Analyzing the unprecedented gamma-ray flare from the blazar VER J0521+211

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Columbia Nevis Labs REU Program, Summer 2022
Outline

Background
- Why study gamma rays?
- What is VERITAS?
  - IACTs, Physics of Air Showers
- Gamma-ray sources: AGNs/Blazars

Motivation
- The Blazar VER J0521+211
- Project goal

Methods
- Stages of VERITAS analysis (VEGAS)

Results
- Analysis of VER J0521+211

Summary & Next Steps
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Summary & Next Steps
Why study gamma rays?

- Allows us to study the most energetic events in the universe
  - Strong gravitational & magnetic fields
- Indirectly aids search for cosmic ray sources

HE (~30 MeV - 300 GeV)
VHE (~30 GeV - 300 TeV)

Image credits: “The electromagnetic spectrum and its transmittance through Earth’s atmosphere”, NASA
IACTs, Air Showers

- Gamma rays cannot fully penetrate atmosphere
  - Air showers
  - Pair production and bremsstrahlung radiation
- Imaging atmospheric Cherenkov telescopes (IACTs)
  - Can image the Cherenkov light produced by the relativistic particles
- Can trace origin of incident gamma rays
- Cosmic rays also induce air showers

Image credits: “Atmospheric Cherenkov telescopes for high-energy γ-ray astronomy”, VERITAS Collaboration
What is VERITAS?

- Very Energetic Radiation Imaging Telescope Array System
- Array of four ground-based telescopes
- Observes VHE gamma rays from ~85 GeV - 30 TeV
- Located at Fred Whipple Observatory in Arizona
Gamma-ray sources: AGN/Blazars

- **Active Galactic Nuclei (AGN):** Central SMBH outshines rest of galaxy
  - High energy emission originates from plasma jets
- **Blazars:** Class of jetted AGN directed towards us
  - Majority of sources detected by VERITAS
  - Relativistic beaming
    - Superluminal motion
    - High luminosity
    - Fast variability
  - BL Lac vs. FSRQ
Superluminal motion

Image credits: Hubble image of M87 jet (left); "Superluminal motions in astronomical sources", Michael Richmond (right)
Superluminal motion

\[ D = \text{distance from observer at point A} \]

\[ v = \beta c = \text{actual velocity of blob} \]

\[ \Delta \tau = \text{time to move from point A to B} \]

\[ \Delta x = \text{transverse motion (what we observe)} \]

\[ = v \Delta \tau \sin \theta \]

\[ = \beta c \Delta \tau \sin \theta \]

\[ \Delta y = \text{motion towards observer} \]

\[ = \beta c \Delta \tau \cos \theta \]

Superluminal motion

Apparent time measured by the observer:
\[\Delta\tau_{\text{apparent}} = \Delta\tau(1 - \beta \cos\theta)\]

Apparent velocity measured by the observer:
\[
\beta_{\text{apparent}} = \frac{\Delta x}{c \Delta\tau_{\text{apparent}}} = \frac{\beta \sin\theta}{1 - \beta \cos\theta}
\]

Maximized when: \[\cos\theta = \beta \text{ or } \theta = 1/\Gamma\]

(Small angles and actual velocity close to speed of light)
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Summary & Next Steps
The Blazar VER J0521+211

- Blazar discovered by VERITAS in 2009
- BL Lac (IBL)
- Highly variable on daily timescales
- Redshift lower limit: $z > 0.18$
- Recent gamma-ray flare in February 2020

Image credits: http://tevcat.uchicago.edu/
Project goal

- Analyzing gamma-ray flare from the blazar VER J0521+21
  - Generate sky maps, spectra, light curves
  - Characterize brightness and speed of flare
  - Calculate size of emission region
  - Additionally, plot light curves in years after the flare
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Summary & Next Steps
Stages of VERITAS analysis (VEGAS)

Stages: [1]

1. **Calibration calculation**: Raw data → Calibration data
2. **Calibration application**: Raw + calibration data → Calibrated events
3. **Image parameterization**: Calibrated events → Parameterized events
4. **Shower reconstruction**: Parameterized events → Reconstructed showers
5. **Event selection**: Reconstructed showers → Selected events
6. **Results**: Selected events → Stats and figures
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Summary & Next Steps
Strong statistical significance of VER J0521+211
Spectrum of VER J0521+211

Spectrum

\[ \frac{dN}{dE} \text{ (TeV}\ ^{-1}\ \text{m}^2\ \text{s}^{-1}) \]

\[
\begin{align*}
\chi^2 / \text{ndf} & : 4.97 / 4 \\
\text{Prob} & : 0.2904 \\
\text{Norm} & : 1.764e-07 \pm 8.462e-09 \\
\text{Alpha} & : 3.368 \pm 0.104 \\
\text{Beta} & : 0.4455 \pm 0.06399 \\
E_0 & : 1 \pm 0
\end{align*}
\]
Fast variability of VER J0521+211

2019-2020 Season

Flux > 350 GeV (m$^{-2}$s$^{-1}$)

Time (MJD)
Variability timescale & characterizing rise/fall time

\[ F(t) = F_0 e^{-(t-t_{\text{peak}})/t_{\text{decay}}} + F_{\text{const}} \]

\[ F(t) = \begin{cases} 
F_0 e^{(t-t_{\text{peak}})/t_{\text{rise}}} + F_{\text{const}}, & t \leq t_{\text{peak}} \\
F_0 e^{-(t-t_{\text{peak}})/t_{\text{decay}}} + F_{\text{const}}, & t > t_{\text{peak}}, \end{cases} \]
Constraining size of emission region

- Studying variability can help limit size of emission region
- Calculating size of emission region:
  \[ R < c \Delta t_{\text{min}} \frac{\delta}{1 + z} \]
  - Upper limit for radius of region: \( 1.44 \cdot 10^{17} \text{ cm} \approx 0.05 \text{ pc} \)
  - Results help with modeling the jet
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Summary & Next Steps
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- From analysis:
  - Strong significance detection of source
  - Variability on daily timescale
  - Constrain emission region size
- More refined analysis of 2020-2022 light curves needed
  - Different binning method?
  - This would also provide insight into connection with ejection of superluminal knots
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References
