COSMIC RAY ALBEDO γ-RAYS FROM THE QUIET SUN

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Abstract

We estimate the flux of gamma-rays that result from collisions of high energy galactic cosmic rays with the solar atmosphere. An important aspect of our model is the propagation of cosmic rays through the magnetic fields of the inner solar system. We use diffusion to model propagation down to the bottom of the corona. Below the corona we trace particle orbits through the photospheric fields to determine the location of cosmic ray interactions in the solar atmosphere and evolve the resultant cascades. For our nominal choice of parameters, we predict an integrated flux of gamma rays (at 1 AU) of $F(E_\gamma > 100\text{ MeV}) \approx 5 \times 10^{-8}\text{ cm}^{-2}\text{ sec}^{-1}$. This can be an order of magnitude above the galactic background, and should be observable by EGRET.

Introduction

There are a number of reasons to study the sun as a source of γ-rays produced in cosmic ray cascades. First, there is the purely intellectual question of whether the γ-ray albedo is strong enough to be observed. Second, there is the practical issue of whether the sun could be a strong enough source of γ's to be a confusing background to other sources. Third, many of the same issues that occur in studying solar flares as γ-ray sources are likely to come into the calculation of the γ-ray albedo from cosmic ray interactions. These include the structure of the magnetic fields near the sun and charged particle propagation through those fields. The details of those issues will be different in the two cases, and so studying the γ-ray albedo may give one a new perspective on solar flare models. Finally, whereas models of other astrophysical γ-ray sources may be largely speculation, due to the sun's proximity models of the solar source may be directly tested in other ways. Successful modeling of the sun may lead to better models of other more remote sources.

In this contribution, we summarize a recent paper[1] in which we discuss a model for estimating the albedo γ-ray flux from cosmic ray cascades in the solar atmosphere. Our model explicitly includes several 'heliomagnetic' effects. A naive estimate might assume that the cosmic ray flux incident on the sun's surface equals the flux at Earth, and that the solar albedo, like the Earth's, might be quite small. We argue that the situation is just the reverse: interplanetary (IMF) and coronal magnetic fields suppress the flux reaching the solar surface, but photospheric magnetic fields result in an efficient albedo. These conclusions coupled with a Monte Carlo study of the photon production by cascades in the solar atmosphere lead to a prediction of a flux that is detectable by the EGRET[10] instrument on the Arthur H. Compton Gamma Ray Observatory (GRO). We raise and discuss some questions for future study.

Cosmic Ray Absorption by the Sun

Framework for Absorption. We write the absorption rate for cosmic rays of energy E as

$$\Gamma(E) = 4\pi r^2 j(E), \tag{1}$$

where j is the net radial flux of cosmic rays. For a simple model ignoring magnetic fields, charged particles travel in straight lines and j is given by $j_N = (R_\odot/2r)^2 f_\infty(E)\beta(E)c$, where $f_\infty(E)$ is the differential density of cosmic rays at $r = \infty$, βc is their velocity, and the subscript N indicates that this is the naive value for absorption on a sphere of radius $R_\odot$. We take $f_\infty(E) = f_\oplus(E)$, the observed density at Earth[2]. The naive absorption rate is then

$$\Gamma_N = \pi R_\odot^2 f_\oplus \beta. \tag{2}$$

More generally, we write the absorption rate as

$$\Gamma = \frac{AC_D\Gamma_N}{A + C_D - AC_D}, \tag{3}$$

where C_D is a correction factor to account for propagation through the IMF and corona, and A is the probability that a primary which reaches the photosphere will be absorbed there instead of being reflected back into the corona. The denominator arises from considering the possibility that a cosmic ray which was reflected back into the corona may diffuse back to the photosphere and be absorbed on the 2^{nd}, 3^{rd}, ... penetration of the photosphere before totally escaping the solar system.

