$

Here $\mathbf{n}$ is the normal to the surface $z = \zeta(x, y, t)$. Taking $k_0|\zeta| \ll 1$ and $q|\zeta| \ll 1$, in a linear approximation in ζ, Eq. (1) yields fields $E_{-1} \sim \zeta^{*} E_0$ and $E_1 \sim \zeta E_0$, which are bilinear in the amplitudes of the SW and incident field.

$$\begin{aligned} \mathbf{E}_{-1}^{R,T} &= -\left(\frac{1}{2}\right) i\zeta(\varepsilon - 1)\left[\mathbf{C}_{-1}^{R,T} E_{0y}^{T} + \mathbf{B}_{-1}^{R,T} H_{oy}^{T}\right], \\ \mathbf{E}_{1}^{R,T} &= -\left(\frac{1}{2}\right) i\zeta(\varepsilon - 1)\left[\mathbf{C}_{1}^{R,T} E_{0y}^{T} + \mathbf{B}_{1}^{R,T} H_{oy}^{T}\right], \end{aligned} \tag{2}$$

Mandel'stam-Raman electromagnetic fields

$$\mathbf{E}_{-1}^{R,T} = -(1/2)i\zeta(\varepsilon - 1)\left[\mathbf{C}_{-1}^{R,T}E_{0y}^{T} + \mathbf{B}_{-1}^{R,T}H_{oy}^{T}\right],$$

$$\mathbf{E}_{+1}^{R,T} = -(1/2)i\zeta(\varepsilon - 1)\left[\mathbf{C}_{1}^{R,T}E_{0y}^{T} + \mathbf{B}_{1}^{R,T}H_{oy}^{T}\right],$$

$$C_{-1x}^{R,T} = -a_{-1}k_{-1x}k_{-1y}, \quad C_{-1y}^{R,T} = a_{-1}(k_{-1x}^{2} - k_{-1z}^{R}k_{-1z}^{T}),$$

$$C_{-1z}^{R,T} = a_{-1}k_{-1y}k_{-1z}^{T,R},$$

$$B_{-1x}^{R} = d_{-1}\left[\varepsilon k_{0x}k_{-1x}k_{-1z}^{R} - k_{0z}^{T}(k_{-1z}^{R}k_{-1z}^{T} - k_{-1y}^{2})\right],$$

$$B_{-1y}^{R} = d_{-1}k_{-1y}(\varepsilon k_{0x}k_{-1z}^{R} - k_{-1x}k_{-1z}^{T}),$$

$$B_{-1z}^{R} = d_{-1}\left[\varepsilon k_{0x}(k_{-1x}^{2} + k_{-1y}^{2}) - k_{-1x}k_{0z}^{T}k_{-1z}^{T})\right],$$

$$\varepsilon = \varepsilon^{II} / \varepsilon^{I}, \quad a_{-1} = (k_{-1z}^{T} - \varepsilon k_{-1z}^{R})^{-1}, \quad d_{-1} = a_{-1}c / \omega\varepsilon^{II}.$$

The Wood's anomaly and estimates for the scattered fields

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

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

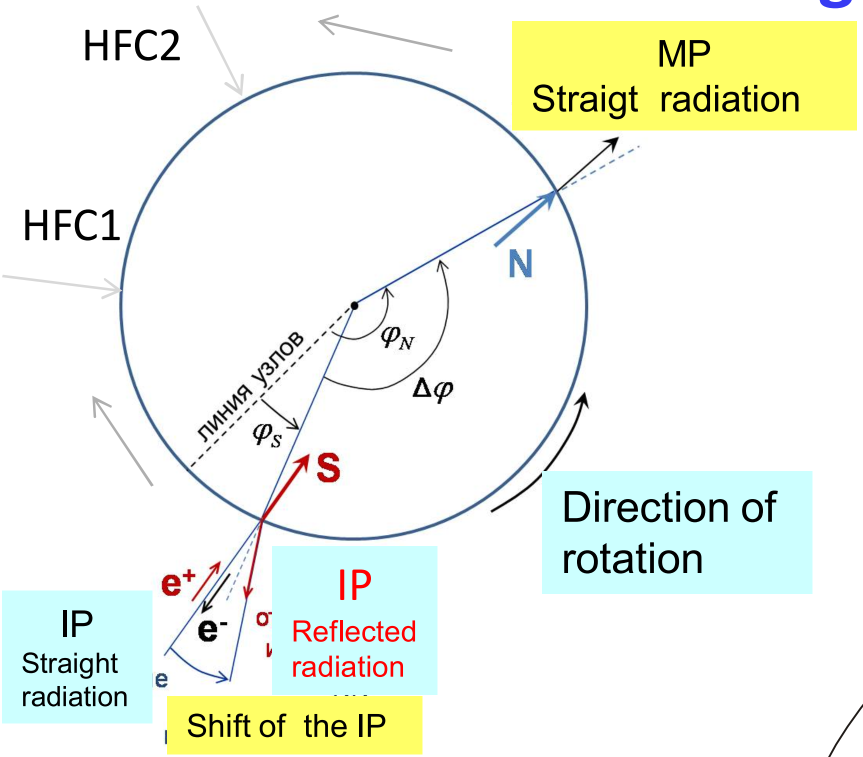
far from the Wood's anomaly has the form (1),

