PHYSICAL LINKS BETWEEN THE RADIO AND HIGH-ENERGY EMISSIONS OF PULSARS

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ABSTRACT

The radio photon reprocessing by the relativistically gyrating plasma particles in the open field line tube of a pulsar is considered. The particle relativistic gyration results from the resonant absorption of radio photons in the outer magnetosphere. The spontaneous synchrotron re-emission of the particles falls into the optical and soft X-ray ranges and thus contributes to the non-thermal high-energy emission of a pulsar. The radio photon scattering off the relativistically gyrating particles also deposits photons into the high-energy range. Both processes can underlie the potentially observable features of the radio-high energy connection in pulsars and, in particular, account for the manifestations already observed in the Crab and Vela pulsars. In the framework of our theory, the strongest correlation is expected for the low-frequency radio photons.

Observational evidence

• The radio emission and non-thermal high-energy emission of pulsars are characterized by essentially distinct energetics and spectra. They are undoubtedly generated by distinct mechanisms in different sites in the magnetosphere.

• Nevertheless, the simultaneous observations in radio and at high energies have revealed peculiar correlations:

- ❑ the optical pulses of the Crab pulsar coincident with giant radio pulses are 3% brighter (Shearer et al. 2003, see Fig. 1)
- ❑ the soft X-ray profile of the Vela pulsar changes with radio pulse intensity (Lommen et al. 2007, see Fig. 2)

• Summary of the observational results:

- ❑ the radio – high-energy connection does exist
- ❑ the fluctuations of the high-energy emission are much less pronounced as compared to those in the radio band
- ❑ the high-energy emission related to the radio pulse fluctuations changes not only in intensity but also in the profile shape

We suggest that the radio – high-energy correlation is a consequence of propagation effects in pulsar magnetosphere. It results from radio photon reprocessing to high energies in the secondary electron-positron plasma inside the open field line tube of a pulsar

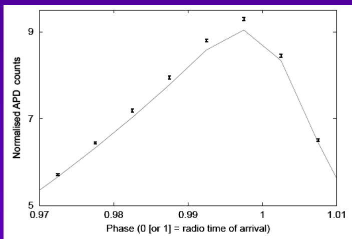


Fig. 1. *(Shearer et al. 2003).* Optical profile of the Crab pulsar*:* *solid line* – the average profile, *crosses* – the profile averaged over the pulses coincident with giant radio pulses

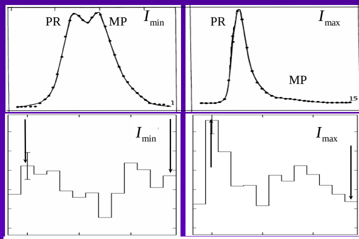


Fig. 2. *Top* – radio profile of the Vela pulsar (*Krishnamohan & Downs 1983*) for the lowest (*right*) and highest (*left*) radio intensity. *Bottom* – soft X-ray profile of the Vela (*Lommen et al. 2007*) at 2-16 keV for the lowest and highest radio intensity, respectively; *arrows* indicate the phase regions where the profile changes markedly

Resonant absorption of radio emission

• In the outer magnetosphere, at distances ~(0.1-1)R, where R is the light cylinder radius, the radio waves meet the condition of cyclotron resonance, $\omega' \equiv \omega\gamma(1-\beta\cos\theta) = \omega_G \equiv eB/mc$

• In the resonance region,

- ❑ the particles perform induced transitions between the Landau levels, absorbing or emitting resonance photons
- ❑ in total, the radio emission is partially absorbed
- ❑ the average pitch-angle of the absorbing particles, $\psi = p_\perp / p_\parallel$, increases monotonically up to ~0.1 and stays fixed, while the total particle momentum can increase by a factor of ~1000 (Lyubarsky & Petrova 1998, Petrova 2002)

• The particles with the evolved momenta are the source of spontaneous synchrotron emission, which falls into the optical and soft X-ray range. This is suggested as a mechanism of non-thermal high-energy emission of pulsars (Lyubarsky & Petrova 1998, Petrova 2003, Harding et al. 2005, 2008)

• The mechanism for the first time implies a physical connection between the radio and high-energy emission of pulsars.

• The first observational manifestation of such a connection has been discovered in the Crab pulsar. The excess of optical emission during its giant radio pulses can be understood as follows. As a giant radio pulse comes into the resonance region, the momentum evolution of the particles becomes more pronounced and their synchrotron emission is stronger.

Radio – high-energy correlation at low radio frequencies

• The resonant absorption and the spontaneous scattering by spiraling particles both become much more efficient at low radio frequencies.

