Cosmic-Ray Propagation Around the Sun – Investigating the Influence of the Solar Magnetic Field on the Cosmic-Ray Sun Shadow

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Abstract. The cosmic-ray Sun shadow, which is caused by high-energy charged cosmic rays being blocked and deflected by the Sun and its magnetic field, has been observed by various experiments such as Argo-YBJ, HAWC, Tibet, and IceCube. Most notably, the shadow’s size and depth was recently shown to correlate with the 11-year solar cycle. The interpretation of such measurements, which help to bridge the gap between solar physics and high-energy particle astrophysics, requires a solid theoretical understanding of cosmic-ray propagation in the coronal magnetic field. It is the aim of this paper to establish theoretical predictions for the cosmic-ray Sun shadow in order to identify observables that can be used to study this link in more detail.

To determine the cosmic-ray Sun shadow, we numerically compute trajectories of charged cosmic rays in the energy range of 5 to 316 TeV for five different mass numbers. We present and analyse the resulting shadow images for protons and iron, as well as for typically measured cosmic-ray compositions. We confirm the observationally established correlation between the magnitude of the shadowing effect and both the mean sunspot number and the polarity of the magnetic field during the solar cycle. We also show that during low solar activity, the Sun’s shadow behaves similarly to that of a dipole, for which we find a non-monotonous dependence on energy. In particular, the shadow can become significantly more pronounced than the geometrical disk expected for a totally unmagnetized Sun. For times of high solar activity, we instead predict the shadow to depend monotonously on energy, and to be generally weaker than the geometrical shadow for all tested energies. These effects should become visible in energy-resolved measurements of the Sun shadow, and may in the future become an independent measure for the level of disorder in the solar magnetic field.

Keywords: cosmic rays – magnetic fields – Sun: activity – Sun: magnetic field
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1 Introduction

Cosmic rays being blocked by the Sun, as first proposed in [1], are an interesting topic for the investigation of cosmic-ray properties. In particular, it was predicted that the interactions of cosmic rays with the Sun would result in gamma- and neutrino-production that would eventually be detectable (see [2]). Even cosmic-ray electrons were predicted to produce a halo component in gamma-rays. Today, the gamma-ray signatures can indeed be measured: the halo component has been verified at an intensity level as expected by the prediction in [2], see [3, 4]. The disk component, however, was found to be an order of magnitude higher than expected [5], a discrepancy that could still not be resolved in the literature. The neutrino signal that accompanies the disk component has been re-calculated in the past few years [6–8], as it is now an important background for dark-matter searches with neutrino telescopes from the direction of the Sun. See also [9] for a general discussion of the possibilities of using the Sun as a laboratory for astroparticle physics.

The proper modeling of the cosmic-ray component itself only became important in recent years when ground-based detectors started to detect the shadow of the Sun in cosmic rays produced by their interactions with the solar surface and corona. The Tibet AS-Gamma experiment was the first to demonstrate that the cosmic-ray Sun shadow varies with time, in correlation with the variation of the sunspot number [10]. As the latter is in turn correlated with the magnetic field strength and structure, these measurements were first to prove an effect of cosmic-ray deflection in the inner heliospheric field on the Sun shadow. Most recently, a similar study at higher energies ($\langle E_{\text{CR}} \rangle \sim 40$ TeV) has been performed with the IceCube detector [11], and a general temporal variation of the cosmic-ray Sun shadow was verified. A correlation with the sunspot number, however, could not be validated yet because the solar cycle during the time of the measurements (2010/2011 – 2014/2015) did not vary enough to allow for a statistically significant statement [12]. The HAWC collaboration [13, 14] also observed a deficit of cosmic rays from the direction of the Sun for the years 2013 and 2014 between 1 TeV and 142 TeV. A study of the variability of the Sun shadow could, however, not be presented yet. In the upcoming years, different experiments are expected to be able to probe the variation of the cosmic-ray Sun shadow with the solar magnetic field in a broad energy range and with a better time resolution.

It is the aim of this paper to investigate which effects are present and how the cosmic-ray shadow varies with time in the $\sim 5$ TeV to $\sim 316$ TeV energy range based on numerical calculations of particle propagation. Our studies are particularly aimed at the quantification of the energy behavior of the Sun shadow. While Tibet, IceCube, and HAWC measurements present results at different energies, they are not comparable at this point for two central reasons: (1) the Sun shadow is presented on the event level and therefore, the individual measures for the shadow cannot be compared directly; (2) measurements are not necessarily performed during the same year/solar cycle. Thus, this study is aiming for a first theoretical investigation of the energy behavior in order to make a prediction if and how observatories could study cosmic-ray propagation in even more detail. With the high statistics level reached with Tibet, IceCube, and HAWC, this should certainly be possible in the future.