Diffusion. We estimate C_D using a diffusion model for cosmic ray propagation in the inner solar system. Since the IMF is expected to be nearly radial inside the Earth's orbit[3], we take the diffusion problem to be spherically symmetric with a partially absorbing boundary condition at the photosphere. The inward flux is given by $j = -Df'$, which may be used in Eq. 1 to solve for Γ. For the diffusion 'constant' we consider the form,

$$D(E,r) = D_\oplus \, (r/r_\oplus)^\alpha \, (E/1 \text{ GeV})^\beta, \tag{4}$$

where D is normalized to $D_\oplus$, its value at $E = 1$ GeV and $r = r_\oplus$. Eq. 4 is subject to the constraint $D(E,r) < rc/8$, which is dictated by causality, *i.e.* the net flux j cannot exceed j_N. Our nominal choice of diffusion parameters[4] is $(D_\oplus, \alpha, \beta) = (0.03, 2, 1)$, where $D_\oplus$ is given in units of $c \times$ A.U. Unfortunately, the diffusion parameters are mostly based upon measurements by spacecraft in Earth orbit or the outer solar system, and this leads to uncertainty in our predictions. On the other hand, an observation of the signals we propose may provide a new way to probe the inner solar system.

The Absorption Coefficient, A. To determine the absorption probability we take an isotropic flux of cosmic rays at the bottom of the corona and propagate them inward including both magnetic effects and absorption by the ambient gas. For this part of our calculation we abandon diffusion and trace the particle orbits exactly. The small scale magnetic structure[5] used for this calculation is illustrated in Fig. 1. It consists of a loose network of flux tubes which penetrate the photosphere at the corners of convective cells, where the field is swept by the moving fluid. The tubes open up to a space filling 'canopy' at the bottom of the corona which we take to be 1250 km above the photosphere. We use field strengths within the tubes of 1500 G at the photosphere and 6.5 G at the bottom of the corona. We assume the flux tubes maintain pressure equilibrium with the gas, *i.e.* $B^2 \sim P_{gas}$. Due to the pinching of the flux tubes, most primaries are mirrored and return to the corona without interacting; however, there is a small loss cone where nearly vertical cosmic rays penetrate to sufficient depth to be absorbed. For the nominal parameters we find an absorption probability of $A = .0052$ for protons; and .0088 for ^{4}He.

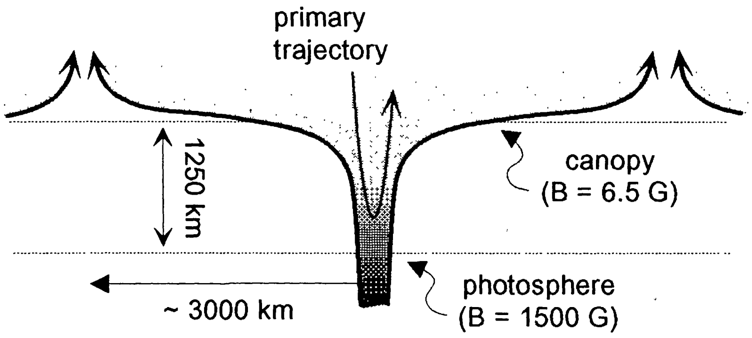

Figure 1: Model of magnetic fields near the photosphere. Shading increases with magnetic field intensity.

The discussion so far is valid only for relatively low energy primaries, which we argue will be trapped on field lines and necessarily enter the flux tubes. Higher energy primaries will not be trapped if their gyroradii are comparable to the distance bewteen flux tubes. We estimate the threshold for trapping to be $E_T \approx 3$ TeV, and take $A(E > E_T) = 1$. As cosmic rays with such high energies are relatively rare the uncertainty in E_T should not strongly affect our results.

Absorption Rates. We show our nominal absorption rate for protons as the bold curve in Fig. 2. We also show, as dashed lines, the results for a pessimistic $(D_\oplus, \alpha, \beta) = (0.01, 2, 0.5)$, and optimistic (0.1, 1.5, 2) choice of diffusion parameters; and, as light, solid curves, three different absorption coefficients ($A = 0.001, 0.01, 0.1$). We also show the naive flux from Eq. 2.