• These processes may be responsible for the low-frequency turnover in pulsar spectrum, which is observed in old pulsars at frequencies <100 MHz. If so, the original radio luminosity is much larger than the observed one, and the radio luminosity lacking beyond the turnover should appear at high energies.

• The correlation between the radio emission beyond the turnover and the high-energy emission should be most pronounced.

• In several old pulsars, there is indeed the unexpected excess of the non-thermal high-energy emission (Becker et al. 2006).

• The propagation origin of the spectral turnover should imply peculiar radio intensity statistics at lower frequencies (see Fig. 4). Even small variations in the plasma flow may cause substantial change of the efficiency of reprocessing and affect the outgoing radio intensity drastically.

• The distribution of single-pulse radio intensities beyond the turnover appears essentially asymmetric, in contrast to that at high radio frequencies. The radiation beyond the turnover is dominated by several strong pulses, while the overwhelming majority of the pulses are well below the average. This trend is compatible with the observed pulse statistics at low radio frequencies (e.g. Ulyanov & Zakharenko 2012).

Radio photon scattering by relativistic spiraling particles

• Pulsar radio emission is essentially broadband, and hence the resonance region is quite extended.

• Over most part of the resonance region, there is a significant amount of the under-resonance photons, with frequencies $\omega' \ll \omega_G$.

• The particles acquire relativistic gyration at the very bottom of the resonance region, and further on the under-resonance photons can be scattered off the relativistically gyrating particles.

• In contrast to the common magnetized scattering by straightly moving particles, the under-resonance photons are chiefly scattered to high harmonics of the particle gyrofrequency, $\omega'_{sc} = \omega' + s\omega_G$ with $s \sim \gamma_0^3$ (here γ_0 is the Lorentz-factor of the particle gyration), and the total scattering cross-section is much larger (Petrova 2008).

• Fig. 3 shows the spectral distribution of the scattered power as compared to the synchrotron spectrum of the same particle. The peak of the scattered radiation is markedly shifted beyond the synchrotron maximum. Although the total power scattered is always less than the synchrotron power, in the region beyond the synchrotron maximum the contribution of the scattered radiation can be substantial.

• The scattered power is a very strong function of the particle gyration energy, $L_{sc} \propto \gamma_0^6$

• γ_0 is the quantity that is determined by the radio intensity coming into the resonance region and causing the particle momentum evolution.

• It is the scattered component that is tightly connected with the radio emission characteristics, and this connection should be most prominent beyond the synchrotron maximum.

• In application to the Vela pulsar, the peaks of the synchrotron and scattered radiation, $\hbar\omega_{syn} = 0.2$ keV and $\hbar\omega_{sc} = 1.5$ keV, well agree with the spectral maximum of the trough component and the range of its pronounced correlation with radio. The total synchrotron power, $L_{syn} = 10^{31}\ \mathrm{erg \cdot s^{-1}}$, is compatible with the observed luminosity of this component (Petrova 2009).

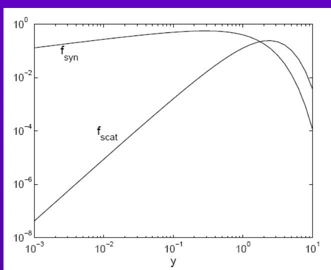


Fig. 3. Spectral distributions of the scattered and synchrotron powers of the particle; $y \equiv (2/3)s\gamma_0^{-3}$.

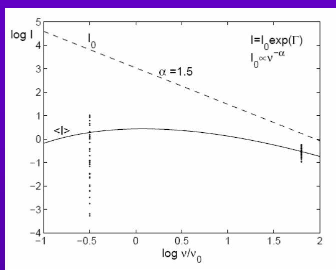
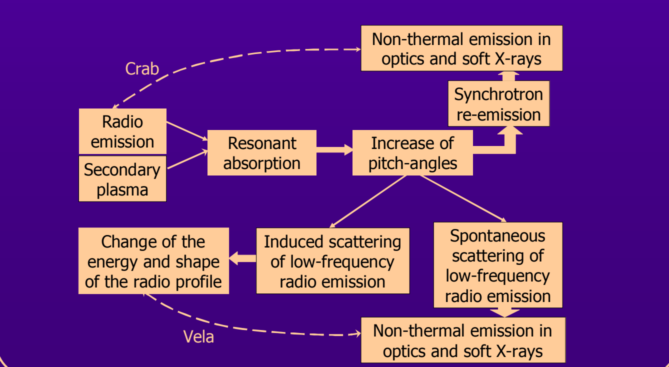


Fig. 4. Simulated radio spectrum of a pulsar with account for the radio photon reprocessing to high energies (*solid line*), the original spectrum (*dashed line*), and the distributions of the single-pulse intensities at two radio frequencies.

Radio photon reprocessing in pulsar magnetosphere and its consequences



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