Galactic Novae Simulations for the Cherenkov Telescope Array

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Outline

• Introduction
  – Why and how do we study VHE gamma rays?
  – What is the Cherenkov Telescope Array?
  – What are Galactic novae?

• Methods
  – How can we study Galactic novae with CTA?
  – What can we learn from these measurements?

• Results

• Conclusion & Outlook
INTRODUCTION
Motivation

• Why study high-energy gamma rays?
  – Understanding particle acceleration in extreme astrophysical environments (intense gravitational or magnetic fields)
    • Active Galactic Nuclei (AGN)
    • Supernova remnants
    • Gamma-ray bursts
      – As gravity wave follow-ups (see Sierra’s talk)
  • Galactic novae
    – Indirect search for dark matter
      • Gamma ray production from Weakly Interacting Massive Particle (WIMP) annihilation
Motivation

http://inspirehep.net/record/1425507/plots
Motivation

• Gamma rays collide with atmospheric nuclei
• Collision induces cascade of secondary particles
• Charged secondary particles emit Cherenkov radiation
• Detected by Imaging Atmospheric Cherenkov Telescopes (IACTs)
What is CTA?

• The Cherenkov Telescope Array
  – A next-generation ground-based γ-ray telescope array
• 2 arrays (one in each hemisphere) of multi-sized IACTs searching for gamma-induced air showers
• CTA specs
  – Order of magnitude improvement in sensitivity over existing instruments
  – Angular resolution approaching 1 arcminute at TeV energies
  – 8° field of view
The Cherenkov Telescope Array

**Low energies**
20 GeV – 1 TeV
23 m diameter
4 large-size telescopes

**Medium energies**
100 GeV – 10 TeV
9.5 to 12 m diameter
25 to 40 medium-size telescopes

**High energies**
5 - 300 TeV
4 to 6 m diameter
70 small-size telescopes
South only
What are novae?

- Classical novae originate in binary systems consisting of a white dwarf and typically a late-type main-sequence star.
- Material (mostly hydrogen and helium) accretes from the companion star onto the surface of the white dwarf.

[Diagram of a binary system with a white dwarf and a main-sequence companion, illustrating mass transfer and accretion.]
What are novae?

- The base of the accreted layer is compressed, causing the material to become degenerate.
- The temperature and accreted mass rise to a critical point, initiating nuclear burning and eventually a runaway thermonuclear chain reaction.

Credit: K. Ulaczyk / Warsaw University Observatory
What are novae? [video]

Credit: NASA/JPL-Caltech/T. Pyle (SSC)
Nova frequency/distribution

• A recent estimate puts the Galactic novae rate at $50^{\pm31}_{\pm23} \, yr^{-1}$ (Shafter, A.W. 2017)
• Novae remain luminous in gamma rays for 2-3 weeks
• Can reasonably expect that at least 1 nova will be gamma-ray active in the Galaxy at any point in time
• A catalog of observed novae places a strong concentration of towards the Galactic plane and bulge
Novae as γ-ray producers

• The \textit{Fermi} Large Area Telescope (LAT) detected > 100 MeV gamma rays from 5 classical novae

• Unexpected
  – The nova outflow needs something to collide with in order to accelerate particles via shocks
  – Symbiotic novae (also detected by the LAT) have a dense wind surrounding white dwarf
  – Classical novae do not

https://science.nasa.gov/toolkits/spacecraft-icons
Shocks in novae?

