Multi-TeV Emission From the Vela Pulsar

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VHE emission from pulsars

Pulsed emission above 10 GeV detected from three pulsars by ACTs

**Crab:** VERITAS > 120 GeV
MAGIC: 40 GeV – 1 TeV (Ansoldi et al. 2016)

**Geminga!**
MAGIC: P2 > 30 GeV

![Graph showing energy distribution and counts](image)
Vela pulsar – H.E.S.S. II

10 – 80 GeV (Abdalla et al. 2018)

Continuation of Fermi spectrum (curved sub-exponential) or power law?

Curvature favored by H.E.S.S. II at $> 3.0\sigma$
Vela pulsar – H.E.S.S. II

2004 – 2016: 60 hours in stereoscopic mode

$3 \rightarrow 7 \text{ TeV}!! \ 5.6\sigma$ (Djannati-Atai 2018)

Additional component distinct from GeV spectrum?
SSC emission from Vela pulsar

Harding & Kalapotharakos 2015

$\alpha = 75^0, \zeta = 60^0$

$M_+ = 6 \times 10^3 \times 10^5$

Diagram showing photon flux as a function of energy for different processes: Prim CR, Prim SR, Prim SSC, Pair SR, Pair SSC.
What produces the $> 7$ TeV emission?
ICS model for Vela TeV emission

Rudak & Dyks 2017

Outer gap model
- Emission inside light cylinder
- PC pairs produce SR IR/optical
- Accelerated primaries scatter IR/optical photons
Recent pulsar models


Most particle acceleration occurs in and near the current sheet
See Kalapotharakos poster
Modeling TeV+ emission from Vela

Harding et al. 2018
See also Barnard poster

Near force-free magnetosphere
- PC pairs produce SR IR/optical at lower altitude, injected only where global model allows
- Primary particles (mostly positrons) in current sheet scatter IR/optical to produce 10 TeV ICS emission
- Pairs scatter IR/optical to produce SSC hard X-rays

From Kalapotharakos+ 2018
Simulation of pulsar radiation

Harding & Kalapotharakos 2015

Two models for IR/Optical

1. Toy model:
   Power law \(0.005 - 4\) eV
   Uniform emission from
   \(R_{\text{NS}} - 0.5 R_{\text{LC}}\)

2. SR from pairs:
   Radio altitude \(0.3 R_{\text{LC}}\)

\[\varepsilon_B = \gamma \varepsilon_R (1 - \beta \cos \theta)\]

Petrova & Lybarski 1998
Harding et al. 2008

Radio cone beam
Magnetic axis
Resonant absorption of radio photons when
Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018

\( \alpha = 75^0, \zeta = 65^0, \text{pair } M_+ = 6 \times 10^3 \)

- Detectable component at 10 TeV!
- Pair SR matches optical spectrum

The dangers of limited energy scale! We could have predicted 10 TeV emission from Vela in 2015 ...
Model light curves

Fermi P2/P1 increases with energy – higher $\gamma$ particles produce P2

P2 only at > 3TeV – ICS from highest $\gamma$ particles

Large model $\gamma$-ray/radio phase lag due to azimuthally symmetric emission in current sheet

Harding, Kalapotharakos, Venter & Barnard 2018
GeV emission

Curvature? (Kalapotharakos et al. 2014, 2017, 2018) \( \gamma \sim 10^7 - 10^8 \)

Or Synchrotron? (Cerutti et al. 2016, Philippov & Spitkovsky 2018) \( \gamma \sim 10^5 - 10^6 \)
Summary

• Updated model for Vela pulsar emission
  • 18 decades in energy
  • “Primary” particles accelerated primarily in current sheet
  • More accurate particle trajectories

• SR from PC pairs can produce observed IR/optical

• ICS from particles in current sheet produce emission component peaking around 30 TeV (maximum particle energy)

• Pulsed > 3-7 TeV emission implies mostly CR contributes to GeV emission

• Primary ICS above 10 TeV from a number of young pulsars – more with CTA