The Sun at TeV energies: 
gammas, neutrons, neutrinos and a cosmic ray shadow

Miguel Gutiérrez, Manuel Masip

CAFPE and Departamento de Física Teórica y del Cosmos
Universidad de Granada, E-18071 Granada, Spain

mgg,masip@ugr.es

Abstract

High energy cosmic rays reach the surface of the Sun and start showers with thousands of secondary particles. Most of them will be absorbed by the Sun, but a fraction of the neutral ones will escape and reach the Earth. Here we incorporate a new ingredient that is essential to understand the flux of these solar particles: the cosmic ray shadow of the Sun. We use Liouville’s theorem to argue that the only effect of the solar magnetic field on the isotropic cosmic ray flux is to interrupt some of the trajectories that were aiming to the Earth and create a shadow. This shadow reveals the average solar depth crossed by cosmic rays of a given rigidity. The absorbed cosmic ray flux is then processed in the thin Solar surface and, assuming that the emission of neutral particles by low-energy charged particles is isotropic, we obtain (i) a flux of gammas that is consistent with Fermi-LAT observations, (ii) a flux of 100–300 neutrons/(year m²) produced basically in the spallation of primary He nuclei, and (iii) a neutrino flux that is above the atmospheric neutrino background at energies above 0.1–0.6 TeV (depending on the solar phase and the zenith inclination). More precise measurements of the cosmic ray shadow and of the solar gamma flux, together with the possible discovery of the neutron and neutrino signals, would provide valuable information about the magnetic field, the cycle, and the interior of the Sun.
High energy astroparticles provide a picture of the sky that complements the one obtained with light at different frequencies. Their study during more than 100 years has helped us to understand the environment where these particles are produced (supernovas, pulsars, active galactic nuclei or gamma ray bursts) and the medium that they find on their way to the Earth. Indeed, we expect them from any event where nature reaches extreme conditions, also the neutron star mergers recently discovered through gravitational waves [1]. We may distinguish three types of astroparticles: cosmic rays (CRs, including atomic nuclei and electrons), gamma rays and neutrinos. CRs are charged particles, they are the only ones to be accelerated in astrophysical processes but lose directionality as they propagate along the magnetic fields present in the cosmos at all scales. In contrast, gammas and neutrinos appear as secondary particles produced when CRs interact with matter or light, and they always point to the source. It is then apparent that the observations in these three channels provide different pieces of the same puzzle.

Here we will focus on an astrophysical object that seems difficult to overlook but that still keeps some very significant secrets: the Sun. With a temperature around 1 keV, one may think that any solar particles with energy in the GeV–TeV range may be a sign of new physics, e.g., the annihilation of massive dark matter particles captured by the Sun. This, however, is not necessarily the case. In 1991 Seckel, Stanev and Gaisser [2] described a flux (SSG flux) of high energy particles produced by CRs showering in the surface of the Sun. More recently the Fermi-LAT observatory has detected solar gammas both during a minimum and near a peak of solar activity (2014–2017) [3] (see also [4]). The flux exhibits a hard spectrum ($\propto E^{-2}$) between 1 and 200 GeV, with a possible dip at $E \approx 40$ GeV [5], and then it seems to drop. The flux is 10 times above the diffuse gamma ray background and around 7 times larger than the SSG estimate, although its modulation with the solar cycle seems a clear indication of its CR origin.