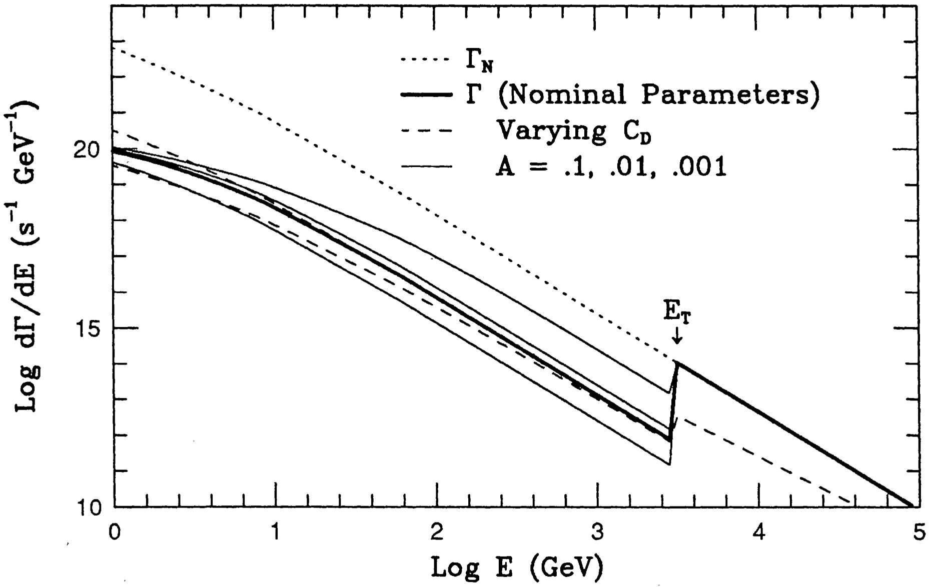

Figure 2: Absorption rate of cosmic ray protons by the sun. The bold curve is our nominal result. Varying the diffusion parameters results in the dashed curves. Varying the absorption coefficient yields the light, solid lines. The naive result (Eq. 2) is shown as a dotted curve for comparison.

The γ-ray Albedo

In calculating the γ-ray albedo we distinguish between two energy regimes; $E < E_T$ and $E > E_T$. As stated above, for $E > E_T$, cosmic rays are not trapped on flux lines and we may ignore local magnetic fields. The γ-ray albedo of these cascades will be very small, with contributions only from incident protons grazing the photosphere. Primaries with $E < E_T$, on the other hand, are assumed to stay within the flux tubes. Due to magnetic mirroring the albedo from these cascades may be significant.

Two Models for Cascade Propagation. Nearly vertical cosmic rays in the interior of the loss cone interact before being mirrored, *i.e.* while still having a downward velocity (Fig. 3a). At the boundary of the loss cone, however, is a region where protons may interact *after* being mirrored (Fig. 3b). These interactions will contribute to an upward flux of gamma-rays. We find that there is roughly a 25% chance that primary interactions will take place after the primary has been mirrored. Since γ-ray mean free paths are comparable to those for the primary hadrons, the albedo of the sun is considerable.

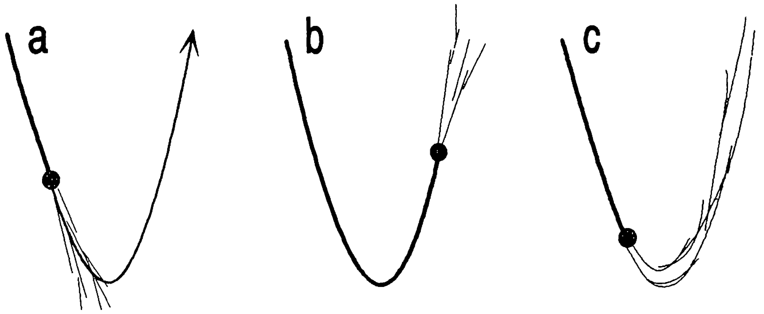

Figure 3: Cascade geometries for production of the γ-ray albedo. Shaded circles indicate interaction sites. Heavy lines show the primary trajectory before the interaction. The curved arrow in a) indicates the path the primary would take if no interaction occurred. a) Interaction occurs before the primary is mirrored. No albedo is produced if the cascade develops linearly. b) Interaction occurs after the primary is mirrored. This case contributes to the albedo. c) Interaction occurs early, but if the whole cascade is mirrored albedo photons may still result.