The propagation of cosmic rays can generally be modeled by using either an ensemble- or a single-particle approach. The collective behavior of the many-particle approach is typically applied in diffusive regimes in which the gyro-radii of the particles are small compared to the system size, such that a high number of interactions with the turbulent magnetic field for particle trajectories in the considered volume is expected, see, e.g. [15]. This type of
particle propagation is particularly useful for Galactic cosmic-ray propagation. Sophisticated simulation schemes have been developed during the past decades. In particular resulting in the propagation tool frameworks GALPROP, see e.g. [16–18] and newer propagation software, such as DRAGON [19], which is capable to address questions of anisotropy, PICARD [20], and CRPropa 3.1 [21]. In the solar environment, the gyro-radius of TeV particles is large relative to the extent of the region. Thus, a ballistic (single-particle) treatment, as is also used for extragalactic propagation with CRPropa [22], is a reasonable approach here. For reasons of efficiency, a back-tracing scheme is set up in which anti-particles are propagated toward the Sun.

This paper is organized as follows: In Section 2, some general properties and the modeling of the solar magnetic field are discussed. Afterwards, we describe the details of the numerical propagation, the weighting scheme, and the final analysis quantifying the strength of the Sun shadow (Section 3). The results obtained are then presented in Section 4, followed by a summary (Section 5) and an outlook (Section 6).

2 The Solar magnetic field

In this section, we summarize some general properties of the solar magnetic field (see section 2.1), followed by the details of the implementation used in this work (see section 2.2).

2.1 General properties

The Sun goes through a cycle of approximately 11 years during which the solar magnetic field varies in strength and structure. At the beginning of each cycle, the magnetic field strength is minimal and the magnetic field near the solar surface can approximately be described by a dipole field which gets deformed into a radial field by the solar wind with increasing radius. After five to six years, the magnetic field strength reaches its maximum and the dipole structure disappears. In this period of time, the structure is highly irregular and also changes on the timescale of solar rotation [e.g. 23]. After a total of approximately 11 years, the structure returns to a dipole structure with reversed polarity. Measurements show that maxima and minima of solar magnetic activity correlate with maxima and minima of the sunspot number, see e.g. [24, 25]. Figure 1 shows the sunspot number from 2007 through 2017 covering the analyzed time frames. Since our aim is to qualitatively compare our results to the IceCube measurements reported by [11], we define a season to consist of the months November through February of each Antarctic summer. The magnetic field strength at the solar surface is measured using observatories on Earth or in space. Such measurements are called magnetograms and are produced for each Carrington rotation (CR).

2.2 Implementation

The Global Oscillation Network Group (GONG) [27] provides integral synoptic magnetograms, which we use in order to extrapolate to a full three-dimensional magnetic field using different models. Here, we use the Potential Field Source Surface (PFSS) model [28, 29]. The magnetic field is computed using the FDIPS software [30], which allows the user to define parameters, such as the grid resolution at which the field will be computed or the so-called source surface radius $R_{\text{SS}}$ at which the magnetic field is assumed to be purely radial. More details can be found in, e.g., [31]. The result are field components on a spherical grid equidistant in the radius $r$, longitude $\phi$, and the sine of the co-latitude $\vartheta$. Here, we choose $R_{\text{SS}} = 2.5R_\odot$. For $r > R_{\text{SS}}$ the magnetic field is implemented as purely radial and with a magnitude decreasing
Figure 1. The sunspot numbers taken from [26] and averaged over the four months of each season are shown for a ten-year time period. The seasons 07/08 and 08/09 report a low sunspot number, while in seasons 11/12, 12/13, 13/14 and 14/15 a higher number has been detected, before decreasing again afterwards. This approximately describes the solar activity cycle of 11 years, see, e.g. [25].

proportional to the inverse square of the distance. This implementation neglects angular components of the magnetic field as present in the Parker spiral model [32]. However, we restrict our study to a region close to the Sun in which these angular components do not contribute significantly to the deflection of the tracked particles (compare section 3.1). An alternative approach for extrapolating from magnetograms to a three-dimensional solar magnetic field is the CSSS model [33], which additionally uses a so-called cusp surface located at a cusp radius $R_{cp}$. Beyond this radius, all field lines are assumed to be open. In both the PFSS and the CSSS model, field lines are assumed to be purely radial at $r > R_{SS}$.

3 Simulation of the Sun shadow

The basic setup of our simulation framework includes the solar magnetic field and anti-particles that are traced back in the vicinity of the Sun. The back-tracing ensures that only those particles are considered that propagate in the direction of Earth after they have traversed the magnetic field (those particles, in turn, are relevant for the cosmic-ray Sun shadow observed at Earth).

The Sun shadow is determined by defining a quadratic, planar injection window with a side length of four solar radii, located at a distance of five solar radii from the Sun’s center and arranged such that it is parallel to the $yz$-plane of the Heliocentric Earth equatorial (HEEQ) coordinate system, i.e. it is parallel to the Sun’s rotation axis and perpendicular to the intersection of the solar equator and the solar central meridian as seen from Earth.
For simplicity, we will assume the solar rotational axis to be perpendicular to the ecliptic, thus neglecting the Sun’s obliquity of 7.25° throughout this paper.

