Gamma ray production mechanism

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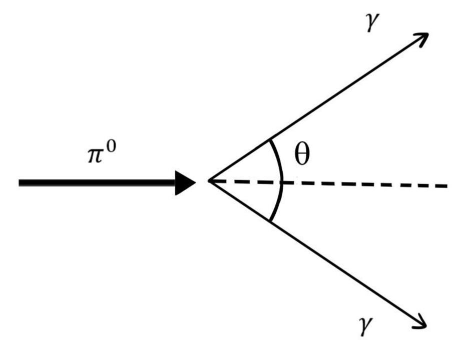
Solar gamma ray emissivity

When the cosmic ray hit the sun, the **proton in the cosmic ray** and the proton in the solar atmosphere will undergo inelastic proton-proton interactions. The subsequent decay of the secondary neutral pion and eta mesons will produce gamma-ray and some of the photon will escape from the sun. Solar disk gamma ray emission was first detected by EGRET and was done with better precision by Fermi-LAT.

The neutral pion decay mechanism is the main interest in this study:

$$\pi^0 \to \gamma\gamma$$



Neutral pion is produced from the p-p interaction happened when the protons in cosmic ray collide with the solar atmosphere, the production rate of pion mesons by definition can be expressed as:

$$q_\pi(E_\pi) = \tilde{n}\frac{cn_H}{K_H}\sigma_{inel}J_p$$

where $\tilde{n}$ and K_H are free parameter

Here n_H is the density of the sun, σ_{inel} is the cross-section area of inelastic collision. Together with the speed of light, $cn_H\sigma_{inel}$ give the probability of interaction per particle per second (optical depth); and J_p is the proton spectrum in cosmic ray which is referenced from Particle Data Group 2020.

Hence, the emissivity of gamma ray(**production rate per volume per solid angle**) is as follow:

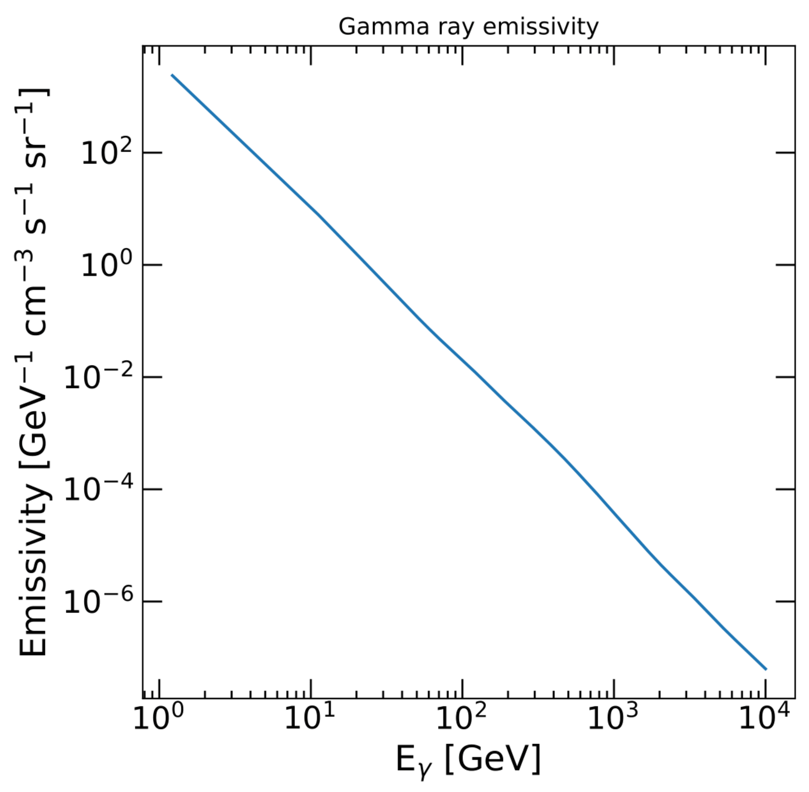
$$\varepsilon = \frac{dN_\gamma}{dE_\gamma} = 2\int_{E_{min}}^{\infty}\frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}}dE_\pi$$

$$f(E_\gamma|E_\pi) = \begin{cases} \sqrt{E_\pi^2 - m_\pi^2}^{\,-1} & for\ \frac{1}{2}E_\pi(1-\beta_\pi) \le E_\gamma \le \frac{1}{2}E_\pi(1+\beta_\pi) \\ 0 & otherwise \end{cases}$$

Due to the kinematic with relativistic correction, the minimum energy for pion required to produce a photon with given energy is found to be $E_\gamma + m_\pi^2/4E_\gamma$ which act as the lower integration limit. The factor of $\sqrt{E_\pi^2 - m_\pi^2}^{\,-1}$ is required for transferring the pion spectrum to gamma-ray spectrum.

Emissivity plot

The gamma ray emissivity obtained is as follow:



The trend of the emissivity mainly contributed by the proton spectrum in cosmic ray (J_p). Since the σ_{inel} can be considered as a constant in this energy range. Hence, the only variable left is proton spectrum and distribution of gamma ray(which is only a function of momentum).

