PROCEEDINGS OF SCIENCE

Surprising variation of gamma rays from the Sun over the Solar Cycle revealed by Fermi

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The steady-state gamma-ray emission from the Sun arises from interactions with Galactic cosmic rays and consists of two components: (1) a hadronic disk component and (2) a leptonic component peaking at the solar edge and extending into the heliosphere. Their flux is expected to vary with the 11-year solar cycle, peaking at solar minimum due to the higher cosmic-ray flux. However, no previous study has separately analyzed the temporal evolution of these components over multiple solar cycles.

This work focuses on investigating the flux variation of each component over 15 years of Fermi Large Area Telescope observations and has been originally published in Acharyya et al 2025 ApJL 989 L1 [1]. We analyze their temporal evolution and compare the results with the sunspot number and Galactic cosmic-ray flux from AMS-02. We confirm that the disk component anticorrelates with solar activity and correlates with cosmic-ray protons, supporting the expected emission mechanism. The extended component also exhibits variability with the solar cycle, but its behavior suggests a more complex cosmic-ray transport and modulation in the inner heliosphere than previously assumed or hints at the presence of an additional, unknown gamma-ray or cosmic-ray source.

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1. Introduction

The Sun is recognized as a source of steady-state gamma-ray emission in its quiet phase, that is, in the absence of flares or from non-flaring regions [2]. This emission arises from two primary processes associated with interactions between Galactic cosmic rays (CRs) and the solar environment: (1) a hadronic disk component, generated by CR proton collisions in the solar atmosphere leading to pion decay, and (2) a spatially extended leptonic component, produced by Inverse Compton (IC) scattering of CR electrons on solar photons ([3–5]).

Both components are theoretically expected to vary over the 11-year solar cycle, anticorrelating with solar activity (as indicated by sunspot number) and correlating with CR fluxes near Earth [6], [7] . The disk emission is confined to the solar disk, while the IC component forms a broad halo peaking at the solar limb. While previous studies [8] confirmed gamma-ray flux variations over the cycle, no work had yet disentangled and analyzed the flux variability of the two components separately across multiple solar cycles.

Our study addresses this gap by using 15 years of Fermi-LAT observations, enabling, for the first time, a separate temporal analysis of the solar disk and extended components throughout Solar Cycle 24 and the start of Cycle 25 [1].

2. Method

We analyzed 15 years of Fermi Large Area Telescope (LAT) data (2008–2023) covering 70 MeV to 70 GeV gamma rays. The LAT's wide field of view (2.4 sr at 1 GeV) and uniform sky exposure every 3 hours enabled daily monitoring of the Sun [9].

2.1 Data selection

We used Pass 8 SOURCE class events and excluded periods of South Atlantic Anomaly passage, zenith angles $>90°$, and times when the Sun was close to the Galactic plane, Moon, or bright sources (e.g., Crab, Geminga). Solar flares were removed using LAT catalogs [11] and a custom procedure that identified and excluded time bins with transient flux increases $>5\sigma$ above average. This ensured a clean dataset, albeit reduced by approximately 55%.

2.2 Background evaluation

To account for diffuse and isotropic background and weak sources along the ecliptic, we applied the "fake Sun" method [12], analyzing seven control positions following the Sun's path at different times. The background model was derived through binned maximum likelihood fits [13], with systematic uncertainties on solar fluxes estimated at 3%.

2.3 Solar component analysis

We modeled the Sun's gamma-ray emission as:

- **Disk component:** confined within 0.265° radius (solar disk), representing hadronic CR interactions.

- **Extended component:** inverse Compton emission decreasing inversely with angular distance from the Sun, following IC models [2] [5] [20].

Both components' spectra were fitted with log-parabolic functions and convolved with LAT's energy-dependent point spread function. The fluxes were extracted over 2-year overlapping intervals and analyzed for correlations with sunspot number, CR proton and electron fluxes [21] [22], using Pearson and z-transformed discrete correlation functions.

3. Temporal variation results

We measured separately the temporal variations of the solar disk and extended γ-ray components over 15 years of Fermi-LAT observations (2008–2023). The dataset was divided into 2-year subsamples, shifted by 6 months, and analyzed with a binned likelihood approach in a moving solar frame. Flux variations were then compared with the sunspot number (SSN) and cosmic-ray (CR) fluxes from AMS-02.