This injection window is uniformly filled with an equidistant, rectangular grid of \( N = 100^2 = 10^4 \) starting points of anti-particles. The initial momentum vector of a given anti-particle \( i \) points along a straight line from a virtual point on the \( x \)-axis at \( x = 1 \) AU to the anti-particle’s starting point \( \vec{x}_i(0) \), where \( 1 \leq i \leq N \). In other words, the point of divergence of the initial directions of all anti-particles is at the position of the Earth. An example of the shadow picture of an anti-proton (\( |Z| = 1 \)) with an energy \( E = 40 \) TeV for December 2014 (Carrington rotation CR2158) is shown in Figure 2.

![Figure 2](image)

**Figure 2.** A schematic view of the simulation setup (distances not to scale). Starting points of anti-particles as indicated by the blue bubbles are arranged in the injection window. Timing information for the trajectories of the anti-particles is given in color code. The starting points of those anti-particles hitting the Sun are removed from the plot. This way, the cosmic-ray deficit caused by the Sun is simulated using back-tracing.

### 3.1 Computation of particle trajectories

In general, the relativistic equation of motion for a particle of rest mass \( m \) under the influence of an external force \( \vec{F} \) is given by

\[
\vec{F} = \frac{d}{dt}(\gamma(v) m \vec{v}) .
\]  

(3.1)
In this equation, \( \vec{v} \) is the velocity and \( \gamma \) is the Lorentz factor. The motional electric field at radius \( r \) is of order \( r \Omega B \), with the solar angular rotational speed \( \Omega \). Comparing this to the \((\vec{v} \times \vec{B})\) term due to the Lorentz force shows a ratio of \( r \Omega / c \). Since this ratio is on the order of \( 10^{-5} \), we assume that the particles passing through the solar magnetic field are only affected by the Lorentz force. And since the latter cannot change \( \vec{v} \) in magnitude because it is perpendicular to it, the Lorentz factor is constant and thus unaffected by the time derivative. With that, the equation of motion becomes

\[
\frac{d\vec{v}(t)}{dt} = \frac{q}{\gamma m} \left( \vec{v}(t) \times \vec{B} \right) \quad \text{with} \quad \frac{d\vec{x}(t)}{dt} = \vec{v}(t),
\]

with \( \vec{x} \) and \( q \) denoting the location and the charge of the particle. The equation of motion (3.2) is solved numerically using the so called Boris Push method [35] (see also [36]). The main advantage of the Boris Push method as compared to other standard methods like the Runge-Kutta-based Cash-Karp method is the conservation of energy for the case that there are no electric fields (which is shown in [37]). Also its relatively short computing time compared to Runge-Kutta algorithms with comparable accuracy is beneficial. Given the initial conditions \( \vec{x}(t_0) \) and \( \vec{v}(t_0) \), \( \vec{v}(t_0 + \Delta t) \) and \( \vec{x}(t_0 + \Delta t) \) can be determined as follows:

\[
\vec{l} = \frac{qB \Delta t}{2\gamma m},
\]

\[
\vec{s} = \frac{2\vec{l}}{1 + |\vec{l}|^2},
\]

\[
\vec{v}' = \vec{v}_\perp(t_0) + \vec{v}_\perp(t_0) \times \vec{l},
\]

\[
\vec{v}(t_0 + \Delta t) = \vec{v}(t_0) + \vec{v}' \times \vec{s},
\]

\[
\vec{x}(t_0 + \Delta t) = \vec{x}(t_0) + \vec{v}(t_0 + \Delta t) \Delta t
\]

(and analogously for all following time steps), where \( \vec{v}_\perp \) denotes the component of \( \vec{v} \) perpendicular to \( \vec{B} \).

### 3.2 Simulation tests

Various tests of increasing complexity have been conducted prior to the actual runs presented in the ensuing sections in order to confirm the proper operation and reliability of our code. From those tests, we present the noteworthy example of a dipolar magnetic field. This exercise is useful because its results will help us to understand and interpret the ones of the actual Solar magnetic field, for which a dipole is often used as a crude approximation.

