Observation of the Moon and Sun with the HAWC Observatory

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Outline

1. Using the MoonShadow to look for anti-protons in the cosmic ray spectrum.

2. Searching for TeV gamma rays from the Sun.
Direct measurements of p-bar/p

- AMS measurements up to 350 GeV
- Unexpected, constant ratio of p-bar/p
- Constant ratio of positrons to anti-protons
- Ongoing search for explanations and potential for HAWC to contribute.
- TeV limits
High Altitude Water Cherenkov Observatory
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- 4100 m above sea level
- Sierra Negra and Pico de Orizaba in Mexico
- 300 water tanks with 4 PMT’s each
High Altitude Water Cherenkov Observatory

- 4100 m above sea level
- Sierra Negra and Pico de Orizaba in Mexico
- 300 water tanks with 4 PMT’s each
- 2 sr instantaneous field of view
- Area 22,000 m²
- Trigger rate of 25 kHz
- Energy range 300 GeV to > 100 TeV
Charge discrimination with Moon Shadow

- Observed with high significance.

- Offset in RA described by, \( \delta \theta = 1.6^\circ Z \left( \text{TeV} / E \right) \)

- The deflection in \( \Delta \alpha \) shows that most of the CR flux consists of protons (\( Z = 1 \))

- In principle, negatively charged particles should cast a shadow in the opposite direction.
Searching for Antiprotons

➤ We fit the moon shadow with a 2d gaussian and take its centroid position to be the deflection, ∆R.A.

➤ Assume the map is a superposition of deficits due to protons and antiprotons.

\[ \delta I = \frac{N(\alpha_i, \delta_i) - \langle N(\alpha_i, \delta_i) \rangle}{\langle N(\alpha_i, \delta_i) \rangle} \]

➤ We describe it by a sum of two gaussians,

\[ S(x, y) = f_p(x, y) + f_{\bar{p}}(x, y) \]

➤ The ratio of the amplitudes of the two functions \( \sim \frac{\bar{p}}{p} \)

\[ f_i(x, y) = A_i \exp \left(-\frac{(x - x_0)^2}{2\sigma_x^2} - \frac{(y - y_0)^2}{2\sigma_y^2}\right) \]

➤ Quantity of interest \( \frac{A_{\bar{p}}}{A_{p}} \)
Fitting the moon shadow

- MCMC fit
- Bayesian calculation. Tried different combinations of free and fixed parameters to get the most robust fit.
- Widths of the shadows $\sigma$, centroids $x_0$ and $y_0$ and the amplitudes $A_p$ and $A_{p-bar}$.
- Uniform priors constrained within physical boundaries.
95% Credible Limits on $p$-bar/$p$

Anti-proton to proton ratio as function of energy

Preliminary
Upper Limits and Previous Measurements

Anti-proton to proton ratio as function of energy

Preliminary
Outlook

- Light component (p/He) separation from heavier elements not yet accomplished.
- Limits likely to improve with more data and can be extended beyond 10 TeV.
- Strongest yet available limits in the > 1 TeV range.
- In the absence of direct measurements, these can be used to constrain propagation scenarios, energy losses for galactic CR, local sources and dark matter annihilation/decay.
Part 2
TeV Gamma Rays from the Sun
Production Mechanisms

- Hadronic interactions
- Cosmic rays scattering in the sun’s atmosphere.
- Solar disk component 0.5°
- Inverse Compton scattering of cosmic ray electrons
- Leptonic component halo up to 10° in diameter.
- Hadronic cosmic rays will also be accompanied by neutrinos

*Observed in GeV in FERMI data.*
Detection Prospects

The Sun is a bright source of GeV gamma rays, due to cosmic rays interacting with solar matter and photons. Key aspects of the underlying processes remain mysterious. The emission in the TeV range, for which there are neither observational nor theoretical studies, could provide crucial clues. The new experiments HAWC (running) and LHAASO (planned) can look with unprecedented sensitivity. In this paper, we predict the very high energy (up to 1000 TeV) gamma-ray flux from the solar disk and halo, due to cosmic-ray hadrons and electrons, respectively. We neglect solar magnetic effects, which is valid at TeV energies; at lower energies, this gives a theoretical lower bound on the disk flux and a theoretical upper bound on the halo flux. We show that the solar-halo gamma-ray flux allows the first test of the $\sim 5–70$ TeV cosmic-ray electron spectrum. Further, we show HAWC can immediately make an even stronger test with non-directional observations of electron cosmic rays. Together, these gamma-ray and electron studies will provide new insights about the local density of cosmic rays and their interactions with the Sun and its magnetic environment. These studies will also be an important input to tests of new physics, including dark matter.