The disk flux above 250 MeV, 500 MeV, and 1 GeV shows consistent variations of ±40% with respect to the average value (see Fig. 1a). As expected for hadronic emission, the flux anticorrelates with solar activity (Fig. 1b) and correlates with the CR proton flux measured near Earth (Fig. 1c). A similar trend is observed with the lunar flux (Fig. 1d). These results confirm the hadronic origin of the disk emission and the consistency of CR modulation at Earth and at the Sun.

The extended component shows larger variations (from –60% to +40%) with higher systematic uncertainties (Fig. 2a). Unlike the disk, it does not display a clear anticorrelation with SSN or correlation with CR electron flux over the full dataset (Figs. 2b–c). Only in the early years (2008–2012) do we observe the expected anticorrelation with SSN and correlation with the disk flux (Fig. 2d). After 2012, the behavior becomes more complex, with no significant correlation with either SSN or CR electrons. This unexpected trend suggests that CR transport and modulation within 1 au are more complicated than currently modeled and may depend on solar magnetic polarity.

4. Discussion and Conclusions

Over more than one solar cycle, *Fermi–LAT* observations have enabled us to track the temporal evolution of the two quiet-Sun γ-ray components, separating the hadronic disk emission from the spatially extended inverse-Compton (IC) halo [2–5, 7, 9]. For the disk, we confirm a robust anticorrelation with solar activity and a clear correlation with the near-Earth cosmic-ray (CR) proton flux, in line with expectations for hadronic production on the solar surface; the trend is consistently mirrored by the lunar γ-ray variability, reinforcing the common CR origin [10, 12, 21]. Within our energy range, the fractional variability is approximately energy-independent above a few hundred MeV, a behavior suggestive of the role of the solar magnetic field in shaping the temporal response [6, 20].

The extended component exhibits larger variations and a more complex behavior. During the early part of our baseline it follows the anticipated anticorrelation with solar activity and correlates with the disk flux, but these relations weaken (or break down) afterwards; moreover, no robust

