Multiwavelength modeling of the Vela pulsar pulses – from Optical light to VHE gamma-rays

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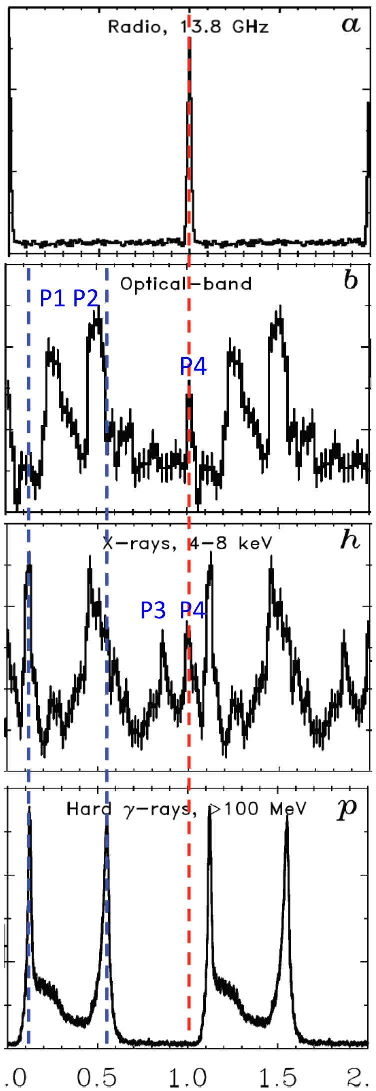


Abstract:
The pulsed radiation from PSR B0833-45 (Vela) has a phased-averaged spectral energy distribution of apparently simple structure across a wide energy range. However, in narrow energy bands the pulses reveal astonishing complexity in the directional pattern of the radiation. We present the results of a 3D modeling of the Vela radiation properties in the scenario when outer gap accelerator coexists with an inner gap accellerator, as they occupy different magnetic field lines. We show how the synchrotron emission as well as the inverse Compton scattering of soft photons by secondary e±-pairs in its magnetic and non-magnetic regimes reproduces qualitatively the observed energy-dependent pulses of Vela. Moreover, we present how ICS of soft synchrotron photons by primary particles can form a pulsed spectral component in the VHE domain. The flux of this component can be within reach by the Cherenkov Telescope Array for more than 50h of observation.

Fig.1 – The Vela lightcurves at radio, optical, hard X-rays and γ-rays (from [5]).

Why P1 and P2 - two main peaks in Optical - are not in phase with two main peaks in gamma-rays (the phases indicated by vertical blue dashed lines)?

What is the origin of P4 - a narrow peak at phase ~0.0 in Optical, UV and hard X-rays (the phase 0.0 indicated by vertical red dashed line)?

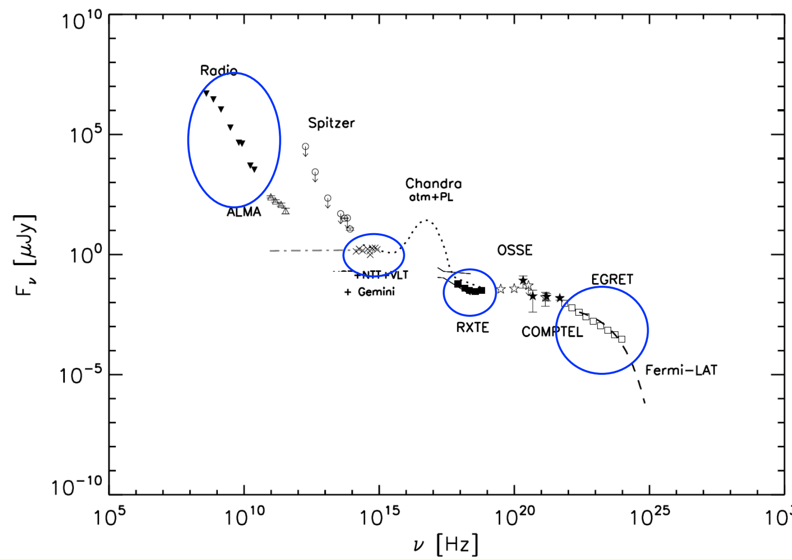


Fig.2:The flux density of Vela pulsar. Encircled in blue are the densities inferred from the flux-density pulsations shown in Fig.1.