then in the Wood's anomaly it goes over into (2).

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

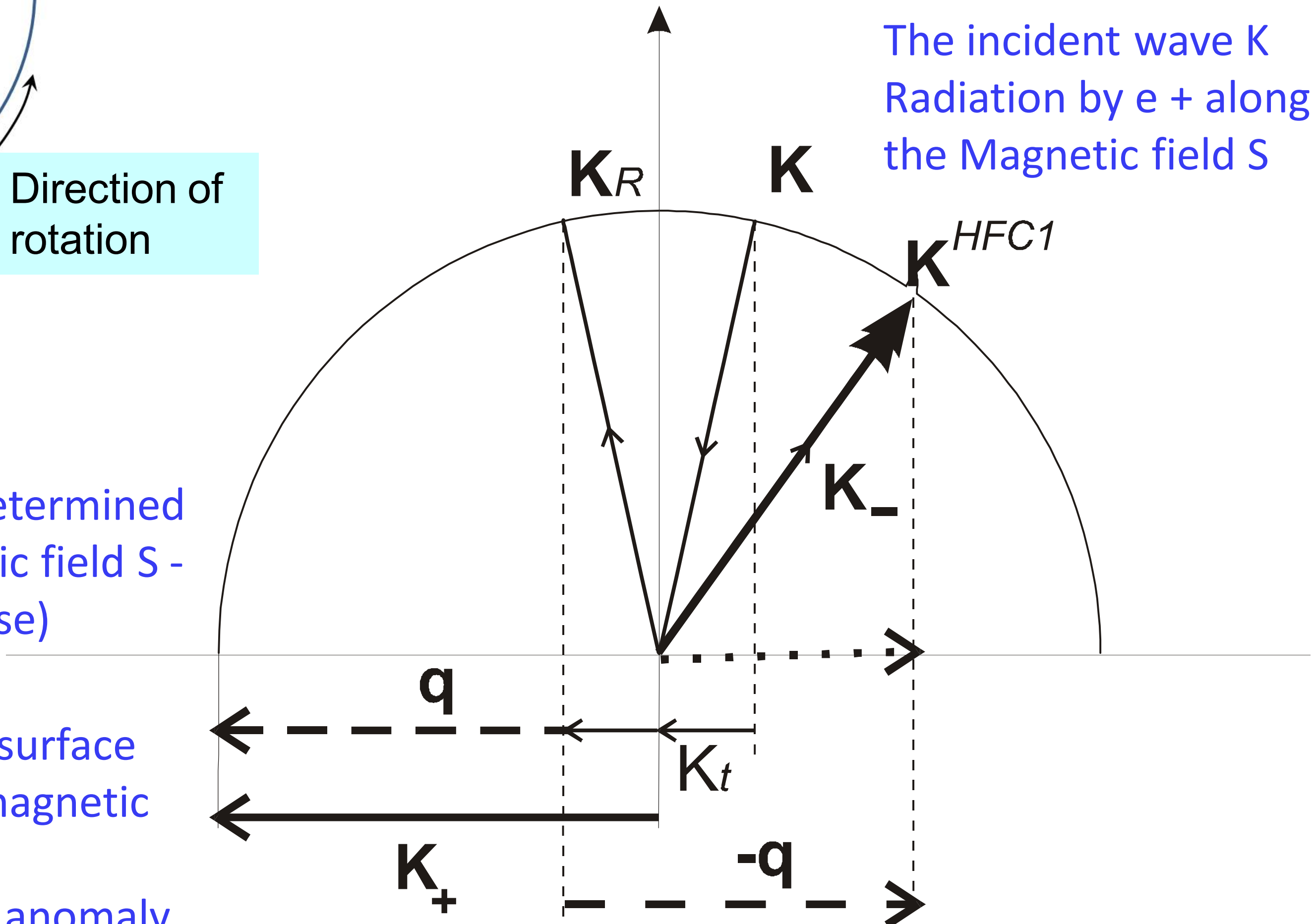
Therefore, in what follows we shall consider the Wood-Rayleigh conditions k_z = 0 as necessary for stimulated scattering.