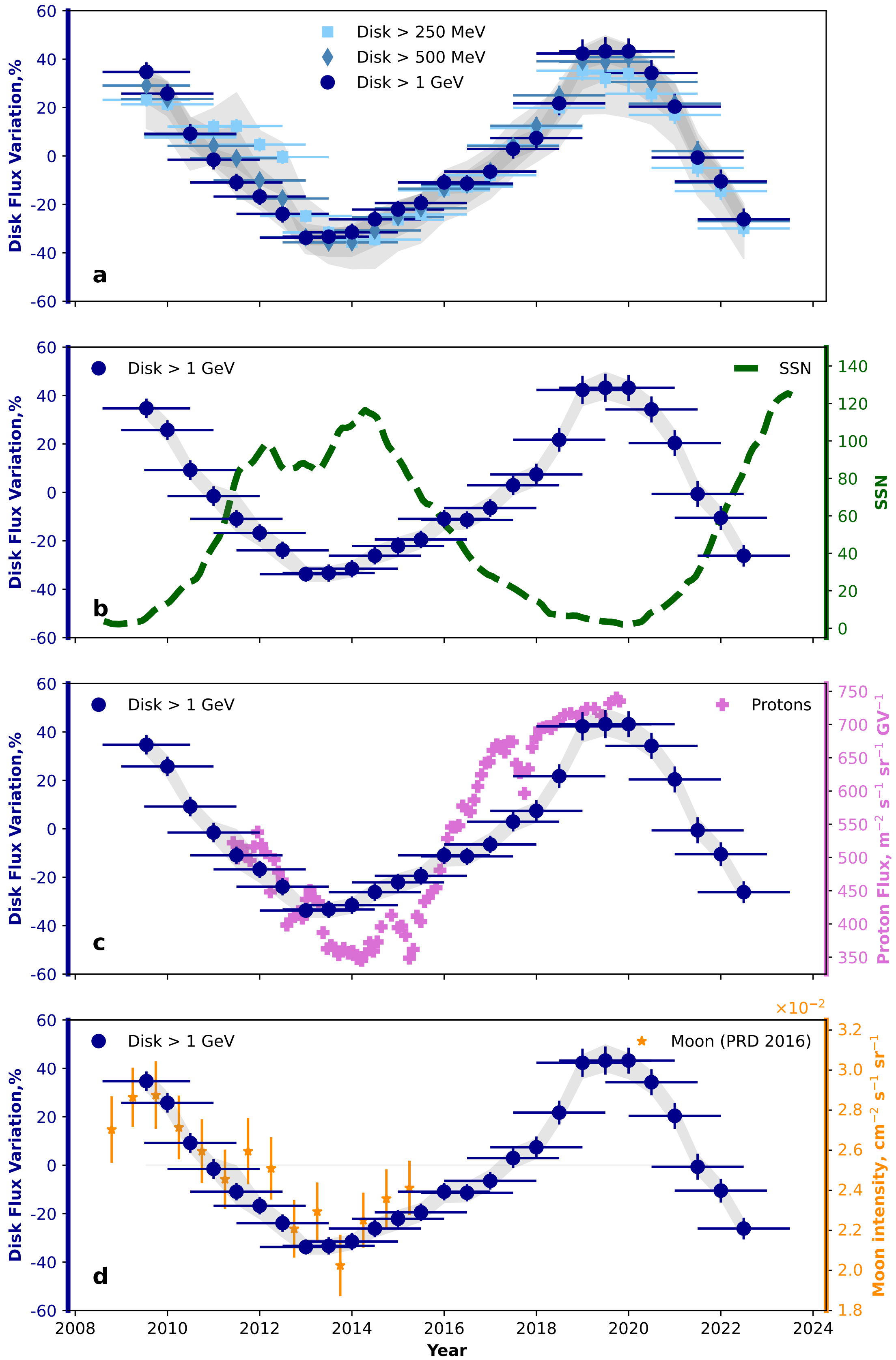

Figure 1: Panel (a): Percentage of the flux variation of the solar disk component above 25 MeV, 500 MeV, and 1 GeV versus time in year. The gray regions define systematic uncertainties. Panel (b): flux variation in time of the solar disk component above 1 GeV compared with the SSN. Panel (c): flux variation in time of the solar disk component above 1 GeV compared with the CR proton flux at 2.14–2.4 GV [21]. Panel (d): flux variation in time of the solar disk component above 1 GeV compared with the Moon's flux above 56 MeV [10].