The main uncertainty in the SSG calculation was caused by the effect of the solar magnetic field on the trajectory of CRs as they approach the surface. At distances beyond 10 solar radii TeV CRs follow ballistic trajectories through the Parker interplanetary field [6], which includes a strong radial component $\propto R^{-2}$ (open lines) carried by the solar wind. Many of the CRs moving towards the Sun will experience a magnetic mirror effect before they reach the surface (see Fig. 1). At closer distances the field lines tend to co-rotate with the Sun ($T \approx 24$ days), turbulence increases and there appears a new type of (closed) field lines that start and finish on the surface. In addition, this magnetism is not stable, it has an 11-year cycle that is correlated with the solar activity. Any numerical or analytical calculation of the absorption rate of CRs by the Sun seems then uncertain. Instead, we can add a key observation that was not available at the time of the SSG analysis: the energy
Figure 1: **Left.** Trajectories through the Parker field in the vicinity of the Sun starting at the Earth for a 5 TeV proton (in AU; closed field lines starting and finishing on the Sun’s surface not included). Only trajectories aligned with the open field lines reach distances $R < 10 R_\odot$ (shaded region). **Right.** CR flux observed at the Earth (dashes) and absorbed flux (solid) consistent with HAWC observations (dots). Blue (red) lines correspond to protons (He nuclei) and black lines to p+He. We include in the plot the absorbed flux expected during a solar minimum (thin solid), which is obtained by reducing $E_{\text{crit}}$ by a factor of 1/3.

A dependent shadow of the Sun measured by HAWC [7]. The shadow, with data taken during a solar maximum (years 2013–2014), is not a black disk of 0.27° radius (the angular size of the Sun). It is a deficit that appears in the CR flux at 2 TeV and extends into an angular region ten times larger than the Sun. HAWC fits this deficit with

$$d(\theta) = -A \exp\left(-\frac{\theta^2}{2\sigma^2}\right),$$

providing the parameters $A$ and $\sigma$ at 3 different energies. Integrating we obtain that at 2 and 8 TeV the deficits are equivalent to 6% and 27% of a black disk, respectively, whereas at CR energies around 50 TeV it adds to a complete shadow (i.e., a deficit of $\pi \theta_\odot^2$, with $\theta_\odot = 0.27^\circ$).

To interpret HAWC’s results we can use Liouville’s theorem, stating that the density of CR trajectories along a trajectory in phase space remains constant. If we consider a given CR energy and a static magnetic field (time variations may change that energy), then the theorem implies that an isotropic CR flux will stay isotropic. A magnetic lens, including
a mirror, will not produce anisotropies, and the only possible effect of the Sun will be to interrupt some of the trajectories that were aiming to the Earth and create a shadow. As we turn around the Sun we face different magnetic configurations; the CR shadow at a given energy may appear and disappear, and its apparent position may change due to the magnetic deflection. At HAWC we see the shadow averaged during the observation period and smeared out (both by the magnetic deflection and by the experimental error) into an angular region of $2.6^\circ$ radius.

The integrated deficit in the CR shadow at different energies reveals then the fraction of the CR flux absorbed by the Sun. We can model this absorbed flux by assuming that the proton trajectories of energy $E$ closest to the Sun and aiming to the Earth through the solar magnetic field cross an average depth (column density of solar matter) $\Delta X_H$, with

$$\Delta X_H(E) = c_H \left( \frac{E}{1 \text{ GeV}} \right)^{1.15},$$

and $c_H = 4.4 \times 10^{-4}$ g/cm$^2$. It follows that Helium nuclei of energy $2E$ (i.e., with the same magnetic rigidity) will cross exactly the same average depth, $\Delta X_{\text{He}}(E) = \Delta X_H(E/2)$. The energy dependent probability of absorption by the Sun $p_{\text{abs}}^H$ is then

$$p_{\text{abs}}^H = 1 - \exp\left( -\frac{\Delta X_H}{\lambda_{\text{int}}^H} \right),$$

where $\lambda_{\text{int}}^H$ is the inelastic interaction length (in g/cm$^2$) for a proton in the Sun. An analogous expression would describe the absorption probability of He nuclei. In Fig. 1 (right) we plot the absorbed flux that we obtain under this hypothesis, which is consistent with HAWC’s observations. We have taken a primary CR flux dominated by protons and He nuclei with slightly different spectral index ($-2.7$ and $-2.6$, respectively), neglecting heavier nuclei. At high energies the total and the absorbed CR fluxes coincide (the CR shadow is complete), whereas at lower energies an increasing fraction of CRs is unable to reach the Sun’s surface (the shadow disappears). Notice that He nuclei have charge +2 and will find it more difficult than protons to reach that surface, but their inelastic interaction length is shorter and the two effects tend to compensate: absorption becomes important at a similar energy for both components.

