Exploring the Sun-Galaxy connection with GeV gamma rays

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Cosmic rays and us

Questions

• What does the magnetic field structure in the (inner) solar system really look like, and why?

• How do cosmic rays propagate through the (inner) solar system?

(Maps onto two Scientific Goals from the 2013 Decadal Survey in Solar and Space Physics)
Sun as a detector of (Galactic) cosmic rays

Target

Beam

charged particles

NASA/ESA
### Leptonic Cosmic Rays: Inverse Compton (IC)

- Photons only
- Extended
- 1 GeV-range peak comes from: \( E \sim \gamma^2 E_{\odot,\text{photon}} \)

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Moskalenko, Porter, Diegel 2006
Orlando, Strong 2008

Orlando, Strong 2008
Hadronic Cosmic Rays

Gammaray energy ~1/10th of primary

For neutrinos, see Gerrit Roellinghoff’s IceCube talk at WIN2021 this week: https://indico.fnal.gov/event/4449/2/

Figure 1: High energy cosmic rays (blue) are not deflected by solar magnetic fields (black). They only produce observable gamma rays when they hit the edge of the Sun. Lower energy cosmic rays (green) are deflected by solar magnetic fields. This allows the cosmic rays to first be reflected and then interact, making the entire solar disk shine in gamma rays. However, at energies relevant to Fermi, cosmic-ray trajectories are twisted by solar magnetic fields. This allows cosmic rays to be reflected before interacting with the solar atmosphere. In this case, where the whole solar disk generates observable gamma rays, the flux is thus enhanced compared to the case without magnetic-field effects.

Our current understanding of gamma rays from the Sun is far from satisfactory. The Fermi collaboration detected the Sun with 1.5 years of data ([2], Abdo2011). Surprisingly, Abdo2011 found that the Sun is almost ten times brighter than predicted by SSG1991. This large unexplained discrepancy demands one to revisit the theories of cosmic rays interacting with the Sun. With new data and new theoretical insights, much important science can be done with high-energy observations of the Sun. This is the main motivation of my proposed study: To complete the observational study of the solar gamma rays, to improve the theoretical understanding of gamma-ray production processes, and to pursue the implications for physics and astronomy.
What are the observations telling us?

What new questions do the observations raise?
Peeling the first onion layer: IC

First 18 months of Fermi mission, Cycle 23/24 solar minimum

Inner heliosphere

Abdo+ 1104.2093 Fermi-LAT collaboration
Peeling the first onion layer: IC

First 18 months of Fermi mission, Cycle 23/24 solar minimum

Inner heliosphere

No modulation
Force field modulation

Abdo+ 1104.2093 Fermi-LAT collaboration
Peeling the first onion layer: IC

Inner heliosphere

11 years of Fermi-LAT data

E < 1 GeV prefer LARGE modulation

E > 1 GeV prefer NO modulation

Stay tuned.

Linden+ 2012.04654
Solar disk high-energy $\gamma$-ray flux with Fermi-LAT and HAWC

- **Cycle 24 minimum Fermi observation**
- **Original disk prediction by Seckel, Stanev & Gaisser (SSG1991)**
- **2014-2017 Fermi observation**
- **Lower bound on disk emission, in the limit of no B fields (Zhou+ 2017)**
- **Unexplained (inexplicable?) dip in the energy spectrum.**
- **Upper bound if no modulation, every GCR makes an outgoing $\gamma$ ray.**
- **2014-2017 HAWC analysis. We are getting prepped for the Cycle 25 minimum analysis.**
- **Sensitivity of future facilities**

Modified from Nisa+ 1903.06349
The center: hadronic observations

Linden et al. 1803.05436
The center: hadronic observations

Linden+ 2012.04654
The center: hadronic predictions

- No magnetic fields.
- No photospheric fields but include the corona.
- Include the photospheric fields but not the corona above 1000 km.
No magnetic fields

Fermi data points from Linden+ 2012.04654

Overshoot
B = 0, CRs isotropic

Undershoot

Fermi 11.4-yr data

Predicted $\gamma$ flux

$\pi^0$ bump

Zhu et al., in prep.

Fermi data points from Linden+ 2012.04654
w/corona but no photosphere

PFSS model during solar min and solar max

Becker Tjus+ 1903.12638
w/corona but no photosphere

See Mehr’s talk for this!

Li+ 2009.03888
w/photosphere B but no corona

Propagation and interaction in chromo/photosphere

Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

Seckel, Stanev, 1992

Zhu et al., in prep.
Hints with corona + photosphere together

Mazziotta+ 2001.09933
Summary of weird stuff we can’t explain
(because no predictions fully work)

• Why IC prefers different force-field modulation at different energies.
• “Dip” in gammas at ~40 GeV (hadrons).
• The overall hardness of the energy spectrum but for the dip.
• Time variability of the energy spectrum.
• Spatial morphology of gamma-ray emission.
• Differences in last two solar minima?
Going forward

Probably B fields at all scales (inner heliosphere, corona, solar atmosphere, photosphere) matter to more-or-less similar degrees to explain the observed properties.

New collab with solar/space physicists (Cohen, Sokolov) + our OSU-based team.

From Ofer Cohen
Cosmic ray shadow

Protons 0.3-100 TeV

FIG. 1. Year-to-year variation of the observed Sun's shadow between 1996 and 2009. Each panel displays a 2 dimensional contour map of the observed flux deficit ($D_{\text{obs}}$). The map in 2006 is omitted because of insufficient statistics for drawing a map.

The modal energy of the Tibet-II array configuration are estimated to be 0.9° and 10 TeV, respectively. For the analysis of the Sun's shadow, the number of on-source events ($N_{\text{on}}$) is defined as the number of events arriving from the direction within a circle of 0.9° radius centered at the given point on the celestial sphere. The number of background or off-source events ($\langle N_{\text{off}} \rangle$) is then calculated by averaging the number of events within each of the eight off-source windows which are located at the same zenith angle as the on-source window [12]. We then estimate the flux deficit relative to the number of background events as $D_{\text{obs}} = (N_{\text{on}} - \langle N_{\text{off}} \rangle) / \langle N_{\text{off}} \rangle$ at every 0.1° grid of Geocentric Solar Ecliptic (GSE) longitude and latitude surrounding the optical center of the Sun.

Shown in Fig. 1 are yearly maps of $D_{\text{obs}}$ in % from 1996 to 2009. We exclude the year of 2006 due to low statistics. Inspection of Fig. 1 shows that the Sun's shadow is considerably darker (with larger negative $D_{\text{obs}}$) around 1996 and 2008 when the solar activity was close to the minimum, while it becomes quite faint (with smaller negative $D_{\text{obs}}$) around 2000 when the activity was high.

III. MC SIMULATION

We have carried out Monte Carlo (MC) simulations to interpret the observed solar cycle variation of the Sun's shadow. For the primary cosmic rays, we used the energy spectra and chemical composition obtained mainly by direct observations [10, 13–15] in the energy.

More w/HAWC and Tibet coming soon.