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.

As can be seen from the Figures, at some frequencies that are different from each other, both the main pulse and the interpulse disappear. A natural explanation connects these phenomena with the change of the radiation mechanisms in the internal polar gap.
The disappearance of the components is due to the cessation of radiation at longitudinal acceleration and the transition to the predominance of relativistic radiation (KF). Shifting of the IP (KT) and the appearance of the HF component (K) from the point of view under discussion means that as the frequency increases, the reflection of a narrowly directed radiation of relativistic positrons from the surface of a pulsar enters the game. The unusual nature of this explanation is due to the fact that, without exception, all the previously considered mechanisms of pulsar radiation were associated with the motion of particles or plasma flows outward from the surface of the star.
Radiation (hard, absorbed by the surface) of relativistic positrons flying to the surface was considered earlier in connection with the problem of its heating (See Refs in (B)

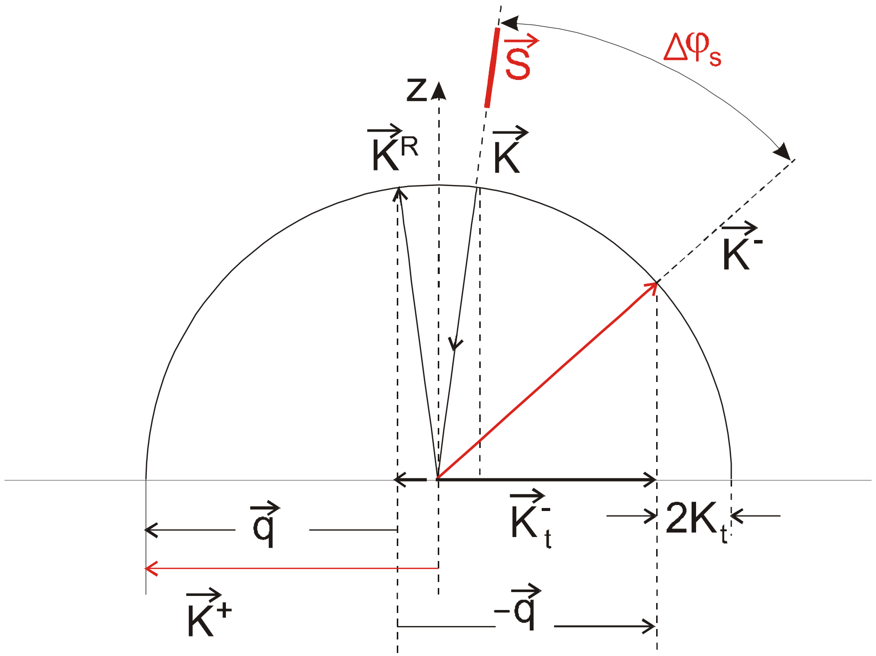
High-frequency radiation of positrons flying to the star, as far as we know, no one has considered.

(KF) **V.M. Kontorovich, A.B. Flanchik,** Astrophysics and Space Sci **345**, №1, 169 (2013). ArXiv: 1210.2958, JETP **143**, #1, 92 (2013).

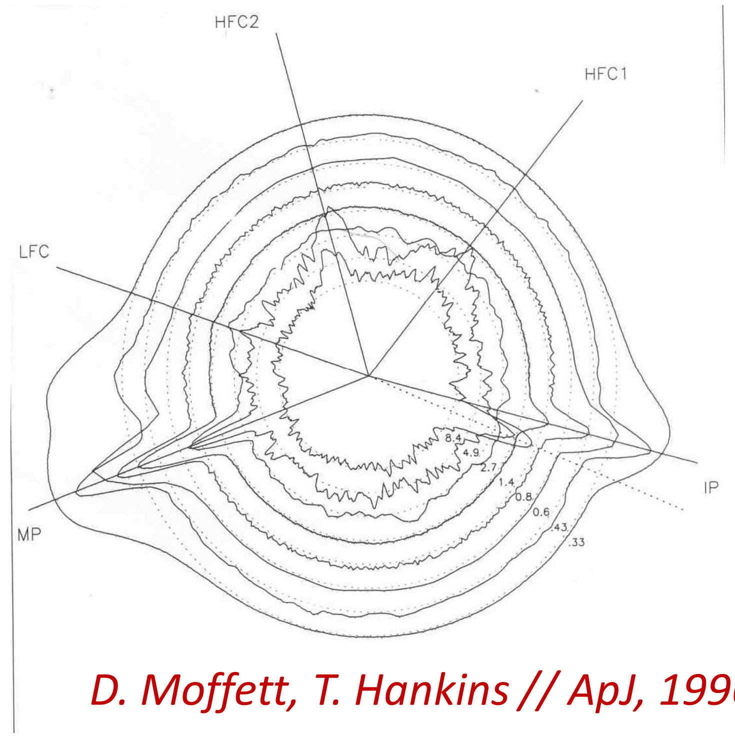
(KT) **V.M. Kontorovich and S.V. Trofymenko,** arXiv:1606.02966.