Three-component Model of the MWL lightcurves and the spectral component in the VHE domain in the Vela pulsar*)

Component 1: Outer Gap

We use retarded dipolar magnetosphere in vacuum approximation. The numerical 3D code calculates curvature radiation (**CR**) from primary charges in the inertial observer frame (IOF) as described in [3] and [2]. The charges (primary $e^{\pm}$) are subject to accelerating electric field assumed to be constant in the gaps. The primaries (blue arrows in Cartoon) reach Lorentz factors $\gamma \sim$ a few x 10^7, and the CR cooling is included to obtain realistic Lorentz factors. These are then used to calculate the inverse Compton scattering (ICS) of primaries with SR photons in the optical-infrared domain.

The model doesn't follow pair creation due to interaction of CR photons with a soft-photon field. Instead, we assume that secondary $e^{\pm}$ of $\gamma \sim 10^2$ - 10^3 are formed in a layer which is attached to (placed on top of) the outer gap layer (green arrows in Cartoon). These pairs are the source of the soft photon field - synchrotron radiation (**SR**) which extends across the wide energy range, from hard X-rays to UV to optical and likely to far IR (0.001 eV). To determine directional characteristics of the SR radiation which would agree with the observed pulses from Vela, we start first with the geometrical version of OG [3]. The geometrical model assumes a uniform distribution of emissivity in the energy range of interest. Therefore, for a given location of the layer in terms of the magnetic-line footprints on the polar cap, the properties of the pulses of radiation (CR in the case of the gap, or SR in the case of the secondary-pairs layer) will be a function of two angles: the inclination angle a of the magnetic axis with respect to the spin axis, and the viewing angle ζ between the line-of-sight and the spin axis.

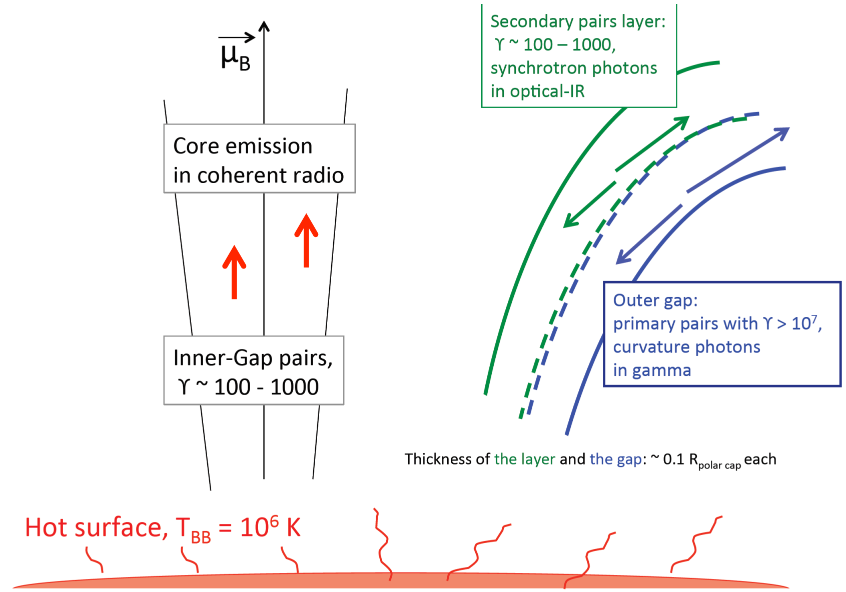
*)For more details see [11].

Component 2: Inner Gap coexisting with the Outer Gap

The e±-pairs (red arrows in Cartoon) of $\gamma \sim 10^2 – 10^3$ are assumed to be created in the inner part of open magnetic field-lines, concentrated around the magnetic axis. The outer gap and its adjacent SR layer occupy about 20% (in terms of the polar cap radius) of the open magnetic-field lines. The inner part of polar cap is thus able to develope a potential drop across it, high enough to lead eventually to creation of electron-positron pairs. A narrow radio pulse ("a core" emission) present in Vela speaks in favour of this picture.

