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TeV Cosmic Rays Around the Sun: Sun's Shadow and Solar Gamma Rays

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High rigidity cosmic rays in the TeV range offer a unique tool in the exploration of the magnetic field structure close to the Sun. TeV protons are essentially unmodulated at Earth's orbit but can be significantly deflected by the strong magnetic fields near the Sun. Cosmic rays hitting the Sun are absorbed and create a cosmic ray shadow that has been detected and studied in detail by air-shower observations in the multi TeV range. Cosmic rays can also interact with matter near the solar surface and create gamma rays that are observed by the Fermi LAT instrument. Both the Sun's shadow and solar gammas exhibit a marked solar cycle dependence sharing some common features. In this work we perform numerical simulations to estimate the energy dependence of cosmic ray flux near the Sun that can create gammas seen at Earth from different solar latitudes. We consider particle transport in a simple model of the Sun including regions of open and closed magnetic fluxes.

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1. Introduction

High rigidity cosmic rays in the TeV range offer a unique tool in the exploration of the magnetic field structure close to the Sun. TeV protons are essentially unmodulated at Earth's orbit. They cross most of the Heliosphere in straight line but can be significantly deflected by the strong magnetic fields in the immediate proximity of the Sun. Cosmic rays hitting the Sun are absorbed and can create a cosmic ray shadow that has been detected and studied in detail by air-shower observations [1], [2] in the multi TeV range.

Cosmic rays can also interact with matter near the solar surface and create gamma rays that are observed by the Fermi LAT instrument [4] and other gamma observations such as ARGO,HAWC, and LHAASO.These observations detect much higher gamma flux than predicted by early theoretical work of [3].

Both the Sun's shadow and solar gammas exhibit marked solar cycle dependence sharing some common features. In this work we perform numerical simulations to estimate the solar cycle variation of TeV proton flux near the Sun, that can create gammas to seen at Earth coming from different solar latitudes. We consider particle trajectories in a simple model of the Sun including regions of open and closed magnetic field lines. This project is still in initial stage, the present contribution is intended to outline our plans for near future.

2. Key Observations and their Implications

2.1 Cosmic-Ray Shadow of the Sun

In this section we summarize some aspects of the measurement of Sun'shadow i.e. directions from which the Sun blocks the path of cosmic rays toward Earth at 1 AU. This measurement is only possible at TeV and multi-TeV cosmic ray primaries that cross the heliosphere in almost straight lines, and are deflected only in the strong magnetic field near the Sun. At lower energies we do not expect a shadow, the magnetic field around the Sun will shield the Sun from GCRs in similar way as our magnetosphere shields the Earth from GCRs. Some shadow may appear from the open field at the poles.

The Tibet collaboration [2] observed air-showers from $\sim$ 10 TeV cosmic-ray primaries, most of them protons. The shadow, which was near to the full optical size during solar minima, or even exceeded it during 1996-1998, diminished during the period of increasing solar activity and almost disappeared during the years of solar maximum.

Numerical simulations of the authors [2] adopting different potential-field models and using observed magnetic field data successfully explained the solar cycle variation observations both for the size and the displacement of the shadow relative to the optical direction. The simulations followed a practical avenue: the trajectories of pseudo particles from various arrival directions were traced back in time (or time-forward with changing the particle's charge). Trajectories hitting the Sun indicated blocked arrival directions.

The notable deviation from expectation was that observations were better fitted with relatively large radius of the source surface [2]. A possible cause of this deviation could be that the deflection of cosmic ray primaries are sensitive to the transverse component of the magnetic field while the standard potential field models force a radial field at the source surface at some distance from the Sun.

It is interesting to note that a fully radial field would leave the cosmic-ray shadow identical with the optical view even if we allow the field strength and polarity change between adjacent radial lines. The conservation of the angular momentum dictates that the shadow may rotate around the center of the Sun with the disk remaining the same.

A less practical way of exploring the structure of the Sun's shadow would be to eject pseudo-particles, so called shadow-particles in all outgoing directions from the surface of the Sun. The trajectories of these shadow particles mark the areas of cosmic rays shadow. At solar minimum these trajectories would mostly connect to the free interplanetary space, while a large part of them would return and hit the Sun, never connecting to free space, similarly as asymptotic directions behave in the Earth's magnetic field. Estimation the flux of TeV primaries hitting the Sun we shall face a similar problem.

An interesting and tantalizing observation was that, in the years of 1996-1998, the Sun's cosmic ray shadow exceeded its optical size. The study of these shadow particles could reveal if there may be a focusing effect, conceivably by the heliospheric current sheet (HCS). These were the years of solar minimum, with almost completely flat HCS. Whether focusing effect could be reconciled with Liouville's theorem is a question to be answered. This could be a potentially interesting side-product of our study.

2.2 Gamma Rays from the Sun

The first and for a long time the only theoretical work on the potential flux of gamma-rays from the Sun was published by Seckel, Stanev & Gaisser [3] in 1991. This work has likely overestimated the modulation of galactic cosmic rays, hence underestimated the density of GCR primaries near the Sun. The first observations of Fermi LAT [4] detected 7 times higher flux then predicted by [3]. This large difference is still posing a challenge to interpretations.

An intriguing feature of the Fermi observations is the apparent gap at around 50 GeV energies [5]. If real, this might indicate a combination of two different processes at work.

The most likely process at high energies is pion production. GCR protons interact with nuclei in the the dense region of the photosphere producing pions which then quickly decay into two gammas. A cardinal problem is that incoming GCRs have to turn around to produce outgoing gammas. This may happen at strong horizontal fields, and is discussed at this conference by Puzzoni et al. [6].