(K) **V.M. Kontorovich** , Low Temperature Physics, Том 42, #8, 854-862 (2016)

(B) **D.Barsukov et al**, Astro Rep, **93,** 569 (2016)



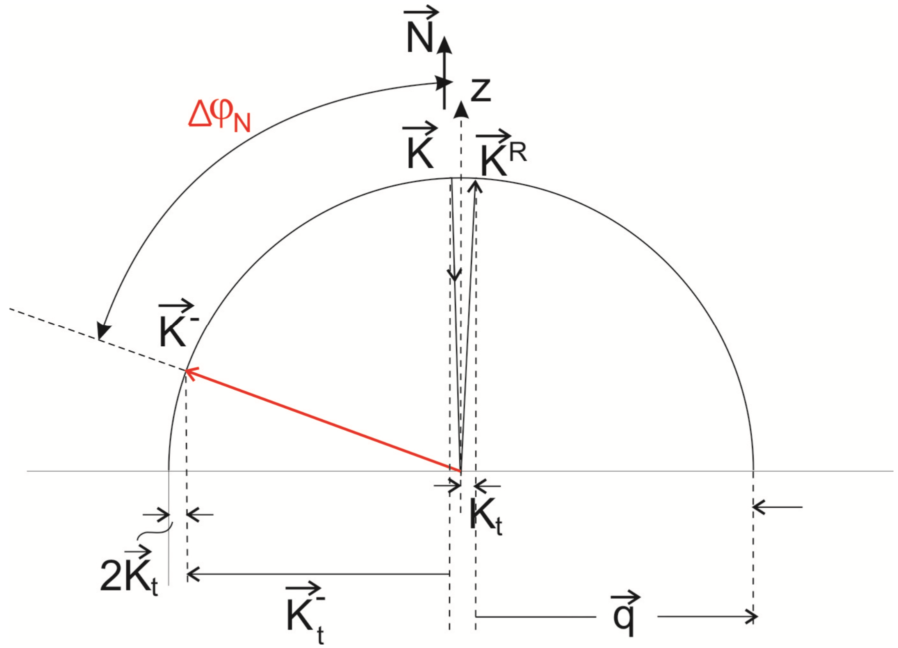
The scheme of the appearance of Combination Raman Spectra of the first order at the pole S at stimulated scattering of radiation by returning Positrons



D. Moffett, T. Hankins // ApJ, 1996

V.M.Kontorovich
LTP, **42**, № 8, 854-862 (2016)

The scheme for appearance of the first-order Raman spectra at the pole N.
The direction of the phase shift here is inverse compared to the pole S.