Component 3: Blackbody soft X-rays

The field of thermal soft X-ray photons, with $T_{bb} = 10^6$K and luminosity L_x = $2x10^{32}$ erg/s from the pulsar surface [6].



Not to scale

Cartoon: scheme of the physical model

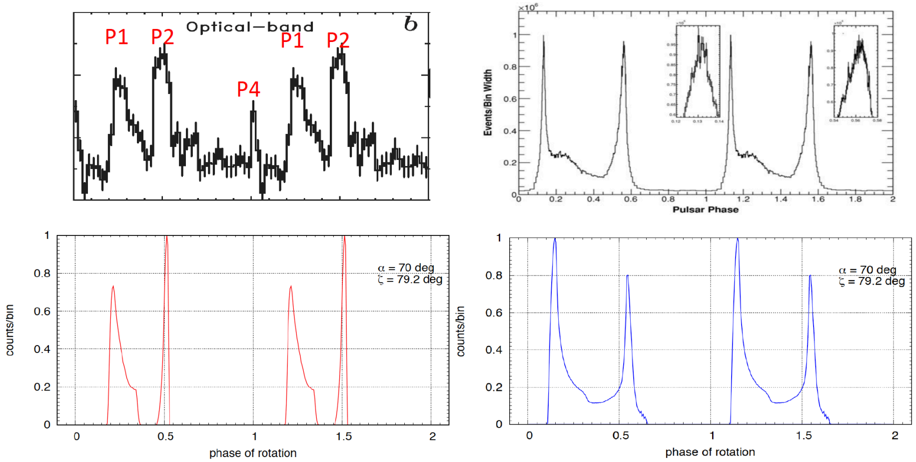


Fig.3 Top - the lightcurves of Vela in optical [4] and gamma rays [1].
Bottom - their counterparts in the *uniform-emissivity* version of the OG model obtained for the inclination angle α = 70° and the viewing angle ζ = 79°.

α = 70° The ICS core component in optical-UV

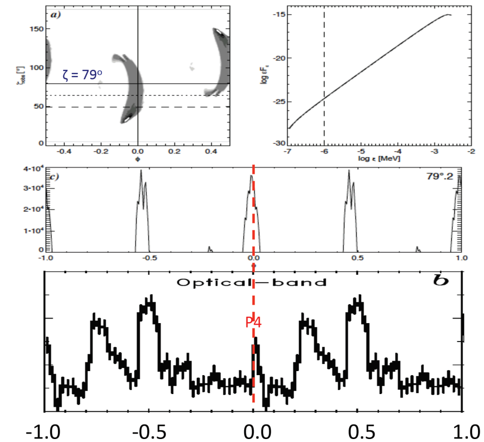


Fig. 4

The photon shows the distribution of optical photons (1eV) formed due to the ICS between the primary pairs and the optical-to-nearIR radiation from the synchrotron layer. The phase-averaged ICS spectrum (note: the Y-axis scale is in 'model' units) and the ICS lightcurve for 1eV are included (top right panel and middle panel, respectively).

Three different ICS processes were considered in an attempt to explain the existence of specific features in the Vela's non-thermal radiation:

1. primary electrons in the gap interacting with optical-infrared photons originating from the SR layer,
2. inner PC pairs interacting with optical-infrared photons originating from the SR layer,
3. inner PC pairs interacting with thermal X-ray photons from the neutron star surface.

These processes are expected to lead to the formation of, respectively,:

1. spectral component in the VHE range (a prediction),
2. core-like pulse (known as P4) detected in optical as well as in UV ([4], [9]) at the phase of the radio core pulse,
3. core-like pulse detected in hard X-rays ([8]) at the phase of the radio core pulse (see also [5]).