Our test setup consists of an ensemble of mono-energetic protons (charge \(+e\), mass \(m_p\)) being deflected in the magnetic field

\[
\vec{B} = -\nabla \left( \frac{\vec{p} \cdot \vec{r}}{r^3} \right) = \frac{3\vec{r}(\vec{p} \cdot \vec{r})}{r^5} - \frac{\vec{p}}{r^3}
\]

of a dipole with magnetic moment \( \vec{p} = p \vec{e}_z \) and strength \( p = B_{\text{dip}} R^3_\odot \), such that the magnetic field strength at the equator \((x^2 + y^2 = R^2_\odot, z = 0)\) equals exactly \( B_{\text{dip}} = 1 \, \text{G} \). Normalizing all lengths to \( R_\odot \) and speeds to light speed \( c \), we obtain

\[
\frac{d\vec{v}}{dt} = \eta \, \vec{v} \times \vec{B} \quad \text{with} \quad \eta = \frac{ZeB_0 c R_\odot}{\gamma m_p c^2} \approx 20.88 \frac{Z B_0 \, [\text{G}]}{E_{\text{kin}} \, [\text{TeV}]}
\]
Figure 3. Shadow maps for mono-energetic protons in the magnetic field of a dipole, using the example of $E_{\text{kin}} = 3$ TeV (left) and $E_{\text{kin}} = 12$ TeV (right), and $100 \times 100$ particles in each case. Green squares represent the starting points of particle trajectories intersecting the solar surface. The shadow-to-disk ratio amounts to 0.787 for the left case and 1.516 on the right. To guide the eye, blue circles indicate projected radii of $1 \, R_{\odot}$ (solid) and $R_{\text{SS}} = 2.5 \, R_{\odot}$ (dashed). Note that for the right plot, the lateral half-length $d$ of the quadratic injection window was decreased from $d = 1.5^\circ$ to $d = 0.8^\circ$ for improved resolution.

(in which dimensionless quantities are denoted by a bar and normalization constants with a lower index '0') as the dimensionless form of Equation (3.2). We may thus easily identify $\eta$, which is proportional to the normalization field strength divided by the particle’s (unchanging) rigidity, as the only external parameter of relevance in this case. For protons in a static field, it is therefore sufficient to vary only the particle energy between different simulations.

Figure 3 shows shadow maps obtained in this way for two specific energies. Somewhat surprisingly, we see that, as opposed to what might have been expected in view of previous observations showing the Sun’s shadow diminishing with increased magnetic activity, the shadow’s total area may in fact exceed that of the solar disk considerably at certain energies. Figure 4 summarizes the relative shadow size $s$ as a function of the particle energy employed in each simulation. Here, the shadow size is determined as the total shadow area as seen in green color in Fig. 3, divided by the area of the solar disk when projected onto the injection window. We see that, as expected, this ratio approaches unity for very large energies (or very small field strengths) because trajectories are then almost straight lines tracing the geometrical, circular shape of the projected Sun. Interestingly, we may also confirm that the shadow size does in fact increase toward smaller energies, reaching a maximum of about 185 percent of the geometrical disk area before declining again. But only at comparatively low energies does this value decrease below unity as the shape of the shadow starts to break apart, and would finally dissolve beyond recognition as it fragments into smaller and smaller “islands.”

This simple example may serve to illustrate that, at least for large-scale magnetic fields, the shadow may not necessarily become less pronounced with increasing energy, but may in fact get amplified considerably compared to the case of a non-magnetized shadow-casting
Figure 4. Total shadow area $s$ as a function of particle energy for the dipolar field (3.8), normalized to the area of the geometrical disk. The two arrows indicate the respective energy values of 3 and 12 TeV, for which shadow images are shown in Figure 3. The respective side length $2d$ of the injection window was chosen as $3.0^\circ$ ($1.6^\circ$, $1.0^\circ$) for $E \in [1, 10]$ ([10, 20], [20, 100]) TeV to optimize spatial resolution while at the same time keeping the field of view large enough not to lose any “shadow particles.”

obstacle. We will come back to this phenomenon in section 4.3.

3.3 Models of the primary cosmic-ray spectrum and composition

For the energy spectrum and composition of the simulations, we use the model from Gaisser [38] with a mixed extragalactic component (hereinafter called HGm model) and from Gaisser & Honda [39] (hereinafter called GH model).

3.4 Passing probability and weighting scheme

In order to mimic the rotation of the solar magnetic field within a Carrington rotation, which has a synodic rotation period of $\sim 27.3$ days, a total of 36 calculations is performed revolving the injection plane (instead of the solar magnetic field) in steps of $10^\circ$ around the rotation axis of the Sun. To quantify how likely it is for a particle with energy $E$ and atomic number $Z$ coming from direction $i$ to pass the Sun without hitting its surface, we then define the passing probability $p$ of a specific Carrington rotation CR as the number $n_{\text{pass}}$ of angular steps for which the particle passes the Sun, divided by the total number $n_{\text{tot}} = 36$ of angular steps:

$$p_{i,Z,E,\text{CR}} = \frac{n_{\text{pass}}}{n_{\text{tot}}}. \quad (3.10)$$

This is done for the nuclei of hydrogen, helium, nitrogen, aluminum, and iron with particle energies of $10^{1.0}$, $10^{1.6}$, and $10^{2.2}$ TeV (corresponding to 10, $\sim 40$ and $\sim 158$ TeV). Particles
with higher energies are neglected due to their lower particle flux. We run our computations for the Carrington rotations approximately covering the time window between November and February of each season, since only in between these months does the IceCube detector observe the cosmic-ray flux from a window around the Sun, considering the seasons 2007/2008 to 2016/2017.