Another aspect of the low energy cascades is that the charged particles will follow the same trajectory the parent cosmic ray would have followed if it had not interacted; *i.e.* the whole cascade is to some extent mirrored (Fig. 3c), even though some of the cascade energy is neutral. To explore this effect we took two extreme models; one where the cascade developed along a constant zenith angle, and one where it developed along the path of a charged particle being mirrored out of the photosphere. In the first model photons can arise only from incident cosmic rays that interact after being mirrored, but in the second even cosmic rays which interact while moving downward can produce an upward flux of γ-rays.

Given these preliminaries, we calculate the γ-ray albedo by evolving 'atmospheric' cascades from the point where the primary cosmic ray interacts, through the solar material, to the surface. In the first model, the path length distribution is given by the slant depth from the interaction site. Cascades from primaries which interact before being mirrored are given infinite path lengths and produce no albedo γ-rays. In the second model the path lengths are computed as if all particles are charged, in which case all cascades may in principle produce albedo γ-rays.

γ-ray Production. The γ-ray flux at Earth is given by

$$\phi(E_\gamma) = \frac{1}{4\pi r_\oplus^2} \frac{dL_\gamma}{dE_\gamma}, \tag{5}$$

where the γ-ray luminosity of the sun is given by

$$\frac{dL_\gamma}{dE_\gamma}(E_\gamma) = \sum_i \int_E^\infty Y_i(E_\gamma, E_i)\Gamma_i(E_i) dE_i. \tag{6}$$

The sum over i includes both p and ^{4}He primaries, and Γ_i is given by Eq. 3. The γ-ray yield per absorbed primary of energy E is given by averaging over the path length distribution

$$Y_i(E_\gamma, E_i) = \int y_i(E_\gamma, E_i, x) \frac{dP_i}{dx} dx, \tag{7}$$

where y_i is the yield of photons of energy E_γ that result from cascades with path length x initiated by primaries of energy E_i, and dP_i/dx is the probability that a primary of species i produces a cascade with path length x. In separating $P_i(x)$ and $\Gamma_i(E)$ we have ignored the slow energy dependence of the hadronic cross-section. The yields, y_i, are calculated using standard Monte Carlo techniques[6,7] including both hadronic and electromagnetic interactions. Note that the density is low enough that for primaries with $E < E_T$, all mesons decay before they are absorbed or stop.