The ICS core component in hard X-rays

α = 70°

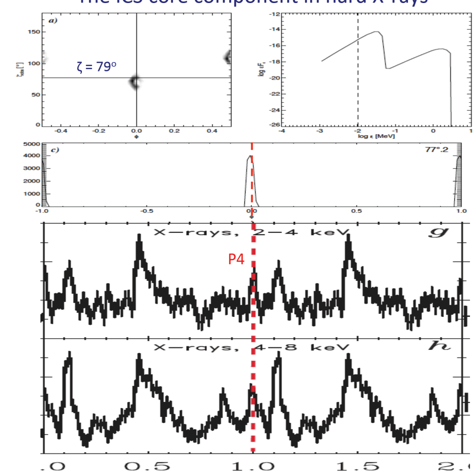


Fig.5

Same as Fig4, but for he distribution of X-ray photons (10keV) formed due to the ICS between the inner PC pairs and the X-rays from the neutron star surface

The OG model - ICS component in VHE

α = 70°

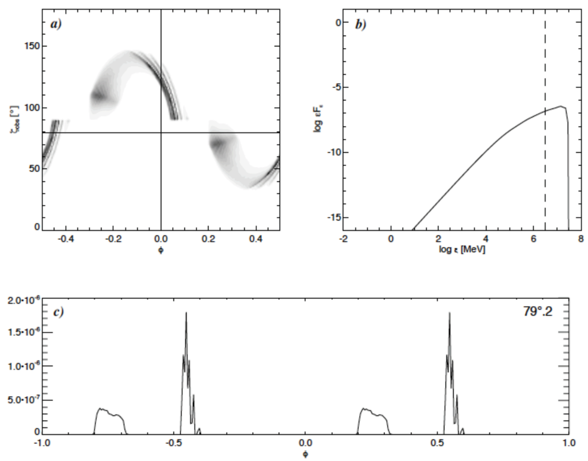


Figure 6: Panel a): The photon map shows the distribution of 3TeV photons due to the ICS between the primary pairs and the optical radiation from the synchrotron layer. The horizontal line is for
ζ = 79deg and two periods of rotation are shown for the phase f for clarity.
Panel b): The phase-averaged energy spectrum of the ICS component for ζ = 79 is shown. The Y-axis scale is in ’model’ units.
Panel c) The lightcurve of the ICS at 3TeV consists of two pulses of different shapes, located at 0.2–0.3 and 0.5–0.6 in phase.

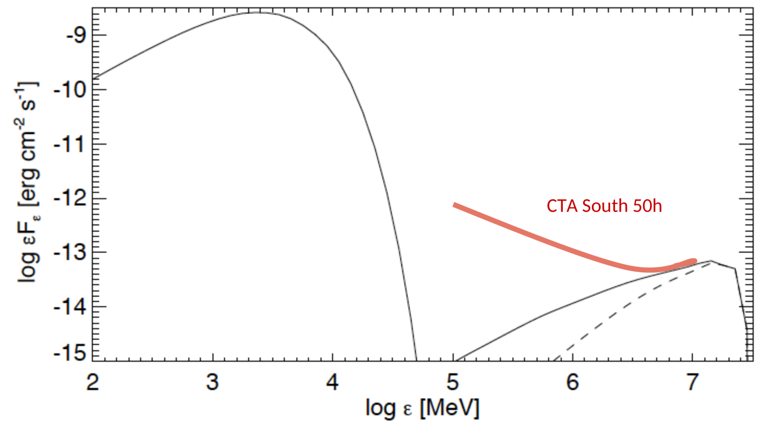


Figure 7: The CR and ICS components. For the ICS:
continuous – soft photon field optical to far-IR
dashed – soft photon field optical to near-IR.

Summary

In the optical-UV and the hard X-rays domains:

If an inner gap with e^--e^+ pairs coexists with outer gaps, then

- core-like pulses can form in optical, UV and hard X-rays,
- they are in phase with the core-like radio pulse.

In the VHE domain:

- Formation of pulsed VHE-spectral component is possible in the Vela pulsar in the case of high inclination angle,
- its lightcurve would consists of two pulses at the phases ~0.2 and ~0.6,
- its expected phase-averaged flux can be within reach by CTA South for > 50h.

References

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