Drift of the HF component in the Stimulated Scattering model

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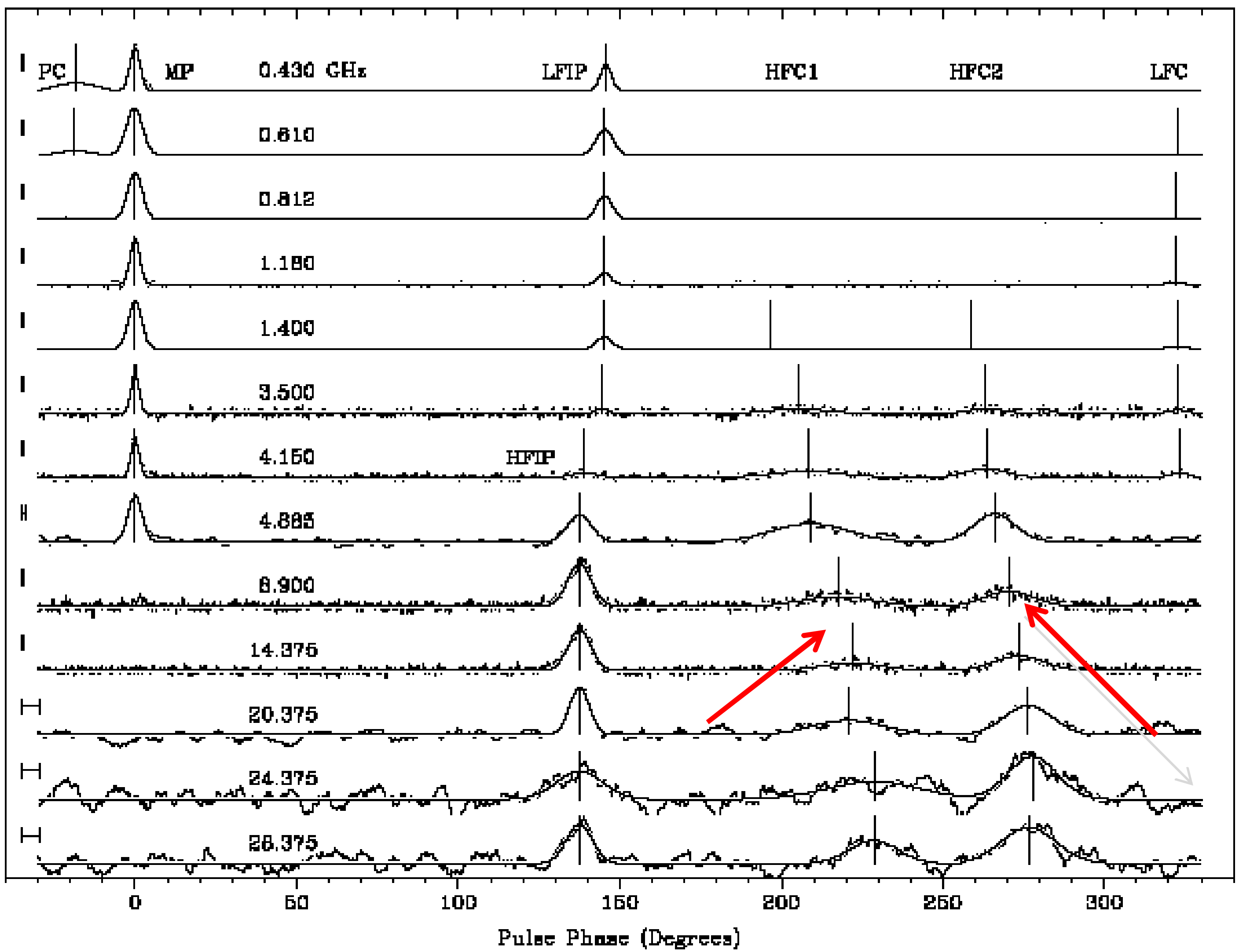
The frequency drift of the components