- Shocks could form in the presence of two distinct outflows
- Initial slow outflow with toroidal geometry
- Fast outflow with spherical geometry collides with it

(Metzger et al. 2015)
Shocks and gamma rays

• Suggestion that shocks in novae could be responsible for this emission
  – Theory from Metzger et al. (2015, 2016)
• Hadronic production via neutral pion decay

http://www.astro.wisc.edu/~gvance/index.html
**Fermi** detections

- *Fermi*-LAT has diminished sensitivity at higher energies
  - Difficult to resolve the shape of the spectrum
- Metzger et al. (2016) suggests that gamma-ray emission could in principle extend up to the energy ranges of IACTs

(Ackermann et al. 2014)
Fermi detections

(Ackermann et al. 2014)
Motivation

- Max particle energy is a function of the shock velocity and upstream gas density
- Shaded region is a rough expectation of nova properties

(Metzger et al. 2016)
Motivation

• Spectrum we measure has an $E_{\text{cutoff}} \sim \frac{E_{\text{max}}}{10}$

• At $E_{\text{max}} = 1\ TeV$, the SED falls within the predicted $5\sigma$ sensitivity of CTA for 0.5 and 5 hr integrations.

(Metzger et al. 2016)
Research questions

• Assuming that nova gamma-ray emission extends into the energy ranges where CTA is sensitive...
  – What is ability of CTA to detect V339 Del - like sources?
  – What additional constraints can CTA provide to complement Fermi-LAT novae detections?
  – At what distance could the CTA detect an average nova during a Galactic plane survey with 30 minute pointings?
METHODS
Deriving Models

\[ \frac{dN_\gamma}{dE} = k_0 \left( \frac{E}{E_0} \right)^\Gamma \exp\left( -\frac{E}{E_{\text{cut}}} \right) \]

• Modeling the differential photon flux with an exponentially cut-off power law (EPL)
  – Prefactor \( k_0 \) [ph cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\) ]
  – Spectral Index \( \Gamma \)
  – Cut-off Energy \( E_{\text{cut}} \) [MeV]
  – Scaling Energy \( E_0 \) [MeV]

• Fixed at 35 GeV for all studies
Deriving Models – V339 Del

Flat model
• Average the 5 significant data points from Fermi and derive a flat power law spectrum from it (— — — on plot)

Fit model
• Use the sloping fitted power law spectrum (— — on plot) from Fermi paper as the model

Add exponential cut-off terms to both models with cut-offs at 30 GeV and 100 GeV

(Ackermann et al. 2014)
Simulations

• Start with an assumed spectra as an input model
• Provide this model to the ctools software package to generate simulated events
• Use a binned likelihood fit of the events to produce spectral flux points
• Perform an unbinned likelihood fit of the events to fit a model and calculate a Test Statistics value for the simulation
Fitting Models

• Method of likelihood fitting performed on simulations
  – Fits the simulated events to an EPL model for the spectrum
    • Free parameters: $k_0$, $\Gamma$, $E_{\text{cut}}$
    • Want to see how well each of these parameters can be resolved
  – Out of this we can get a Test Statistic (TS) value
    • TS computed as a likelihood ratio test of the full model to the background model
    • Source significance $\sigma \sim \sqrt{TS}$
RESULTS
30m integration spectrum

Single sim – *flat* model with 100 GeV cut-off energy

- Run 29 data
- Input model
- Fitted model
- 1σ confidence band
50 sim average – flat model with 100 GeV cut-off energy
30m integration significance

Significance hist – flat model with 100 GeV cut-off energy

Entries: 50
Median: 15.19σ
30m integration spectrum

Single sim – *fit* model with 30 GeV cut-off energy
30m integration spectrum

50 sim average – fit model with 30 GeV cut-off energy

![Graph showing 50 sim average fitted model with 30 GeV cut-off energy]
30m integration significance

Significance hist – fit model with 30 GeV cut-off energy

Entries: 50
Median: 0.03σ
What can CTA add?

• What happens when we include the *Fermi*-LAT flux points when fitting our data?
  
  – From the fits, can use \( \frac{par_{err}}{par_{val}} \) (fractional uncertainty) as a metric for our ability to resolve the shape of the source.
What can CTA add?

**Single sim – fit model with 30 GeV cut-off energy**

- Fermi data
- Simulated CTA data
- Fermi + run 29 data
- Input model
- Fit model
What can the CTA add?

