Outline

Introductory information:
- Energies ranges & IACT detection
- Pulsars & their emission

The first VHE pulsar: the story of the Crab

The Vela pulsar detection (H.E.S.S. II)

Other VHE observations

Some VHE emission theory

Summary
Monte Carlo simulations for a VHE gamma-ray-initiated shower and for a cosmic-ray-initiated shower

IACT Technique

IACTs: H.E.S.S. MAGIC VERITAS
What is a VHE Gamma Ray?

Very high energy (VHE): >100 GeV
High energy (HE) >100 MeV

Disclaimer: these are loose definitions!

*Fermi*-LAT: ~100 MeV – 300 GeV
HE gamma-ray detector!

VERITAS: ~100 GeV – 30 TeV
VHE gamma-ray detector!

Similar argument for H.E.S.S. & MAGIC, but they see well below 100 GeV...
Pulsars & Their Emission
Pulsar Quick Review

Born in supernovae explosions

Rotation periods range from seconds down to about 1 ms

Neutron star masses $\sim 1.4 \ M_{\text{sun}}$

Extremely magnetized: $10^8$ – $10^{15}$ G

NSs roughly 10 km (6.2 mi) in radius – very compact!

corotating magnetosphere!
Magnetospheric Emission

Pulsar magnetosphere filled with co-rotating plasma (Goldreich & Julian 1969) -> electric fields for acceleration are mostly shorted
- A few “gaps” remain for acceleration
- Location of the gaps still debated

Gamma rays up to a few 10 GeV are produced via curvature radiation
- Gamma-ray flux expected to fall rapidly above the cutoff energy
- Other mechanisms for producing gamma rays?

Figure from Aliu et al. (2008)
e.g.: inverse-Compton scattering?
Typical Gamma-Ray Pulsar Spectrum

Characterized by a broad curvature radiation component with natural cut-off above some break energy

Figure from Abdo et al. (2013)
The Story of the First VHE Pulsar: The Crab
Crab Pulsar Review

Remnant of a supernova that occurred in 1054 AD

- Very young!

~2 kpc away; 3.4 pc across

Period: 33 ms

\[ \dot{E} = 4.6 \times 10^{38} \text{ erg/s} \] (highest spin-down power)
Crab Pulsar: MAGIC 2008

Crab pulsar detected >25 GeV!
- $3.4\sigma > 60$ GeV

Very high cut-off energy
- Favors outer-gap type model (emission site needs to be far from NS surface)

P1 and P2 seen to switch dominance

Aliu et al. (2008)
Aliu et al. (2008)
Crab Pulsar: VERITAS 2011

VERITAS detection >100 GeV (6.0σ from $H$-test)!

$\Gamma = -3.8 \pm 0.5$

Now curvature radiation scenario very unlikely

Aliu et al. (2011)
Crab Pulsar: MAGIC 2011

Crab pulsar seen up to ~100 GeV

MAGIC and VERITAS data combined consistent with simple power-law extension of spectrum

\[ \Gamma = -3.4 \pm 0.5 \]

“Even with the systematic uncertainties taken into account, the inconsistency between the extrapolated *Fermi*-LAT spectrum and the observations by MAGIC is significant.”

Aleksić et al. (2011)
Also tested for variability:

Compared two light curves:
- One from 07/08 season (top)
- One from 08/09 season (bottom)

Simple $\chi^2$ test reveals no significant difference

Aleksić et al. (2011)
Crab Pulsar: MAGIC 2014

Detection of bridge emission >50 GeV
° ~135 hr exposure

Ratio of bridge / P1 flux increases with energy

More complicated light curve -> another complication for modelers

Aleksić et al. (2016)
Crab Pulsar: MAGIC 2016

Crab pulsar now seen > 1 TeV!
- ~320 hr exposure

P1 & P2 show no signs of “cutting-off;” simple power laws
- Lower limit cut-off placed @ 700 GeV
- Multiple acceleration mechanisms unlikely

Seems to imply inverse-Compton scattering must be at work

Ansoldi et al. (2016)
Crab Pulsar: VERITAS 2015

Crab pulsar not seen >700 GeV?
  - ~200 hr exposure

Only 2σ above 400 GeV (see light curve; next slide) – a bit of a puzzle

P1+P2: 14.3σ total

Γ = -3.5 ± 0.5
PSRB0531+21 Phaseogram with energies > 400 GeV
Other VHE Pulsar Results:

Vela
Geminga
PSR J1023+0038
The Vela Pulsar seen by H.E.S.S.-II down to below 20 GeV

A. Djannati-Ataï, for the H.E.S.S. Collaboration
APC-CNRS, Paris
H.E.S.S. II Observations

- 2012 upgrade of H.E.S.S.: Addition of a 5th very large dish, CT5, 28m equiv. diameter
- Vela pulsar data:
  - 24 h of commissioning data
- To achieve the lowest threshold
  - Data kept only from CT5
  - Dedicated monoscopic reconstruction pipeline
- Signal of >15000 events with a significance > 15 s.d. from the second peak P2
- P1, P3 show some excess but are not significant - expected from Fermi-LAT
- P1/P2 decreases with increasing E

![Graph showing data and analysis results](image)

20 GeV

![Graph showing effective area vs. true energy](image)
Commissioning using *Fermi-LAT*