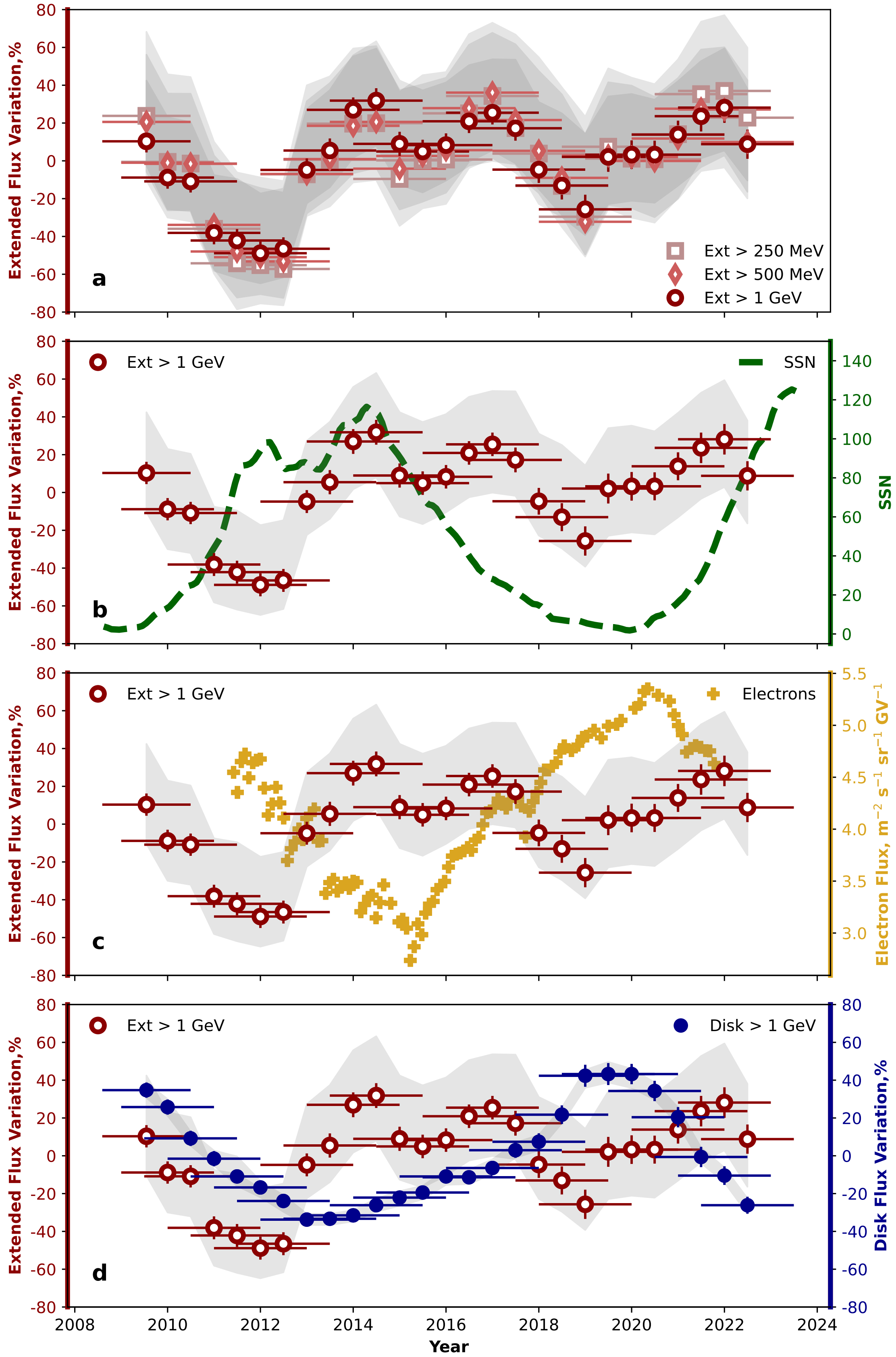

Figure 2: Panel (a): Percentage of the flux variation of the solar extended component above 250 MeV, 500 MeV, and 1 GeV versus time. The gray region defines systematic uncertainties. Panel (b): flux variation of the solar extended component above 1 GeV compared with the SSN. Panel (c): flux variation of the solar extended component above 1 GeV compared with the CR electron flux at 1.00 1.71 GV [22]. Panel (d): flux variation of the solar extended component above 1 GeV compared with the flux variation of the disk component above 1 GeV.

correlation with the CR electron flux is found over the full time span, despite sizeable variations and larger systematics than for the disk [1, 22]. This pattern departs from simple IC-only expectations in which the halo is set by CR electrons scattering solar photons and modulated over the cycle, and it points to transport and modulation effects within $\lesssim$1 au that depend on the evolving large-scale magnetic topology and, potentially, on the polarity and charge-sign drifts [5, 20].

These results add to a growing body of evidence that the quiet-Sun emission encodes physics beyond steady, IC-only interpretations. Prior studies reported spectral and morphological features at GeV energies that are difficult to reconcile with the simplest scenarios, further suggesting additional ingredients in particle transport and/or γ-ray production near the Sun [8]. Phenomenological and theoretical work has begun to explore such possibilities—including polarity-dependent transport, time lags between CR populations, [14–18] and additional components in the inner heliosphere—with scenarios directly relevant to our findings [19].

In this context, models calibrated in the outer heliosphere should not be extrapolated to the inner heliosphere without accounting for polarity-dependent transport and electron energy losses close to the Sun [20]. Continued *Fermi–LAT* monitoring during Solar Cycle 25, combined with contemporaneous AMS-02 proton/electron fluxes and multi-wavelength constraints (e.g., X-ray synchrotron probes of electron populations), will be essential to discriminate among scenarios and to quantify possible polarity-driven effects in the extended solar γ-ray emission [1, 21, 22].

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