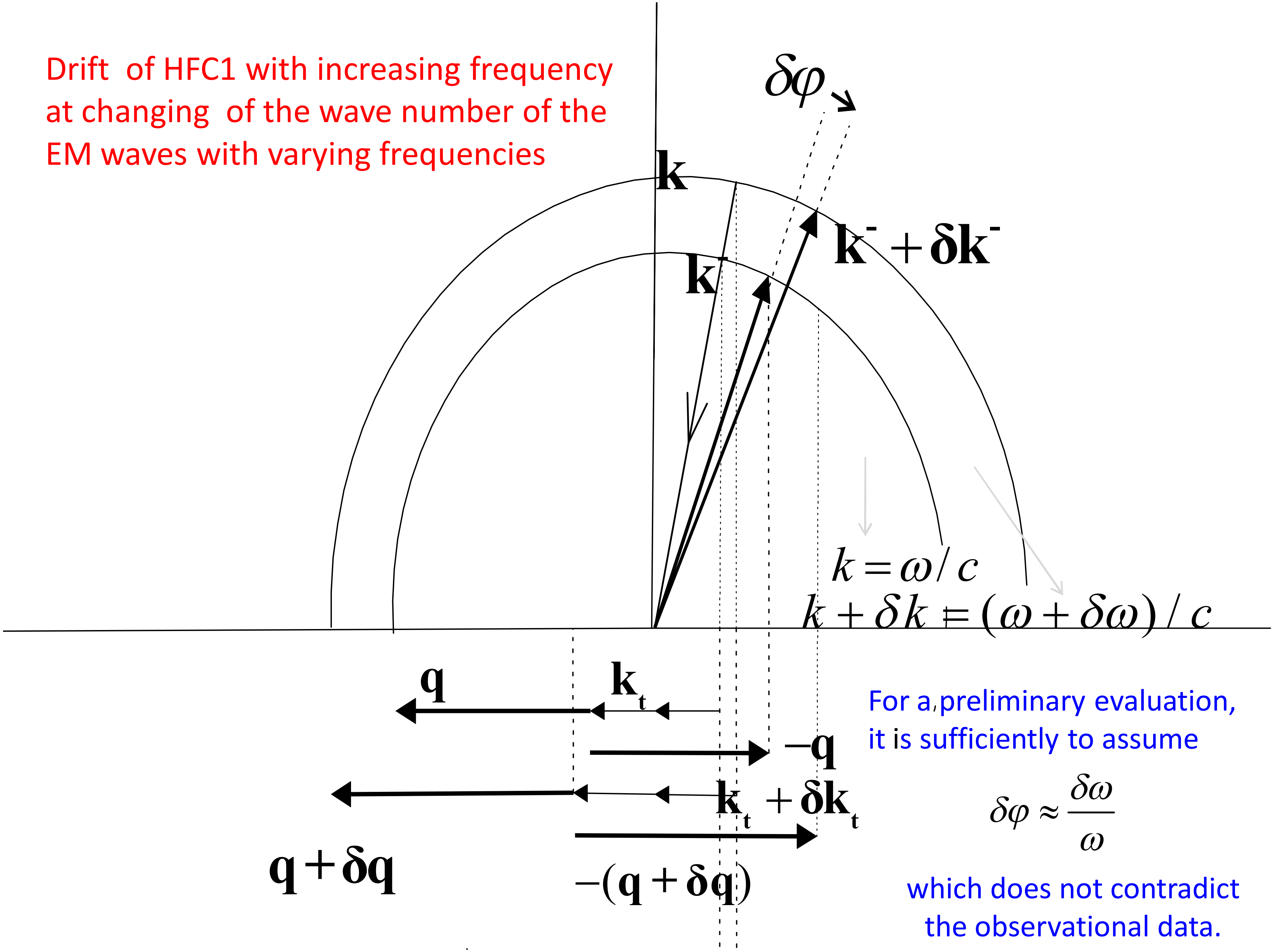
is very important in choosing the right theoretical model. Particularly, the coincidence of its directions for both components is an argument in favor of the birefringence of the scattered wave in anisotropic magnetized pulsar plasma. Returned motion of positrons, arising at penetration of accelerating electric field of the gap in the pair plasma, was considered in literature in connection with heating of the surface by the reverse current. The difference of magnetic field from dipole one, leading in particular to its slope, also was discussed with regard to its toroidal component as well. However, the low-frequency radiation of backflow positrons and reflected radiation from the surface of the pulsar were not considered anywhere until our works.