50 sim average – fit model with 30 GeV cut-off energy

$E^2 \times dN/dE$ (erg cm$^{-2}$ s$^{-1}$)

Fermi data

Simulated CTA data

Input model

Avg model fit
What can CTA add?

### CTA only – average fractional uncertainty of free parameters

<table>
<thead>
<tr>
<th>Sim type</th>
<th>Time</th>
<th>Input cutoff (GeV)</th>
<th>$k_0$ frac err</th>
<th>$\Gamma$ frac err</th>
<th>$E_c$ frac err</th>
<th># sims $TS &gt; 15$</th>
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- This table is produced using only simulations with $TS > 15$
- Some values have been excluded due to unreliable fitting
What can CTA add?

CTA + Fermi – average fractional uncertainty of free parameters

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<th>Input cutoff (GeV)</th>
<th>$k_0$ frac err</th>
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- Significant improvement in fitting precision across all simulations
- Comparison to initial *Fermi* EPL fit shows improvement of $\sim 10\%$ for $\Gamma$ and of $\sim 20\%$ for $E_{cut}$
  - Comes with the caveat that this result requires that novae gamma-ray emission extends into the 10-100 GeV range
Future Nova Detection

• Can model an average nova by using the average reported luminosity and spectral index for 5 *Fermi* detections

\[
\frac{L_\gamma}{4\pi d^2} = \int_{0.1}^{10 \text{ GeV}} E \frac{dN}{dE} dE
\]

• Can find a distance dependent $k_0$ using this equation
• Apply this to our models to see at what distances we can make detections
Future Nova Detection

- *Fit* model with a 30 GeV cutoff energy – 30 minute integration
  - Detectable within 2 kpc
- *Flat* model with a 100 GeV cutoff energy – 30 minute integration
  - Detectable within 8 kpc
    - Distance to the Galactic Center
CONCLUSION & OUTLOOK
Summary of results

• Except in cases of sufficiently high cutoff energies (~100 GeV), CTA alone is unlikely to detect novae even with triggered observations.

• However, CTA has considerable potential to contribute to complementary studies with the Fermi-LAT:
  – Particularly in improving the precision of measuring $E_{\text{cut}}$.
  – Puts constraints on $E_{\text{max}}$, which in turn can provide valuable insights into the environment of a nova.
    • Shock velocity, upstream gas density, etc.
Outlook

- Transient source prospect for Galactic plane survey (GPS)
  - GPS observation strategy revisits the Inner Galaxy on a weekly basis
  - If we were to model the distance distribution of nova in the Galaxy, can estimate how many could be detected as transient sources during a GPS
Acknowledgments

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• Thank you to the Nevis Labs REU Program and its administrative staff – John Parsons, Georgia Karagiorgi, Amy Garwood.
• Thanks to the many members of the CTA/VERITAS group and especially to my primary mentors, Dr. Brian Humensky and Deivid Ribeiro, for their support this summer.

• Questions?
CTA/VERITAS Group
Are these models realistic?

- The shock properties \((n, v_{sh}, \tau_{\nu-\nu})\) are likely to vary in time during the nova outburst, so a spectral cut-off measured at one epoch does not exclude a higher value of \(E_{\text{max}}\) at other times (Metzger et al. 2016)
  - \(n\): upstream photon density
  - \(v_{\text{sh}}\): shock velocity
  - \(\tau_{\nu-\nu}\): optical depth due to photon-photon absorption
Sensitivity

- $E^2 \times \text{Flux Sensitivity (erg cm}^{-2} \text{s}^{-1})$
- Differential flux sensitivity
- Energy $E_R$ (TeV)

- LAT Pass 8 (10y, 192h)
- MAGIC 50 h
- H.E.S.S. 50 h
- VERITAS 50 h
- HAWC 1 year
- HAWC 5 year
- CTA North 50 h
- CTA South 50 h
Angular resolution

Further optimization of event selection can improve the angular resolution!