The result for each set of atomic number and energy is weighted corresponding to its abundance based on the $HGm$ model (see section 3.3). Assuming that the calculated Sun shadow does not vary considerably within an energy range of $\pm 0.3$ in $\log(E)$, we obtain the weighting factors $g_{Z,E}$ by integrating the energy spectra in an integration interval from $10^{2-0.3}$ TeV to $10^{2+0.3}$ TeV for all mentioned energies and atomic numbers. Using these weighting factors, the weighted arithmetic mean of all sets of energy and atomic number is determined for each Carrington rotation (CR) according to

$$\bar{p}_{i,CR} = \frac{\sum_{Z,E} p_{i,Z,E,CR} \cdot g_{Z,E}}{\sum_{Z,E} g_{Z,E}}.$$  \hspace{1cm} (3.11)

In the last step, the mean of $\bar{p}_{i,CR}$ for all Carrington rotations and the corresponding standard deviation are determined.

### 3.5 A quantitative measure for the shadow depth

In order to quantify the calculated shadowing effect of the Sun for a particular Carrington rotation, we compare the computed shadow size with that of an unmagnetized object with the Sun’s size and shape. Since each particle will hit the solar surface with average probability $1 - \bar{p}_{i,CR}$, we expect a total of $N - \sum_{i} \bar{p}_{i,CR}$ particles to contribute to the shadow. With $R_S \equiv \arctan[R_\odot/(1 \text{ AU})] \approx 0.27^\circ$ as the angular radius of the Sun as seen from Earth, the angular area (solid angle) covered by the solar disk amounts to $\pi R_S^2$. Since the injection area of size $\omega \equiv (4R_S)^2$ contains $N$ evenly distributed starting positions, $(\pi R_S^2/\omega)N = (\pi/16)N$ shadowed events are expected from an unmagnetized object with the Sun’s size and shape. The normalized net shadowing effect for one Carrington rotation can therefore be quantified using the ratio

$$s_{CR} = \frac{N - \sum_{i} \bar{p}_{i,CR}}{(\pi R_S^2/\omega)N} = \frac{1}{\pi} \left( 1 - \frac{1}{N} \sum_{i} \bar{p}_{i,CR} \right).$$  \hspace{1cm} (3.12)

In particular, a ratio of $s_{CR} = 1$ would mean that the shadow’s size/depth is equivalent to geometrical shadowing by an unmagnetized Sun. As the last step, the mean of those ratios

$$s = \frac{1}{n_{CR}} \sum_{CR} s_{CR}$$  \hspace{1cm} (3.13)

for the Carrington rotations considered is calculated. The uncertainty of $s$ is calculated as the standard deviation of the ratios of the different Carrington rotations.

### 4 Results

The passing probabilities (compare section 3.4) are visualized on a two-dimensional grid in longitude and latitude. The passing probability for each bin is represented by a color, with
darker colors representing smaller and lighter colors representing larger passing probabilities. A passing probability of 1.0 in a specific bin means that every particle from that bin passed the Sun unimpeded, while a passing probability of 0.0 means that every particle hit the Sun. Two examples for resulting shadow plots can be seen in Figure 5. For reasons of readability,

![Figure 5](image)

**Figure 5.** Examples of visualizing the calculated Sun shadow: shown are the 2008/2009 (left; year of least solar activity) and 2014/2015 (right; year of most solar activity) seasons using the energy spectrum and composition according to the *GH* model.

shadow plots related to the following sections are put into section A in the appendix. For studying the shadow numerically, the shadow size ratio $s$ as described in section 3.5 is used.

### 4.1 Sun shadow as a function of mass number

In Figure 6, the shadow for December 2015 can be seen at $E = 40$ TeV and for all different nuclei that were simulated. As expected, the deflection of particles increases with increasing atomic number (decreasing rigidity). In Figure 7 the ratio $s$ can be seen for pure proton, pure iron, and a mixed composition according to the *Hgm* model for the years from 2007 through 2017. Some obvious features can be seen from the Figures: First of all, as expected, the hydrogen shadow is much more focused and less fragmented as compared to the heavier components. Fragmentation and spread is increasing with increasing charge $Z$. The full shadow plots, displayed in the appendix in Figures 16 and 17 also reveal that the measure

![Figure 6](image)
for the shadow, $s$, is globally smaller for iron than for proton. In addition, the differences between the seasons are less pronounced for iron than for protons. The picture expected in the real world is expected to be proton-dominated up to PeV-energies, as the cosmic-ray spectrum itself is dominated by hydrogen. A detailed investigation of the true Sun shadow follows in the following sub-sections.

**Figure 7.** Calculated Sun shadow size ratio in the years from 2007 through 2017 for pure proton, pure iron, and a mixed composition according to the $HGm$ model.