Once absorbed the CR flux will be processed into secondary particles. One important observation is that the environment where the shower develops is very thin, much thinner than the Earth’s atmosphere: from a vertical trajectory starting at the optical surface of the Sun, it takes 1500 km to cross 100 g/cm$^2$ of matter. As a consequence, TeV pions and muons have plenty of time to decay before they lose energy independently of the inclination of the shower trajectory: just the total depth is relevant to obtain the yield of secondary
particles. As for the albedo flux of neutral particles escaping the Sun, it will depend on two main factors: how deep these particles are produced, and whether they are emitted outwards or inwards.

Our basic scheme is then the following. High energy CRs reach the solar surface aligned with an open (radial) field line, and once there they start a shower. Secondary charged particles will continue penetrating the Sun as long as their energy is above some critical value $E_{\text{crit}} \approx 10$ TeV that depends on the phase in the solar cycle, whereas charged particles of lower energy will be trapped by closed field lines and will shower at the approximated depth where they are produced. Consistent with that, neutral particles produced in collisions and decays of charged particles will head outwards or inwards as a function of the energy of the parent particle: above $E_{\text{crit}}$ most of the emission is inwards, whereas at lower energies the trajectory of charged particles is isotropized and so is their emission. In Fig. 2 we plot the probability for an outwards emission during an active phase of the Sun for different values of the parent energy. The neutral particles produced outwards, in turn, will propagate and eventually emerge from the Sun’s surface.

As the Sun goes into a quiet phase all magnetic effects will decrease. Qualitatively this is what we observe at much lower energies in the flux of galactic CRs, with a larger fraction of 1–10 GeV CRs able to penetrate the heliosphere during those periods. In terms of a critical energy analogous to the one we are using, a reduction by a factor of 1/3 would imply an increase in the total CR energy by a factor of $3^{0.7} = 2.1$, which seems consistent with the observations [8]. Therefore, for a quiet Sun we will assume the same type of reduction by a factor of 1/3 in $E_{\text{crit}}$; this will increase the CR flux absorbed by the Sun (thin lines in Fig. 1)
and will favour the inwards emission of neutral particles within the solar showers.

One important point about these fluxes concerns their distribution on the Sun’s surface seen from the Earth. In our scheme TeV CRs approach the surface aligned with the radial field lines, which suggests spherical symmetry in the absorption (i.e., same CR shadow seen from any direction). Moreover, most gammas and neutrons in this solar albedo flux will be produced very close to the surface (60% of the absorbed CR energy is processed there), which implies that each point on the surface emits these particles isotropically (notice that gammas produced deeper will emerge preferentially along the radial direction). An isotropic gamma emission from each point on the Sun’s surface would imply that at the Earth we see the peripheral regions brighter than the central ones, being the distribution

$$\Phi_\gamma(r) = \Phi_\gamma(0) \frac{1}{\sqrt{1 - \frac{r^2}{R_\odot^2}}} \quad (4)$$

with $\Phi_\gamma$ the gamma flux and $r$ the transverse distance from the center. However, during an active solar phase the open field lines tend to be pushed towards the polar regions, which would favor the CR absorption and the gamma emission from there. In any case, the current volume of data seems insufficient to reach any clear conclusion on this point [4].

