Probing the Anomalous Flux of Very-high-energy Gamma rays from the Sun with HAWC

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Magnetic field of the Sun reverses the path of cosmic rays from ingoing to outgoing.
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The Sun at GeV: Brighter than expected!
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GAD4c: The Surprising Gamma Ray emission from the Sun (Kenny C. Y. Ng), SH5Ee (Zhe Li), DM1e (Davide Serine)

Phys. Rev. D, 95(12):123016, June 2017
Phys. Rev., D98(6):063019, 2018
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Theory
The Sun at GeV: Brighter than expected!

**Observation**

**Theory**

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**References**

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- **Observation**
- **Theory**

**Max. theoretical emission assuming 100% efficiency**

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**Graph Details**

- **Energy Flux [TeV cm$^{-2}$ s$^{-1}$]**
  - **10$^{-10}$**
  - **10$^{-11}$**
  - **10$^{-12}$**

**Energy [TeV]**

- **10$^{-3}$**
- **10$^{-2}$**
- **10$^{-1}$**
- **1**
- **10**
- **10$^2$**

**Fermi-LAT (Solar Min.)**

**Fermi-LAT (2014–2017)**

**ARGO-YBJ**

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**References**

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The Sun at GeV: Brighter than expected!

- Solar Minimum flux is much harder and brighter!
- Unforeseen measurement in a physically interesting range. Mechanism?
- TeV prospects?

Observation

Phys. Rev. D, 95(12):123016, June 2017
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High Altitude Water Cherenkov Observatory

One of the few TeV gamma-ray instruments taking gamma-ray data from the Sun
High Altitude Water Cherenkov Observatory

- 300 water tanks with 4 PMTs each (plus 350 Outriggers)

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High Altitude Water Cherenkov Observatory

- 300 water tanks with 4 PMTs each (plus 350 Outriggers)
- Area 22,000 m$^2$ (100,000 m$^2$)
- Trigger rate of 25 kHz
- 300 GeV to > 100 TeV
- 2/3 sky daily coverage

One of the few TeV gamma-ray instruments taking gamma-ray data from the Sun
HAWC presented its first constraints using data from 2015—2017 just after the solar maximum.
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HAWC should be able to constrain or detect this in the solar min.
Transitioning into the Solar Minimum

International sunspot number $S_n$: last 13 years and forecasts

- Daily
- Monthly
- Monthly smoothed
- SC Predictions
- CM Predictions

HAWC 3 YR

Sol Min.
How is the data changing from one solar cycle to the next?

Change in the intensity of Sun Shadow?

Towards a gamma-ray excess from the Sun?
Sun Shadow Jan 2018 — Dec 2018: Energy Proxy Bins 1—6
The Sun Shadow is deeper during the solar minimum

PRELIMINARY
RoI shadow
Potential Signal

Background
Potential Signal

Background

Shadow
Data Away from the Solar Minimum

PRELIMINARY

PRELIMINARY

PRELIMINARY

2015

2016

2017
2018 Data: Enter Solar Minimum

![Graph showing integrated excess (raw data) against radius with Solar Min Bin 1 marked.]

PRELIMINARY
Shadow Subtraction

• The gamma-ray signal is contaminated by the sun shadow.
• We should subtract an estimate of the shadow from the data.
• Use solar max shadow as a first guess.
• Note: this would still be an underestimate of the contamination because the solarmax shadow is not as deep as solar min.
• We know we are not over-subtracting.
• We use the gaussian fit to 2015–2017 data as our model of the shadow.
Before and after shadow subtraction
Upper Limits

Energy [ TeV ]

Energy Flux [ TeV cm⁻² s⁻¹ ]

CR Upper Bound

CR Lower Bound

PRELIMINARY

HAWC Sensitivity (Solar Min. 2018)
ARGO-YBJ (Solar Min.)
HAWC 95% C.L.(Solar Min. 2018)
Fermi-LAT (Solar Min.)
Upper Limits

Energy [ TeV ]

Energy Flux [ TeV cm$^{-2}$ s$^{-1}$ ]

HAWC 95% C.L. (2015–2017)
HAWC 95% C.L. (Solar Min. 2018)
Fermi-LAT (Solar Min.)

CR Upper Bound
CR Lower Bound
PRELIMINARY
Summary and Outlook

- HAWC is performing follow-up observations of the Sun during the solar minimum
- Interesting trends in the data with change in solar activity 😎
- Does the hard GeV gamma-ray spectrum continue into the TeV? Solar Minimum data in the upcoming months will yield decisive results. Stay tuned!
- Complements studies in neutrinos and models of solar dark matter.
- Will impact our understanding of CR transport in the inner solar system.
Backup
SolMin data - SolMax Shadow Model

Excess in rings of increasing radius
Net gamma-ray excess using shadow-wide RoI

Following the analysis method in our solarmax paper (Phys. Rev. D 98, 123011 (2018))