### 4.2 Sun shadow as a function of energy

In Figure 8, the shadow depth $s$, calculated as described above, is displayed for the three different energies. Each data point contains contributions by all five elements that were simulated with a composition according to the $HGm$ model. As expected, the points for $E = 10$ TeV overall show the smallest $s$, indicating a weaker shadow, while the points for $E = 158$ TeV overall show the largest $s$, indicating a stronger shadow. Besides that, the separation between the energies becomes stronger for seasons with high solar activity (season 11/12 until season 15/16). This is also expected, as the effect of increasing magnetic activity, and, in turn, magnetic field strength, is stronger the lower the energy of a particle is. In Figure 18, 19, and 20, the full shadow plots can be seen for the different energies. In agreement with the numerical results, the shadow becomes more disk-like for higher energies, yielding $s$ values close to unity, while it shows a distinct temporal variation at lower energies, resulting in a smearing of the shadow in seasons with high solar activity. In Figure 9 and 10, the calculated $s$ is plotted for all 15 different combinations of energy and mass number for the season 08/09 and 14/15, respectively. These seasons were chosen as respective examples for periods with notably low and high solar activity (compare Figure 1). For season 14/15 the behavior of $s$ as a function of energy and mass number is as expected: the shadow is stronger for high-energy particles with low atomic numbers and weaker for low-energy particles with high atomic numbers. For season 08/09, however, the picture is different. While for iron nuclei, $s$
increases with increasing energy, there is a peak structure for aluminum and nitrogen nuclei, and $s$ even decreases for helium and hydrogen nuclei. In order to better understand this effect, we reduce the particle properties to only one parameter in the following section.

Figure 8. Calculated Sun shadow in the years from 2007 through 2017 for the different energies a mixed composition according to the $HGm$ model.

Figure 9. Calculated Sun shadow in the season 2008/2009 for the different energies and mass numbers. Solar activity was comparatively low during this season (compare figure 1).
4.3 Sun shadow as a function of rigidity

In this section, we consider the rigidity $R \sim E/Z$ in order to reduce the dependency of the shadow on energy and atomic number to one parameter. In Figure 11 and 12, the calculated $s$ is plotted as a function of rigidity for the respective seasons 08/09 and 14/15. The expected equivalence of particles with the same rigidity is confirmed for both seasons. As an example, the middle blue square in Figure 12, representing $\sim 10^{1.6}$ TeV nitrogen nuclei, shows an $s$ comparable to that of $\sim 10^{2.2}$ TeV iron nuclei, the rightmost orange pentagon. With rigidities of $\sim 5700$ GV and $\sim 6100$ GV respectively, these particles are expected to show a similar behavior with respect to their gyro-radii. For the season 08/09, however, $s$ does not increase monotonically, as it does in season 14/15, but it rather peaks at a certain rigidity between $10^{3.5}$ and $10^{4.0}$ GV. A possible explanation for this is that $s$ seems to be significantly larger than 1.0 for years with low solar activity (compare section 4.1), i.e. in years where the magnetic field is approximately described by a simple dipole. It seems possible that particles above a certain rigidity do not form the shadow typical for a dipole field anymore, but rather “converge” towards the shadow of an unmagnetized disk, which, by definition, would result in values $s \approx 1$. Particularly in view of the non-monotonous dependence of shadow size on rigidity that was found for the dipolar test case (see section 3.2) and illustrated in Figure 4, the transition between these two regions – $s$ for a dipole field vs. $s$ for an unmagnetized disk – can possibly explain the peak visible in Figure 9 as well.

Thus, our simulations indicate that an energy-dependent study of the Sun shadow by cosmic-ray observatories would be highly beneficial. From these studies, we expect the observatories to see the dipole-like energy dependence, with a monotonic rise up to a peak energy. In the peak, we expect the shadow effect to be up to 40% stronger than the geometrical-disk shadow. At energies above this peak, we expect the shadow to converge to the size of the
geometrical one. In years of high solar activity, we predict a different behavior, which is a purely monotonic increase of the shadow depth, starting at low energies with a shadow much shallower than the geometric one. For all energies, the shadow is expected to be shallower than the geometrical one. Toward high energies, it will converge to the geometrical shadow depth again.

Figure 11. Calculated Sun shadow in the season 2008/2009 as a function of rigidity.

4.4 Sun shadow for different cosmic-ray flux models

In Figure 13, the calculated $s$ is plotted for the $HGm$ and $GH$ models for the seasons 07/08 to 16/17. While there is a systematic offset in the total magnitude of $s$, its temporal variation is very similar for both models, suggesting that the shape of the temporal variation does not depend significantly on the primary cosmic-ray model used. In Figure 21 and 22 (see appendix), the calculated passing probabilities and full shadow plots for the $HGm$ and $GH$ models for seasons 07/08 to 16/17 can be seen.

