Multiwavelength studies of pulsars

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Multiwavelength properties of

- middle-aged pulsars: Vela (update), + Geminga (very old results) for comparison
- young pulsars: B0540-69 (update)

Constraints on emission regions loci in middle-aged pulsars from the lightcurves

Outline

Cartoons by Benoit Cerutti
Pulsar detections from radio to gamma rays

~ 2600 in radio
3 in mIR, 5 in nIR,
10 in optical,
10 in nUV, 4 in fUV

> 100 in X-rays (mostly Chandra and XMM Newton)
211 in gamma-rays (Fermi LAT, AGILE)

Cherenkov arrays:

Crab pulsar: 25 GeV – 1.5 TeV (MAGIC,VERITAS)

Vela pulsar: 20 – 120 GeV (H.E.S.S. II, mono), 3 TeV & 7 TeV (H.E.S.S. I, stereo)
UVOIR measurements

from compilation by Mignani et al. 2010

Young

Middle aged

Crab PSR
\(\tau = 1.2 \times 10^3\) yr

Vela PSR
\(\tau = 1.1 \times 10^4\) yr

PSR B0540–69
\(\tau = 1.7 \times 10^3\) yr

Geminga
\(\tau = 3.4 \times 10^5\) yr
Optical and IR photon fields – potential targets for ICS -> GeV, TeV

Young

Crab PSR
\( \tau = 1.2 \times 10^3 \) yr

Middle aged

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The SED of Vela

\[ F_\nu \quad [\mu \text{Jy}] \]

\[ \nu \quad [\text{Hz}] \]

- Radio
- Spitzer
- ALMA
- Chandra atm+PL
- HST+NTT+VLT + Gemini
- OSSE
- EGRET
- RXTE
- COMPTEL
- Fermi-LAT

*terra incognita*
The Vela lightcurves

Spolon et al. 2019

See Strickman et al. 2001 for details
Transition region between coherent and incoherent emission

At what frequency does the transition occur?

How does the lightcurve change?

Are the radio spectrum and the IR-O-UV spectrum disconnected?

Vela is the first pulsar detected with ALMA (Mignani et al. 2017)
The ALMA fluxes imply high brightness temperatures \( T_b \sim 10^{17} - 10^{15} \) K for 10km x 10km.
The pulse is in phase with the pulse at low frequencies.

Mean flux density „in general consistent with Mignani et al. 2017 (while slightly higher)”.

Kuo Liu et al. in prep.
mid-IR observations of Vela in the future (2021+)

Single narrow pulse down to far-IR?

Two broad pulses up to mid-IR at P1 and P2 phases?
If UVOnIR is synchrotron then where is the low-energy turnover (break) located?
At what altitude the SR at $\sim E_{ct}$ forms?

Assume ‘the very-small-pitch-angle approximation’ (Epstein 1973):

$$\psi \gamma \ll 1, \text{ with } \gamma \gg 1.$$ 

For electrons with

$$\frac{dN}{d\gamma} \sim \gamma^{-2}, \gamma > \gamma_{\text{min}}$$

the SR flux density $F_{nu}$ is

$$\sim \text{const} \quad \text{for } E > E_{ct} \quad \text{(needed for Vela)},$$

$$\sim E \quad \text{for } E < E_{ct}.$$
Low-energy break $E_{ct}$ in SR spectrum of Vela – why does it matter?

$$E_{ct} = 2 \gamma_{\text{min}} \frac{h e B}{2\pi m_e c}$$

For the vacuum dipole it yields a lower boundary of the radius $r_{ct}$ where the densest soft-photon field is located.

$$\frac{r_{ct}}{r_{ns}} \approx 130 \left[ \frac{B_0 (\text{TG}) \gamma^+}{E_{ct} (\text{eV}) 100} \right]^{1/3}$$

For $E_{ct} = 0.1 \text{ eV (mid-IR)}$, $\gamma_{\text{min}} = 100$, $B_0 = 4 \text{ TG}$

$r_{ct} \approx r_{LC}$. Location suitable for ICS process generating GeV-TeV emission
Gemina – is it similar to Vela?

Shearer 1998

Fermi-LAT

Kargaltsev et al. 2005
The first UV detection of PSR B0540-69 in LMC

Mignani et al. 2019

Observations with the HST:

Space Telescope Imaging Spectrograph, NUV- and FUV-MAMA in the TIME-TAG mode with a net total integration time of 9650 s

The pulsar: $m_{\text{NUV}} = 21.45$, $m_{\text{FUV}} = 21.83$
The NUV and FUV lightcurves of PSR B0540-69

Mignani et al. 2019
PSR B0540-69 multi-epoch lightcurves

Fermi LAT Collab. 2015
Mignani et al. 2019
The UVOIR spectrum of PSR B0540-69

$\alpha_{\text{UV}} \sim 3$

$F_\nu \propto \nu^{-\alpha}$

Dramatic break in the UVOIR spectrum, not seen in other pulsars

Mignani et al. 2019
Vela lightcurve in the optical band vs gamma

Spolon et al. 2019
Vela: optical and gamma-ray emission in an ‘old-fashioned’ simplified OG model

Trajectories in Corotating Reference Frame

SR photons: IR-opt.

Leading Side

e^+

Trailing side

SR photons: IR-opt.

e^+
P1 and P2 pulses in optical and gamma rays and their reconstruction in the *uniform-emissivity* version of the OG model, obtained for inclination angle $\alpha = 70^\circ$, viewing angle $\zeta = 79^\circ$
Vela: P1 & P2 shapes and phases in optical and gamma reproduced with the model of Harding at al. 2018
Vela: what is the origin of P4 at the radio phase in optical-UV-hard Xrays?

Coexisting inner and outer gaps

Hot surface, $T_{BB} = 10^6$ K

Core emission in coherent radio

Inner-Gap pairs, $\gamma \sim 100$

SR photons: IR-opt.

Trajectories in Corotating Reference Frame

Trailing side

Leading Side

$e^+$
1. Primary OG pairs + IR photons (synchrotron photons) \rightarrow\text{pulsed VHE component}

2. Inner Gap pairs + optical-IR photons (synchrotron photons) \rightarrow\text{P4 in optical-UV}

3. Inner Gap pairs + thermal X-ray photons \rightarrow\text{P4 in hard X-rays}
The ICS component in VHE

$\alpha = 70^\circ$
The ICS core component in optical-UV

\[ \alpha = 70^\circ \]
The ICS core component in hard X-rays

$\alpha = 70^\circ$
Conclusions

1. Multiwavelength properties of Vela suggest that its magnetosphere contributes significantly to formation of its radiation (unlike in young pulsars, where ECS zone seems to dominate)

2. Realistic magnetospheric models should contain gaps similar to the gaps of corotating low-density magnetosphere models.

2a. Hints for coexistence of outer gaps and inner gaps in the magnetosphere of Vela:

   - the main optical pulses wrt the gamma-ray pulses

   - the core-like pulses in optical, UV and in hard X-rays, aligned in phase with the core-like radio pulse