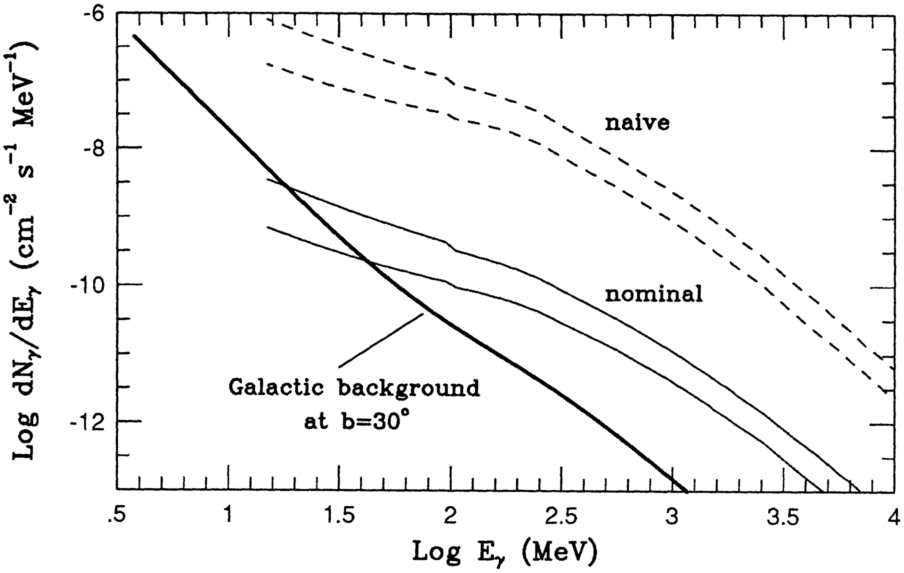

Figure 4: Photon flux at Earth. The solid (dashed) curves show results for the nominal (naive) absorption rate. In each pair, the upper curve shows a model where the cascades are mirrored, while the lower curve assumes the cascades follow straight trajectories. The heavy curve shows the galactic background at $b = 30°$.

Results. The results of our γ-ray calculations are illustrated in Fig. 4. The expected background is due to cosmic ray collisions with intergalactic gas[8], combined with observational data[9] below 200 MeV, and is shown for galactic latitude $b = 30^\circ$. The background should scale as $1/\sin b$. Both signal and background are given for a solid angle equal to the solar disk. The signal is larger than the galactic background for reasonable assumptions about cosmic ray absorption.

Other Albedo Products

We have performed similar calculations[1] to estimate the albedos for other cascade products, which we summarize here.

Neutrons. From the perspective of the GRO the most interesting possibility is a quiet time flux of high energy neutrons from the sun. The primary production mechanisms for neutrons are spallation reactions of ^{4}He and charge exchange interactions between incident protons and target hadrons. Neutrons are unstable, so there is no galactic background to speak of, but as the distance to the sun is comparable to the neutron lifetime, neutrons produced on the sun may still reach the Earth before they decay.

The geometry of the neutron production mechanism is similar to that for photons - the albedo arises from cascades that are mirrored or for which the primary was mirrored before interacting. For neutron production we modified our Monte Carlo of the cascades to include explicit charge separation of protons and neutrons.

We estimate a quiet time neutron flux of $I_n(E_n > 100 \text{ MeV}) \simeq 5 \times 10^{-8}$ cm^{-2} sec^{-1}, approximately a factor of 10^4 below the pre-GRO observational limits[12]. Both COMPTEL[13] and OSSE[14] have sensitivity to neutrons, as evidenced by their detection of neutrons during the June 1991 flares. However, their capabilities are not nearly good enough to detect our predicted quiet time flux. For example, COMPTEL's source sensitivity to photons is not quite 10^{-4} cm^{-2} sec^{-1}, and it's neutron sensitivity is even less. It is interesting to note that the integrated neutron flux during the June 9 flare corresponds to ~ 30 yr of our predicted quiet time flux, albeit in a somewhat lower energy band.

Neutrinos. Neutrinos produced by solar cascades are potentially observable through their conversion to a flux of upward going underground muons. The calculation for neutrinos differs qualitatively from that for photons in that the high energy cascades dominate the signal. The relative importance of the high energy cascades arises since they are essentially unaffected by diffusion in the IMF and corona and because there is a roughly linear increase in both the muon production cross-section and range with E_ν. Also note that neutrinos (unlike photons) are not generally absorbed by the sun, and so there is no cutoff at $E > E_T$.

For the neutrino signal the principle background is the flux of neutrinos produced in *terrestrial* cascades[11]. For cascades with $E > 500$ GeV the sun is ~ 10 times more efficient at producing neutrinos than the Earth, due primarily to the larger scale height of the solar atmosphere. As a result if a neutrino telescope could resolve the sun, detection would be signal limited - not background limited. However, for our nominal model we calculate an underground muon flux of $I(E_\mu > 10 \text{ GeV}) \sim 5 \times 10^{-17}$ cm^{-2} sec^{-1}, which is less than one event per year at any operational neutrino telescope, and so we conclude that the neutrino signal is currently unobservable.