I. INTRODUCTION

The Sun is a passive detector for cosmic rays in the inner solar system, where direct measurements are limited. It shines in gamma rays from its disk and from its use halo [1–6]. Disk emission is expected due to cosmic-ray hadrons interacting with solar matter, which produces pions and other secondaries whose decays and interactions lead to gamma rays. Halo emission is expected due to cosmic-ray electrons interacting with solar photons via inverse-Compton scattering. There are no other important astrophysical mechanisms for steady solar gamma-ray production; solar-flare gamma rays are episodic, and are observed up to only a few GeV [7–10].

Gamma-ray observations thus open the possibility of detailed cosmic-ray measurements near the Sun. The hadronic and leptonic components can be distinguished because the disk and halo emission can be separated by direction. Further, the energy spectra of the cosmic rays can be inferred from the gamma-ray spectra, which can be measured over a wide energy range. This would give a significant advance compared to typical satellite detectors in the inner solar system, which only measure the energy-integrated all-particle flux, e.g., Refs [11,12].

Further, gamma-ray data can trace the full solar cycle, testing how solar modulation of cosmic rays depends on energy and position [13,14].

Figure 1 shows that the prospects for measuring TeV solar gamma rays are promising. The solar-disk fluxes measured in the GeV range with Fermi data [5,6] are high, and naive extrapolation suggests that HAWC and LHAASO may detect gamma rays in the TeV range. Further, the GeV observations are significantly higher than the theoretical prediction of Seckel, Stanev, and Gaisser [1], who proposed a compelling mechanism by which the solar-disk gamma-ray flux could be enhanced.

Reference: Ng et al. arXiv:1612.02420
Energy Evolution of the Sun Shadow

Scaled Relative Intensity at 1.1 TeV

Scaled Relative Intensity at 1.7 TeV

Scaled Relative Intensity at 5.0 TeV

Scaled Relative Intensity at 17.2 TeV

Scaled Relative Intensity at 51 TeV

Scaled Relative Intensity above 142 TeV
Preliminary search for gamma excess

No significant gamma excess near the sun

For details of gamma-hadron separation please see arXiv:1701.01778
Computing upper limits

Get $\gamma$ counts in each bin in a 5° region around the sun.

Get expected number of counts from a sun-like source accounting for HAWC detector response and $g/h$ separation.

Estimate the observed flux in each bin and compute 95 CL limits.

$$F(E) = A(E/E_p)^{-i}$$

Assumptions:
1. Point Source
2. No time-dependence
3. Constant dec

Problem
Changing Position of the Sun above HAWC

Sun Elevation in HAWC: 12 May 2017 - 13 May 2017

Sun Elevation in HAWC: 1 Jan 2016 - 31 Dec 2016
Upper Limits on Sun Gamma Flux at different declinations

![Graph showing differential flux versus energy in TeV.](image)

- **HAWC 95% CL**: δ band for Jan, July, March, May, Nov, Sep
- **Fermi data extrapolation**
- **Ng 2016 observation**

**PRELIMINARY**
Upper Limits on Sun Gamma Flux at different declinations

γ-rays from the Sun

Differential flux [TeV⁻¹ cm⁻² s⁻¹]

energy [TeV]

HAWC 95% limits: δ band for Jan
HAWC 95% limits: δ band for July
HAWC 95% limits: δ band for March
HAWC 95% limits: δ band for May
HAWC 95% limits: δ band for Nov
HAWC 95% limits: δ band for Sep
Fermi data extrapolation
Ng 2016 observation

PRELIMINARY
• First upper limits from HAWC on TeV gamma rays from the Sun
• Very simplified analysis. The limits can be made stronger.
• Further analysis in progress: Developing tools to take into account a moving source of gamma rays.
• Back-tracing cosmic rays in the IMF and geomagnetic fields on a GPU cluster.
• Implications for constraining important physical processes including B-field induced flux enhancements, cosmic ray mass composition near the knee and dark matter annihilation in the Sun.
• Prospects for multi-messenger astronomy with neutrino counterparts.