The Vela X pulsar wind nebula through the eyes of H.E.S.S. and Suzaku

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Context

- **pulsar wind nebulae**
  - extreme particle accelerators
  - contribute to CR $e^+/e^-$?

- **Vela X**
  - pulsar wind nebula of Vela pulsar (290 pc)
  - bright emission $>$ TeV
  - spatially resolved study in X-rays and gamma rays

- Vela supernova remnant shell
- Puppis A supernova remnant
- Vela X extended radio nebula
- Vela X cocoon
- 408 MHz
  - 0.1-0.4 keV
  - 0.4-2.4 keV

L. Tibaldo, Vela X with H.E.S.S. and Suzaku, ICRC 2017 Busan
Observations

- **X-rays:** Suzaku XIS
  - 3 archival observations

- **gamma rays:** H.E.S.S.
  - data accumulated from 2004 to 2016
  - 100 h livetime
Spectral extraction regions

- same regions for X-rays and gamma rays
- exclude region around pulsar (3.6 arcmin, XIS PSF 95%)
  - neutron star emission (thermal, magnetospheric)
  - jet-torus structure brightest in X-rays/ not resolved in gamma rays
- 0.3 pc to 5 pc from pulsar wind termination shock
Analysis

- **Suzaku XIS**
  - standard *Suzaku* tools
  - $E > 2.25$ keV: exclude supernova remnant
  - background from night Earth’s observations
  - spectral model
    - power law with interstellar absorption
    - cosmic X-ray background
  - 10% systematic uncertainties + leakage from pulsar in pointing 0

- **H.E.S.S.**
  - two independent calibration, reconstruction, and event selection pipelines
  - only data from 4 12-m telescopes, $E > 0.6$ TeV (uniform threshold)
  - residual background: ring method (map), reflected-region method (spectra)
  - spectral model
    - power law (pointing 0)
    - power law with exponential cutoff (pointing 1 and 2)
  - systematic uncertainties: 20% (flux) + differences between pipelines
H.E.S.S. detection map
Radiative modeling

\[
\frac{dN}{dE} = A \left( \frac{E}{E_0} \right)^{-\alpha} \exp \left[ -\left( \frac{E}{E_{\text{co}}} \right)^\beta \right]
\]

- electrons
  - 30 TeV to > 100 TeV

- magnetic field (B)
  - \rightarrow synchrotron radiation in X-rays

- cosmic microwave background infrared radiation field (Popescu+ 2017)
  - \rightarrow inverse Compton in gamma rays

- fit to multiwavelength spectral energy distributions (SEDs)
  - Markov Chain Monte Carlo (MCMC) scan of parameters
  - software package: naima (Zabalza+ 2015)
- leptonic model naturally reproduces SEDs
- X-rays: harder spectrum in pointing 0?
Model parameters
Magnetic field turbulence?

synchrotron turbulent B
(Kelner+ 2013)

\[ \text{PDF}(B) = (1 - a)\delta(B - B_{\text{RMS}}) + aCB^{-\alpha}H(B - B_{\text{min}})H(B_{\text{max}} - B) \]

example:
- \( \alpha = 3/2 \)
- \( B_{\text{max}} = 100 \times B_{\text{RMS}} \)
- \( C, B_{\text{min}} \rightarrow \text{PDF normalized to } 1, \sqrt{\langle B^2 \rangle} = B_{\text{RMS}} \)

synchrotron

gamma \rightarrow \text{electrons}
Conclusions

- H.E.S.S. + Suzaku $\rightarrow$ spatially-resolved constraints on electron spectrum and magnetic fields - minimal model assumptions
- leptonic model naturally reproduces data
- electron spectra and magnetic field strength remarkably uniform from 0.3 pc to 5 pc from pulsar wind termination shock
- constrain turbulence of magnetic field
- magnetic field $> 5 \, \mu G$
  - $100 \, \text{TeV}$ electron cooling time $< 4 \, \text{kyr} << 20-30 \, \text{kyr}$ (system/pulsar age)
  - efficient particle acceleration/transport within cocoon
- weak constraints on electron cutoff: requires better measurements $> 10 \, \text{TeV}$ (CTA), X-rays $> 10 \, \text{keV}$ (NuStar)