To obtain the flux of neutral particles coming from the Sun we have parametrized the yields in hadron collisions [9] and decays [10] at different energies and have solved cascade equations [11] for 17 species, including the electromagnetic component of the shower [12]. For neutrinos, we have added the inwards flux produced at the hidden side of the Sun. Our results are summarized in Fig. 3. On the left we plot the integrated gamma flux that we obtain for $E > 10$ GeV and the two absorbed fluxes in Fig. 1 together with the two sets of Fermi-LAT data. At low energies the gamma flux is reduced because most CRs are unable to reach the Sun and shower there, while at $E > 1$ TeV it drops because, although the parent CRs always reach the surface, the gammas are produced towards the Sun and never reach the Earth. Our estimate for a quiet Sun (blue line) relative to the active one (red line) shows two different effects: the gamma flux increases at low energies (CRs of lower energy can reach the surface during that phase) but it also drops faster at high energies (parent CRs have a larger tendency to emit the gammas inwards). Notice also that our framework can not accommodate a 40 GeV dip [5] in the solar gamma flux.

On the right-hand side of Fig. 3 we give the fluxes for the three neutral species (gammas, neutrons and neutrinos) coming from the Sun. The neutrino flux is basically twice the gamma one, as neutrinos of $E < 1$ TeV produced in the hidden side of the Sun can also emerge and reach the Earth. At higher energies the albedo neutrino flux vanishes, but neutrinos from the peripheral regions in the hidden side of the Sun can still emerge and reach us. At $E \approx 5$
Figure 3: **Left.** Integrated flux of gammas that we estimate for the absorbed CR fluxes in Fig. 1 together with the Fermi-LAT data (from [4]). The dashed line indicates the maximum gamma flux (obtained if the CRs of all energies showered towards the Earth). **Right.** Fluxes of neutral particles observed at the Earth for the two CR fluxes in Fig. 1 (including the gamma flux plotted on the left).

TeV the neutrino flux becomes independent from the solar cycle and has a spectral index around $-3.3$. The total neutrino flux that we obtain is above the atmospheric background at $E > 100$–600 GeV, depending on the zenith angle and the solar phase; at 5 TeV it is 20 times (4 times) larger than the atmospheric one from vertical (horizontal) directions. Our results for the solar neutrinos are qualitatively similar to the ones obtained by SSG, and at $E > 1$ TeV they agree within a 50% with the results in [13–16]. We estimate that the Sun provides around 2 events per year in a km$^3$ telescope like IceCube [17] or KM3NeT [18].

The solar neutron flux has a very peculiar energy distribution: it mimics the shadow of the Sun observed by HAWC up to 10 TeV and then it drops sharply. The origin of most of these neutrons is the spallation of He nuclei reaching the Sun’s surface, being neutrons and antineutrons from hadronic collisions just 10% of the flux. The signal consists of 100-300 neutrons/(year m$^2$) with a very hard spectrum (see Fig. 3). Our result is a factor of 20 larger than the SSG estimate [2]. In a satellite based detector, a neutron event would provide a distinct signal with no track in the electromagnetic calorimeter but a TeV energy deposition in the hadronic calorimeter. The angular resolution would be poor but, since no cosmic flux of TeV neutrons may be expected, the background (albedo flux from the Earth’s atmosphere) would be small.

The Sun is one of the brightest objects in the sky at TeV energies in the neutrino and the gamma channels. It is also the only possible source of TeV neutrons: since they have a 881 s lifetime, at these energies they can not reach us from anywhere else. In addition, the Sun generates a shadow in the otherwise isotropic (at the 0.1% level) CR flux. Of
course, the observation of any of these TeV solar fluxes in ground based detectors is very challenging: gamma ray telescopes operate only at night (HAWC is one of the few the exceptions), neutrino telescopes face large atmospheric backgrounds, and the detection of a 0.54° diameter object requires in all the cases a very good angular resolution. Satellite based detectors avoid some of these problems, which has allowed EGRET [19] or Fermi-LAT to detect solar gammas and makes the neutron flux look accessible. Our work here correlates the signals in these four channels, in particular, we show that the use of the CR shadow eliminates the main uncertainty (namely, the effects of the solar magnetic field) that plague previous calculations. The discovery of the neutron and neutrino signals, plus more complete results in the gamma and CR channels, would provide important information about the magnetic field, the cycle and the interior of the Sun.

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