Measurement of a Cosmic-ray Electron Spectrum with VERITAS

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Cosmic-Ray Electrons and Positrons at TeV Energies

- Electrons are a unique probe of our local Galaxy - they lose energy very quickly via IC and synchrotron processes during propagation.

- Prior to HESS, all measurements of CR electrons came from satellites and balloon measurements.

- Ground-based electron measurements can extend spectra out to higher energies:
  - much higher effective area (by 5 orders of magnitude \( \sim 10^5 \text{ m}^2 \))
  - large systematics:
    - atmospheric fluctuations/models
    - hadronic interaction models
  - high background rates
Cosmic-Ray Electrons and Positrons

The current results point to the existence of a positron rich excess that could be explained in several ways:

- Cosmic ray diffusion/interaction models are wrong (or need to be better pinned down)
- Local emitter that produces positrons, like a nearby pulsar or SNR
- Positron production by particle dark matter

From Marco Cirelli, ICRC 2015
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The signature of a single (or few) source of TeV CREs is predicted to show up 1-10 TeV

→ Additional measurements needed of both the positron fraction + all electron spectra in this energy range

<table>
<thead>
<tr>
<th>SNR</th>
<th>Distance (kpc)</th>
<th>Age (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 185</td>
<td>0.95</td>
<td>1.8 x 10³</td>
</tr>
<tr>
<td>S147</td>
<td>0.80</td>
<td>4.6 x 10³</td>
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<tr>
<td>HB 21</td>
<td>0.80</td>
<td>1.9 x 10⁴</td>
</tr>
<tr>
<td>G65.3+5.7</td>
<td>0.80</td>
<td>2.0 x 10⁴</td>
</tr>
<tr>
<td>Cygnus Loop</td>
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<td>2.0 x 10⁴</td>
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<tr>
<td>Vela</td>
<td>0.30</td>
<td>1.1 x 10⁴</td>
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<tr>
<td>Monogem</td>
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<td>8.6 x 10⁴</td>
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<td>Loop1</td>
<td>0.17</td>
<td>2.0 x 10⁵</td>
</tr>
<tr>
<td>Geminga</td>
<td>0.4</td>
<td>3.4 x 10⁵</td>
</tr>
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</table>
Four 12 meter diameter telescopes
(106 m² total mirror area each)
• Fully operational since 2007
• Multiple upgrades: T1 move in 2009, L2 + PMT replacements in 2011/2012
*** We use 2009–2012 data here ***
• Energy range: ~100 GeV – 30 TeV
• Energy resolution: 15–25%
• Angular Resolution: < 0.1 deg at 1 TeV
• Pointing accuracy error < 50"

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Electrons, Gammas, Protons at VERITAS

- Hadronic showers are much less uniform than EM showers.

- Electrons and gammas showers imaged at VERITAS are very similar → γs become a background, avoid by data selection (extragalactic pointings, exclude regions around any γ-ray candidate).

- Statistically, electrons and gammas have a ~1/2 radiation length difference of first interaction (pair production), this is one of the only differences.

D. Staszak, 2016 ICHEP
Electron Analysis Method

- In the standard analysis method at VERITAS, the background is sampled and subtracted from within the field of view (background including CR electrons, gamma-like hadron events, etc.)

- One of the most discriminating cuts we have is the direction cut

- In an electron analysis these advantages are lost, electrons are a diffuse/isotropic source

- Solution: analyze the full field of view using a machine learning algorithm

\[ \gamma \text{-ray source candidate} \]

Background regions

**Input image and energy reconstruction variables into boosted decision trees**

- MSCW
- MSCL
- EChl2
- EmissionHeight

Solid blue – proton MC or data, shaded orange – electron MC
Data Selection & Hadronic Model

- Extragalactic fields + remove any candidate gamma-ray sources, stars

- Stringent cuts to the data
  - Require 4 telescope images
  - Inner 1 degree of VERITAS field of view
  - Pristine weather conditions, no moonlight data
  - Reconstructed core radius <200m

- **296 hours of data remains**, sampling much of the celestial sphere visible to VERITAS

- BDTs determine for each event a 'BDT Response', 1.0: signal-like, -1.0: background-like

- Comparison of this data and proton MC yields good agreement except at the limits of the BDT response distribution (QGSJetII + URQMD).
Fitting Method: *Extract nElectrons & nProtons in a given energy bin*

- Binned likelihood fit of the data: Fit the relative contributions of proton MC and electron MC distributions to the total (fraction of e/p floats)

- Note the truncated x-axis, this is in effect an analysis cut to focus on the electron dominated region

- We can neglect contributions of helium and higher-Z elements to first order (sufficiently discriminated by the BDTs)

- Red is the Fit, Orange is Gamma MC, Green is Proton MC
Bin-by-bin Fitting: Perform fits for each energy bin to extract number of electrons, form a spectrum

Divide data in a given bin up into several trials (experiments) to estimate the statistical uncertainty on electron fraction in the data – mean value and the error on that mean.
• VERITAS measurement covers ~300 GeV to ~5 TeV

• Best fit yields a $-3.2 \pm 0.1_{\text{STAT}}$ ($-4.1 \pm 0.1_{\text{STAT}}$) spectral index below (above) the energy cutoff at $710 \pm 40$ GeV

• Systematical uncertainty is dominated by the ~20% uncertainty on the VERITAS absolute energy scale
VERITAS CRE Spectrum

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Additional Cross-checks investigated:

- CRE spectrum using SIBYLL proton event generator is within systematical uncertainties
- CRE spectrum without BDTs (simply using existing machinery to fit the distributions of most discriminating variable) agrees within systematical uncertainties
Conclusions:

• The VERITAS CRE spectrum qualitatively agrees with prior satellite- and ground-based measurements within systematical uncertainty

• Second high statistics measurement of a cutoff in the all-electron spectrum just below ~1 TeV

• Provides further evidence of at least one local high energy CRE emitter

• Can't rule out significant contamination from gamma-rays due to the similar nature of electron and gamma showers

• For the future – more data on disk so we will continue to push towards higher energies
Backups...
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