Reference

[1] K. Abe et al., Astrophys. J. 822, 2, 65 (2016)
[2] Nisa, M. U., et al. "The Sun at GeV--TeV Energies: A New Laboratory for Astroparticle Physics." *arXiv preprint arXiv:1903.06349* (2019).
[3] S. R. Kelner, F. A. Aharonian, and V. V. Bugayov. "Energy spectra of gamma-rays, electrons and neutrinos produced at proton-proton interactions in the very high energy regime." *Phys.Rev.D 74* (2006).
[4] Bei Zhou, Kenny C. Y. Ng, John F. Beacom, Annika H. G. Peter (Dec 7, 2016)[5] Sun, Xudong. "Notes on PFSS Extrapolation." (2009).

Set up theoretical boundary for gamma ray energy flux

The energy flux can be obtained by integrating the emissivity of the volume of the emission source and follow the inverse square law considering the flux is observed from Earth.

$$E_\gamma{}^2\cdot\frac{dF_\gamma}{dE_\gamma} = E_\gamma{}^2\cdot\frac{\int\varepsilon\, dV}{4\pi D^2}$$

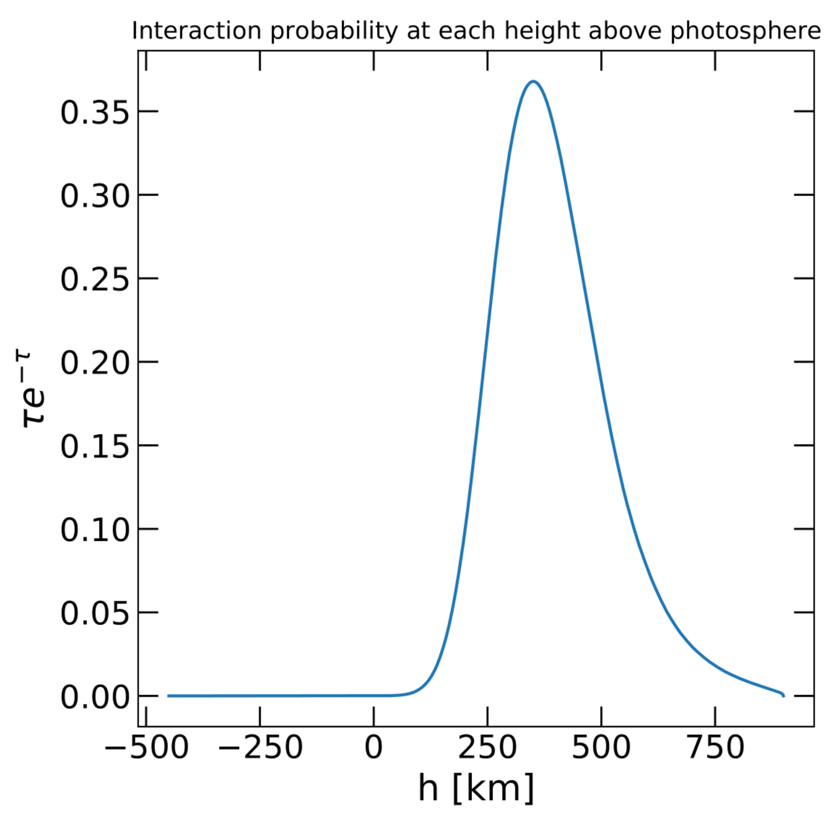
Maximum case: Assuming all cosmic ray are reflected on the photosphere and produced gamma rays all escape from the sun, where τ(optical depth) is chosen to be around 2-3. And the factor of $e^{-\tau}$is also introduced for accounting the probability of escape.