- Detailed comparison to expected signal using Fermi-LAT (P8) data $> 10$ GeV as input
- Power law with $\Gamma = -4.1$
- Very good agreement of low-level reconstructed parameters, e.g. $N_{\text{measured}}/N_{\text{expected}} = 0.84 \pm 0.08 \pm 0.22$
- **40% of detected events have**
  - **True Energy** $< 20$ GeV
  - H.E.S.S. II power-law fit:
    - $\Gamma = -4.1 \pm 0.2$
    - in excellent agreement
  - Curved fit (log parabola):
    - compatible with Fermi but no fit improvement ($<1$ s.d.)
- Second pulsar detected from ground-based observations
- Spectrum of P2 derived above 20 GeV (reco units) in perfect agreement with Fermi-LAT (4-years of data)
- Error box includes 30% systematic error: under investigation
- The curved nature of P2 is not excluded by the H.E.S.S. II measurement
Geminga Pulsar Review

Second-brightest steady gamma-ray source seen by the *Fermi*-LAT

First radio-quiet pulsar discovered

Not so young, but bright: $\tau_c = 300\text{ kyr}$, $\dot{E} = 3.3 \times 10^{34}\text{ erg/s}$

Period: 237 ms

Distance: $\sim 200\text{ pc}$ (also nearby)

https://www.nasa.gov/images/content/365529main_Fermi_pulsar_map_labels_HI.jpg
Geminga Pulsar: VERITAS

VERITAS exposure: ~72 hrs

<table>
<thead>
<tr>
<th>Peak</th>
<th>#Signal</th>
<th>#Background</th>
<th>α</th>
<th>#Scaled Background</th>
<th>#Excess</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>284</td>
<td>1578</td>
<td>0.176</td>
<td>278.9</td>
<td>5.0</td>
<td>0.28σ</td>
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<tr>
<td>P2</td>
<td>211</td>
<td>1578</td>
<td>0.141</td>
<td>223.7</td>
<td>-12.7</td>
<td>-0.80σ</td>
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<tr>
<td>P1+P2</td>
<td>495</td>
<td>1578</td>
<td>0.318</td>
<td>502.6</td>
<td>-7.6</td>
<td>-0.29σ</td>
</tr>
</tbody>
</table>

No detection!
No detection > 100 GeV with VERITAS

Aliu et al. (2015)
Aliu et al. (2015)
Geminga Pulsar: MAGIC

MAGIC exposure: ~75 hrs

<table>
<thead>
<tr>
<th>Energy range (GeV)</th>
<th>P1</th>
<th>P2</th>
<th>P1 + P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥50</td>
<td>0.2σ</td>
<td>−0.1σ</td>
<td>0.1σ</td>
</tr>
<tr>
<td>50–100</td>
<td>−0.2σ</td>
<td>0.2σ</td>
<td>0.0σ</td>
</tr>
<tr>
<td>100–200</td>
<td>0.7σ</td>
<td>−1.4σ</td>
<td>−0.3σ</td>
</tr>
</tbody>
</table>

No detection!
Ahnen et al. (2016)
PSR J1023+0038: VERITAS

Identified as a Low-mass X-ray binary (LMXB) with accretion disk in 2001 (Thorstensen & Armstrong 2005)

Later, optical and X-ray observations revealed disappearance of accretion disk -> now millisecond pulsar (MSP) state (Woudt et al. 2004)

June 2013: radio pulsar disappears, accretion disk reforms (Halpern et al. 2013)

No steady or pulsed detection!
What Can We Learn from Fermi-LAT?

By eye, power-law fits to LAT data $>10$ GeV seem to describe data well
  - But stat. errors are large
  - Cannot confirm no curvature

Still, the brightest Fermi-LAT-detected pulsars can (and have) guided IACT observations

Figure from Lyutikov (2013)
Fermi Pulsar Stacking

115 Fermi-LAT-detected pulsars stacked & analyzed for excess >50 GeV

- Li & Ma (eqn 17) significance of all pulsars stacked shown ->

Average of 4.2 yr of data per pulsar

No significant excess seen >50 GeV

- Other subsets analyzed: just young pulsars, MSPs – no significant excess in any subset

\[ E_{tot}^b = \sum_{i=1}^{N} (N_{on}^{i,b} - \alpha^{i} N_{off}^{i,b}) \]
What Does the Crab Pulsar @ VHEs Mean for Theory?
One Idea:

IC scattering occurs off the pulsed, softer (e.g. IR, X-ray) photons by wind particles.

Wind becomes particle-kinetic dominated far from NS (teal box 20-50 LC radii across) where $e^+ e^-$ are accelerated and up-scatter the photons.

Aharonian et al. (2012)

Same prediction (blue-dot curve) to get emission up to 1 TeV will not work for lower E points.
Another Idea:

Synchrotron-self-Compton (SSC) scattering in a possible large current sheet
- Synchrotron power law up to few 100s of GeV
- SSC presents as an extra component thereafter

But, does not reproduce the Crab pulsar light curve...
Final Thoughts

VHE pulsars represent an active area of research

Vela has joined the Crab pulsar in being detected by an IACT
  ◦ However, just two detections limits what can be learned

The “recent” Crab pulsar detection at VHEs has posed a challenge for magnetospheric models
  ◦ Too early to tell with Vela – curvature could be present in spectrum, even though it extends up to VHEs

Exciting upper limits are being set (e.g. Geminga, PSR J1023+0038)

The future: pulsar observations with next-gen CTA
Thank You!