4.5 Sun shadow compared to solar activity

Figure 14 shows the temporal behavior of $s$ (assuming the $HGm$ model) and the sunspot number averaged over the time periods considered in this work (data taken from [26]). Note that the time range of the Carrington rotations considered for a specific year and the time range in which the sunspot numbers are measured are slightly different, since the duration of a Carrington rotation is always shorter than the duration of a calendrical month. Figure 15 shows the correlation of $s$ with the sunspot number, together with a linear fit of the form

$$s = a + b \cdot \text{SSN}.$$ (4.1)

While $a$ is reasonable close to 1.0, which is expected due to the discussion in sections 4.2 and 4.3, there is currently no straightforward interpretation of $b$. For the Spearman’s rank
Figure 12. Calculated Sun shadow in the season 2014/2015 as a function of rigidity.

Figure 13. Comparison of $s$ for the calculated Sun shadow in the years from 2007 through 2017 between the $HGm$ and $GH$ models.

correlation coefficient $\rho$ of $s$ and the sunspot number, we find

$$\rho_{\text{Spearman}} = -0.86 .$$  \hfill (4.2)
Figure 14. Temporal behavior of shadow ratio $s$ (assuming the $HGm$ model) and the sunspot number in the years from 2007 through 2017. Sunspot numbers are taken from [26].
Figure 15. Correlation of ratio $s$ and the sunspot number in the years from 2007 through 2017. Sunspot numbers are taken from [26].
5 Summary

In this paper, we investigate cosmic-ray transport across the Sun’s corona in the energy range between $\sim 5$ TeV and $\sim 316$ TeV and for hydrogen, helium, nitrogen, aluminum, and iron nuclei. For that purpose, particles with three different energies were studied, namely $10^{1.0}$, $10^{1.6}$, and $10^{2.2}$ TeV (corresponding to $10$, $\sim 40$ and $\sim 158$ TeV). We chose these supporting points in a way that they are equidistant in $\log E_{\text{CR}}$. The energy range is chosen to reflect the range that most detectors measuring the cosmic-ray Sun shadow like IceCube, Tibet, ARGO-YBJ, HAWC and others are sensitive to. The data sample used by IceCube has a median energy of $\langle E_{\text{CR}} \rangle \sim 40$ TeV, with 68% of the events between 11 and 200 TeV. The mass numbers of the nuclei are chosen to reflect the most abundant mass groups, with nitrogen representing the CNO and aluminum representing the MgAlSi element group. By choosing these mass numbers and energies, we are able to compute a generic prediction for the expected time variability of the cosmic-ray Sun shadow that can be compared to measurements by the experiments mentioned above. We associate the above-mentioned time variability with the time-changing solar magnetic field and its influence on the shape and depth of the Sun shadow of cosmic rays studied by ground-based cosmic-ray experiments such as IceCube, Tibet, ARGO-YBJ, and HAWC. In the future, these observatories will be able to further improve their spatial and temporal resolution, possibly contributing to investigations of the solar cycle via indirect measurements of magnetic field properties.

For the purpose mentioned above, we perform a numerical integration of particle trajectories in the solar magnetic field of the past ten years. Magnetogram data are obtained from GONG [27] and interpreted in the PFSS model using the FDIPS code [30]. For each year from 2007 through 2017, the respective four months January, February, November, and December are simulated. We chose to simulate these months as they correspond to the time period per year in which the Sun is visible from the South Pole. This way, our results are easily applicable to the one of the IceCube detector – they correspond to the relevant energy range and observation times. It needs to be noted, however, that no detector effects like a limited acceptance or a limited angular resolution have been taken into account.

The results of our simulations are provided in a two-dimensional representation. The variation of the cosmic-ray Sun shadow is verified in this simulation, and as expected, the effect is strongest at the lowest simulated energy of 10 TeV. The variation of the shadow furthermore shows that in times of low solar activity, the shadow is relatively compact near the Sun’s center. In times of high solar activity, however, the shadow tends to be washed out. It needs to be investigated by IceCube and other cosmic-ray experiments if they can detect such features of systematic deviation from a dipole structure despite their limitations associated with angular resolution. Such a measurement would make it possible to indirectly study the structure of the solar magnetic field and thus to contribute to its understanding. In this sense, our findings of the different energy behavior of the shadow for low activity (dipole-like) and high activity (monotonous) are very interesting, as they would pose another possibility for the detection of a dipole-like shadow behavior. We can make the clear prediction that in times of low solar activity, the energy-behavior should resemble the one of a pure dipole, with a shadow that becomes stronger with energy up to a maximum value, in which it exceeds the depth of the geometrical shadow. For the years studied here, the shadow is expected to become 40% deeper than the geometrical one. Above this peak energy, the shadow is expected to converge to the geometrical size. This behavior is in contrast to years of high activity. Here, we find a monotonous increase of the shadow depth with energy, converging toward the geometrical

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size, never exceeding the geometrical shadow. Future studies will show if this is an effect of the unordered field of the Sun, which is much more significant in years of high solar activity as compared to the low activity years of the Sun.