Drift of the HF component with increasing of frequency



Hankins, Jones & Eilek, arXiv:1502.00677

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

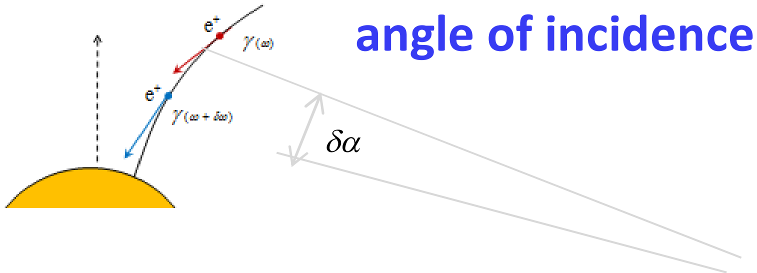


For a preliminary evaluation, it is sufficiently to assume

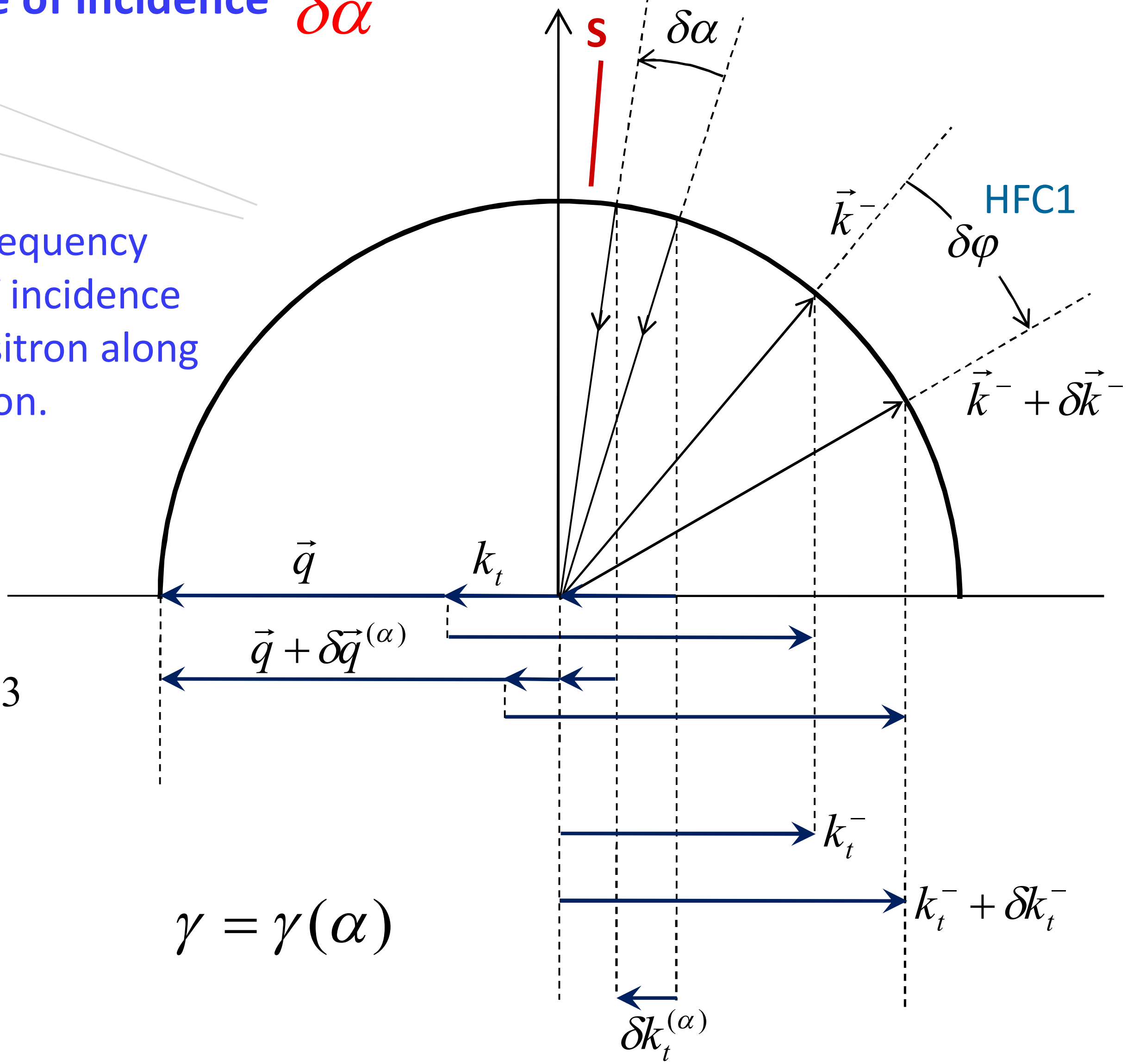
$$\delta\varphi \approx \frac{\delta\omega}{\omega}$$

which does not contradict the observational data.

Drift of HFC1 with increasing frequency due to change of the angle of incidence $\delta\alpha$



Drift of HFC1 with increasing frequency due to a change in the angle of incidence due to displacement of the positron along the force line during acceleration. Increase in gamma factor is necessary to increase the radiation frequency:



$$\omega \geq \omega_{\min} = \frac{c}{R}\gamma^3$$

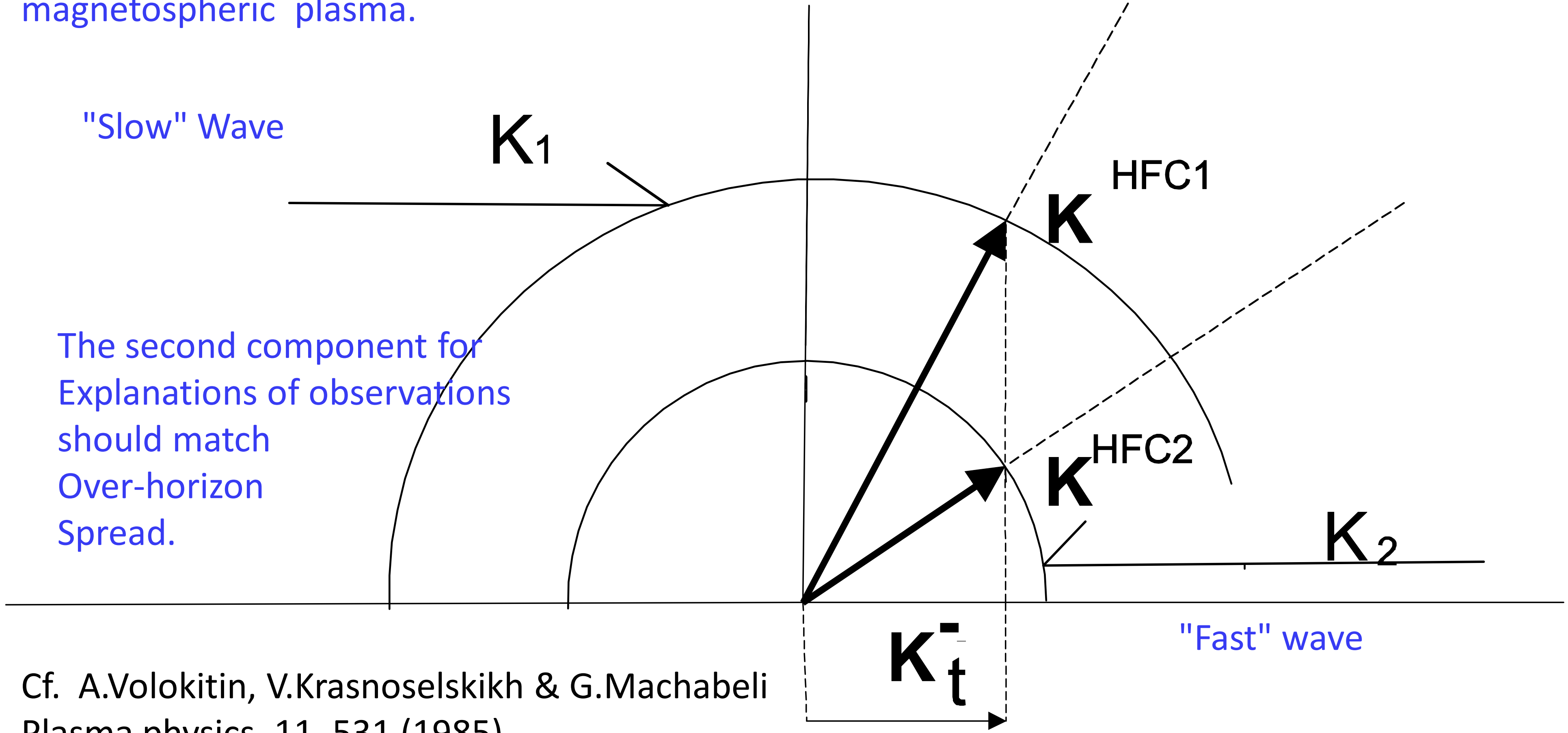
$$\delta\omega \geq \frac{3c}{R}\gamma^2\delta\gamma \qquad \gamma = \gamma(\alpha)$$

$$\delta\gamma = \frac{\partial\gamma}{\partial\alpha}\delta\alpha$$

Gamma is the Lorents-factor of accelerated positron

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).

RESUME

A new mechanism of radiation emission in the polar gap of a pulsar is proposed. It is the curvature radiation which is emitted by positrons moving towards the surface of the neutron star along magnetic field lines and reflects from the surface. Such radiation interferes with transition radiation emitted from the neutron star when positrons hit the surface. It is shown that the proposed mechanism may be applicable for explanation of the mystery of the inter pulse shift in the Crab pulsar at high frequencies discovered by Moffett and Hankins twenty years ago.

Having no other explanations the radiation of high-frequency components of the pulsar in the Crab Nebula can be considered as a manifestation of instability in the nonlinear reflection from the neutron star surface. Reflected radiation is the radiation of relativistic positrons flying from the magnetosphere to the star and accelerated by the electric field of the polar gap. The discussed instability is a stimulated scattering by surface waves, predicted more than forty years ago and still nowhere and by no one observed.

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.

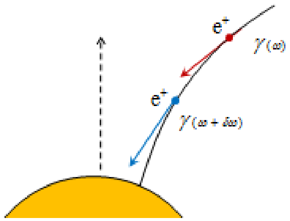
Главным делом жизни вашей
Может стать любой пустяк.
Надо только твердо верить,
Что важнее дела нет.
И тогда не помешает
Вам ни холод, ни жара,
Задыхаясь от восторга,
Заниматься чепухой.

Г.Остер

The main thing in your life
Can be any trifle.
One must only firmly believe
That it is the most important thing.
And then neither cold, nor fever
Will prevent you
Panting with delight
From being engaged in trifles.

G.Oster

Thank you for attention!



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Dear Zhenya,
many happy returns
of the Day!