Antimatter. Finally, we have considered antimatter signals, but do not find them promising. Antiprotons and positrons are charged, and so lack a directional signal. Antineutrons would be difficult to distinguish from a much more copious neutron flux.

Future Directions

We have made a reasonable estimate of the γ-ray albedo from cosmic ray absorption by the sun; however, there are a number of issues that still need to be addressed.

Observing Strategies and Phase I EGRET Observations. The first question - is the signal really there? If the sun were resolved by EGRET then the source strength would be many times the galactic background. However, EGRET's point spread function δ is greater than the size of the sun[15] ($\delta = 1.4°$ for 150 MeV $< E <$ 500 MeV) and so it is important to reduce the background by observing the sun while it is at high galactic latitude. During the phase 1 observing program there are 29 scheduled 2 week observing periods (and several shorter ones), of which 4 (fortuitously) have the sun within EGRET's 20° HWHM field of view during part or all of the observing period. The three best of these (Oct. 3, 1991; Aug. 6, 1992; and April 2, 1992) have the sun's galactic latitude at $|b| > 44°$. It is therefore reasonable to estimate EGRET's exposure during the phase one viewing period as $\sim 1.8 \times 10^9$ cm^2 sec, which would give a yield of approximately 100 photons with $E >$ 100 MeV. By comparison, the total number of galactic background photons detected within δ of the sun during the same exposure is expected to be $\sim$ 240. A three sigma excess would then correspond to roughly 50 photons, and assuming our estimates of the signal are correct, the sun should be an observable source.

Improvements to the Calculations. In the event of a successful detection, there are a number of improvements that could be made without abandoning the basic structure of our model. We anticipate that some of these would increase our predicted flux if included and some would decrease it, but taken as a whole they would not change the results by an amount large compared to the uncertainty in a particular choice of diffusion and canopy parameters.

In no particular order - *a*) Eliminate the discontinuous treatment of absorption at E_T. This should not dramatically affect the flux estimates for E_γ in the range 100 MeV – 1 GeV since their parent primaries typically have $E \ll E_T$. *b*) Include an energy dependent leakage term in the calculation of the absorption rate. In the present model, a low energy primary which reaches the sun is either absorbed in a flux tube or eventually diffuses back out of the solar system. It is also possible that some fraction will leak across field lines to be absorbed in the space between flux tubes. Since these primaries and the resultant cascades would not be mirrored their contribution to the albedo would be suppressed. *c*) In the present Monte Carlo, charged particle secondaries that escape the sun were thrown away; however, it would be consistent with the treatment of non-absorbed primaries to assume that these charged secondaries eventually return to the sun and are absorbed, continuing the cascade after a 'pause'. We estimate that this would increase the γ-ray signal by a factor of 2-3. *d*) Include charge separation in the electromagnetic part of the cascade. *e*) Make the model of the flux tubes two dimensional to account for their finite radial extent, and to allow the magnetic field to have a horizontal component. *f*) Incorporate modulation by the solar wind into the incident flux calculations.

Phenomenological Considerations. Assuming that the signal is seen, there are various features of the γ-ray signal that may be useful either as diagnostics of the absorption model, or as indicators of transport phenomena around the sun. An obvious example is measuring the spectrum of the γ-ray flux and comparing it to the model predictions. Another possibility arises from noting that most of the interplanetary magnetic field is anchored to one of the polar regions of the sun. If the primaries find it difficult to cross field lines (*i.e.* diffusion takes place parallel to but not perpendicular to the local magnetic field) then one might expect the polar caps to be significantly brighter in γ-rays than the equator. Although the diameter of the sun is smaller than EGRET's point spread function one might still hope to pick out a weak dipole pattern upon gathering sufficient data, especially at higher photon energies where EGRET's resolution is better.

This is not a complete list, but as these two examples indicate a study of the γ-ray flux from the sun can potentially provide useful information about γ-ray production mechanisms and cosmic ray transport in the solar system, and by extension to other sites in the Universe.

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