3. Model Simulations

We construct a simple axially symmetric model of the Sun, built from the first few spherical harmonics and adding a 'monopolar' field with different polarities on the Northern and Southern hemispheres. The two important parameters are the open and closed magnetic fluxes, respectively. Keeping the open flux the same, we increase the closed flux to model higher solar activity.

Alternatively we can also prescribe the radial component on the surface of the Sun and solve the Laplace equation on a spherical grid with setting the proper boundary-condition far from the Sun.

PoS(ICRC2023)1296

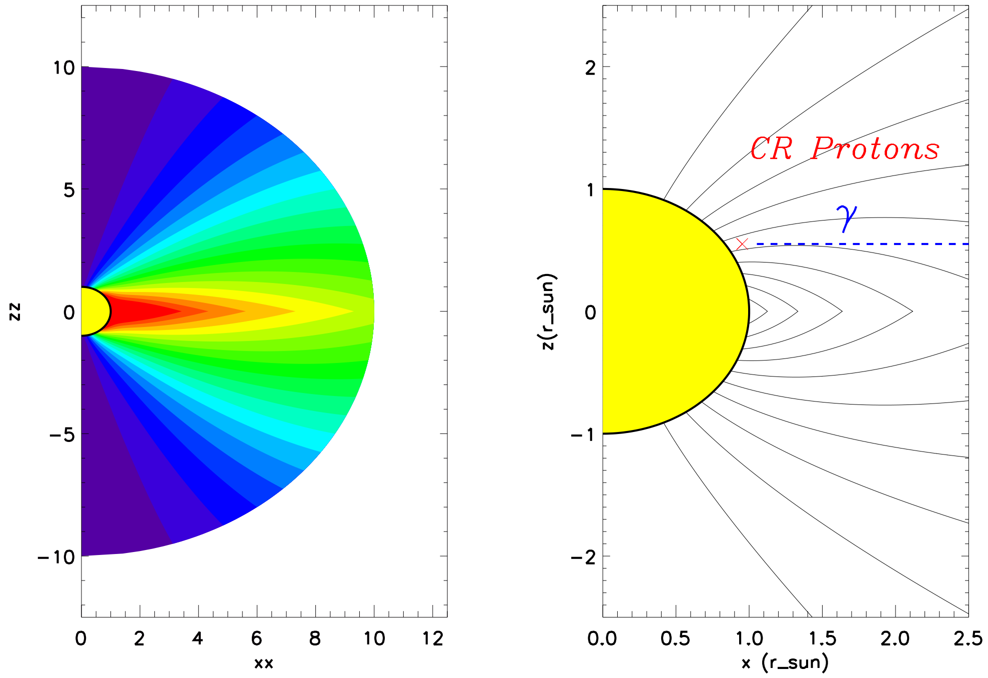

Figure 1: Meridional cut of our axially symmetric Sun model. The left panel illustrates the value of $A(r, \theta)$, which is the total (signed) magnetic flux between the pole and the given latitude. The right panel depicts magnetic field lines close to the Sun

The difference from the standard potential field model is that we do not set a source surface. Our different treatment of the radial and transverse component is partly motivated by the Tibet observations which were best reproduced with a relative large radius of the source surface [2],[8],[7] The standard PFM forces the transverse component to disappear at the source surface. This might be the reason of the apparent discrepancy between the standard potential filed models, and the Tibet Sun-shadow observations.

Here we consider mainly Solar minimum conditions when cosmic ray transport is more transparent. In this work we adopt a simple static magnetic field so that we can make use of axial invariance that yields a relation between the axial component of the angular momentum of GCRs and the vector potential of the field. We consider high energies so the solar wind modulation remains in the percent level, and is negligible. The radial and latitudinal components of our global field model are derived from a potential $A(r, \theta)$ as:

$$B_r = \frac{1}{r^2}\frac{\partial A}{\partial\, cos\theta} \qquad\qquad B_\theta = \frac{1}{r\, sin\theta}\frac{\partial A}{\partial r} \tag{1}$$

Then the axial symmetry mandates that

$$L_z + \frac{e}{c}A = const. \tag{2}$$

where L_z stands for the axial z component of the angular momentum of the cosmic-ray primary proton. A GCR proton can reach the point of prospective interaction point (x in the right panel of Fig.1.) if its trajectory (traced back) connects to free space. To reach free space the trajectory must cross the $A(r,\theta) = A_{open}$ line that divides the open and closed fields. This sets the relation to satisfy:

$$(e/c)\left(A(r_{sun},\theta_1) - A_{open}\right) + r_{sun} sin(\theta_1)\, p_{y,1} = r_2 sin(\theta_2)\, p_{y,2} \tag{3}$$

where 1 and 2 subscripts refer to the starting and crossing places, respectively, while p_y stand for the azimuthal component of the primary's momentum. The RHS of the equation is limited if reqire that the crossing happen within a few (say 5) solar radii. If the LHS of the equation happens to be less than $5p$, we declare the trajectory trapped.

If the trajectory cannot be declared trapped, it still may return to the solar surface and not connect to free space. This can be decided by tracing the trajectory by numerical methods.

4. Results

Preliminary results are expected to be presented at the conference.

5. Summary

The project is still in initial stage, the primary intention of this contribution is to outline our prospective plans for near future. In the first step we perform simple trajectory calculations in the idealistic scatter-free case. In the second step, later in he project, we consider scattering, too.

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PoS(ICRC2023)1296