We can further show that, while the shadow is still significantly distorted at 40 TeV, the deviation from an undisturbed shadow becomes extremely small at 158 TeV (compare section 4.2). Thus, we expect effects of the inner heliospheric field on cosmic-ray propagation to become negligible concerning the variation of the Sun shadow at these high energies. This result is in agreement with recent HAWC measurements [14], which show a symmetric, deep shadow at energies around 100 TeV. Future investigations of several years of data with HAWC will help to further quantify these findings.

The absolute normalization of the shadow depth in our simulation is not directly comparable to IceCube data, as we did not take into account detection effects like a limited acceptance or a limited angular resolution. Comparing the relative change in the deficit between the different years, however, our simulations show a similar temporal variation of the shadow depth as the data taken with IceCube [11].

6 Outlook

We consider this paper as a first step toward achieving a detailed understanding of the effects of the solar magnetic field variation on the Sun’s cosmic-ray shadow measured by different experiments at Earth. In the future, there will be several opportunities for further work, which either need improved data from the experiments or require computationally more involved modeling approaches.

Magnetic field modeling One aspect concerns modeling the inner heliospheric magnetic field, which is done on the basis of available data. The data are collected by spacecraft, such as Helios [40], which do not simultaneously provide data from the far side. We used the PFSS ansatz [28, 29] in order to model the global coronal magnetic field, but it is desirable to compare these results to other models. The Tibet group, for instance, favors the Current Sheet Source Surface (CSSS) model [10], because using this model they found better agreement with the measured data. A similar comparison between these two models and IceCube data would be an asset for a better understanding of the solar coronal magnetic field. Besides the existing studies by Tibet, a comparison of different coronal magnetic field models on the analysis level using IceCube data would be very useful for evaluating the validity of different models. However, as these models both assume a purely radial magnetic field at a defined boundary sphere, no fundamental differences between these two are expected. Ultimately, it will be desirable to probe more complex models like force-free field approximations (see e.g. [41]) or even full magnetohydrodynamic (MHD) simulations of the solar magnetic field.

Quantitative comparison with data In this paper, we compare our results regarding the time variability of the Sun shadow with current IceCube data, which is available for five years (see [11]). In the future, IceCube will extend its data analysis to more years of data, for the same solar cycle. Also, HAWC will be able to provide information in a similar energy range. This way, a comprehensive comparison of data and simulation will be possible. Firstly, by deducing from pure simulation studies which effects the magnetic field shows by itself and secondly by comparing data and simulation on the detector level. Future arrays like IceCube-Gen2 [42] will improve such studies even further, possibly enabling an investigation of the
properties of the magnetic field through the combination of simulation and detection of the cosmic-ray shadow with better angular and time resolution.

Integrating the particle propagation into a detector environment is necessary in order to test which magnetic field configuration fits the data best. This needs to be done for each instrument individually and can only be done by the collaborations themselves. Studies as we present here, without including detector effects, are still desirable, as this is the best way to find effects that arise from the magnetic field. The influence of coronal mass ejections (CMEs) on the cosmic-ray Sun shadow seen by different experiments is also something that can be studied, as has been shown in [43].

**Toward a complete model of transport and interaction** Furthermore, adding particle interactions in the solar corona and in the Earth’s atmosphere to the simulations will be another step that would increase our understanding of the phenomenon of cosmic-ray shadowing.

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A  Shadow plots

A.1  Sun shadow as a function of mass number

In Figure 16 and 17 the Sun shadow can be seen for proton and iron nuclei only.

![Sun shadow plots](image)

**Figure 16.** Calculated Sun shadow in the years from 2007 through 2017 for protons only.

A.2  Sun shadow as a function of energy

In Figure 18, 19 and 20 the Sun shadow can be seen at 10, 40 and 158 TeV, respectively.

A.3  Sun shadow for different cosmic-ray flux models

In Figure 21 and 22 the Sun shadow can be seen for the $Hgm$ and $GH$ model, respectively.
Figure 17. Calculated Sun shadow in the years from 2007 through 2017 for iron nuclei only; note the narrow color scale.
Figure 18. Calculated Sun shadow in the years from 2007 through 2017 for 10 TeV. Each plot contains contributions by all five elements that were simulated with a composition according to the \( HGm \) model.
Figure 19. Calculated Sun shadow in the years from 2007 through 2017 for 40 TeV. Each plot contains contributions by all five elements that were simulated with a composition according to the HGm model.
Figure 20. Calculated Sun shadow in the years from 2007 through 2017 for 158 TeV. Each plot contains contributions by all five elements that were simulated with a composition according to the $HGm$ model.
Figure 21. Calculated Sun shadow in the years from 2007 through 2017 using the energy spectrum and composition according to the \textit{HGm} model.
Figure 22. Calculated Sun shadow in the years from 2007 through 2017 using the energy spectrum and composition according to the GH model.