$$n_H\sigma_{inel}dR = \tau e^{-\tau}$$

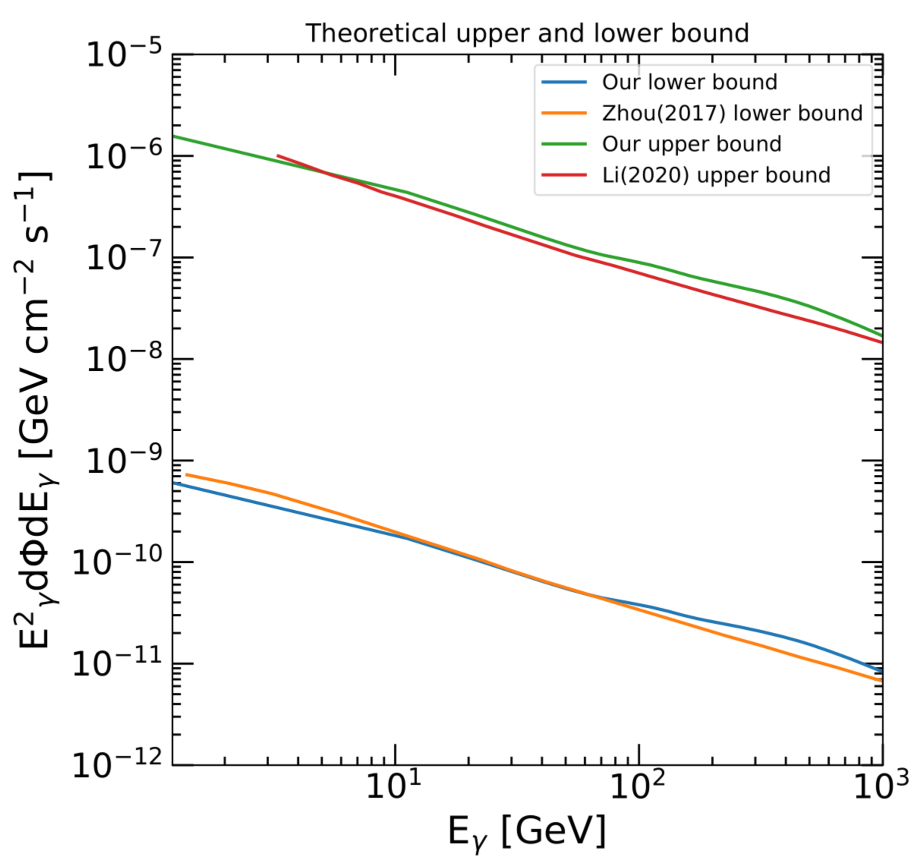
$$E_\gamma{}^2\cdot\frac{dF_\gamma}{dE_\gamma} = E_\gamma{}^2\cdot\frac{\int\varepsilon dV}{4\pi D^2} = E_\gamma{}^2\cdot \underline{n_H\sigma_{inel}dR}\cdot\frac{4\pi R^2}{4\pi D^2}\frac{2\tilde{n}c}{K_H}\int_{E_{min}}^{\infty}\frac{J_p}{\sqrt{E_\pi^2-m_\pi^2}}dE_\pi$$

Minimum case: Assuming gamma ray emission from solar limb with zero magnetic field, line of sight integral of the optical depth is required as the density of the sun is a function of its radius.

$$E_\gamma{}^2\cdot\frac{dF_\gamma}{dE_\gamma} = E_\gamma{}^2\cdot\frac{\int\varepsilon\, dV}{4\pi D^2} = E_\gamma{}^2\cdot\underline{\int\tau e^{-\tau}d\Omega}\cdot\frac{2\tilde{n}c}{4\pi K_H}\int_{E_{min}}^{\infty}\frac{J_p}{\sqrt{E_\pi^2 - m_\pi^2}}dE_\pi$$

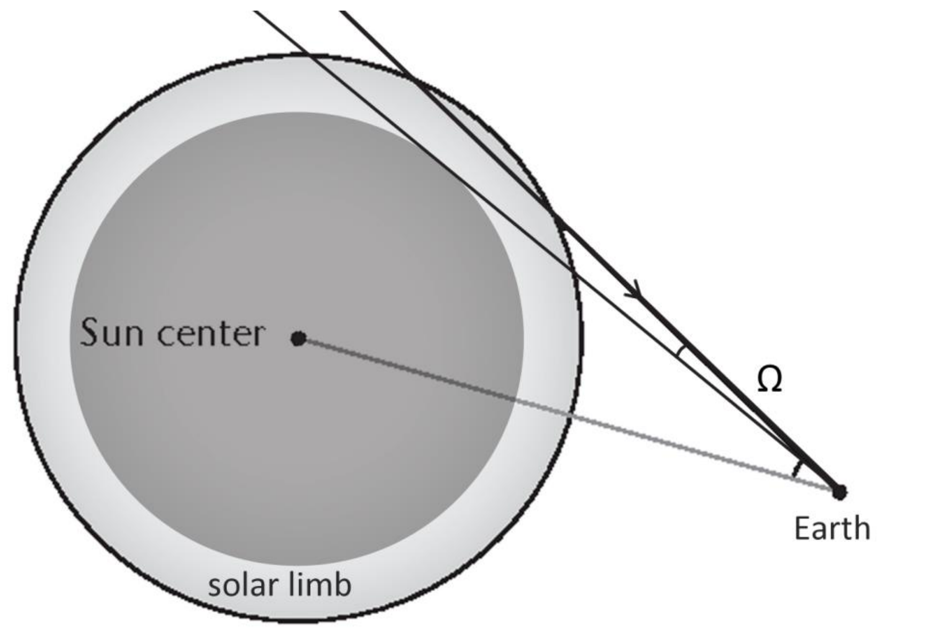


It shows the probability of escaped gamma ray against the height(h) above the photosphere. The probability peak is located around 400km above the photosphere which indicate the most probable region the gamma ray emitted from the sun and the width of the peak is where we define our region of solar limb.



For the upper bound, the emission source is assumed to be a shell structure and the emission of photon is **isotropic** in every unit volume; As for the lower bound, the emission source is assumed to be the solar limb and the produced photon travel in the **same direction** as the original incoming proton.

The left shows the comparison of the flux upper boundary(green) and lower boundary(blue) with the previous work done by LI(2020) and Zhou(2017) respectively.



Solar limb is the region of the sun where the cosmic rays just graze its surface on the trajectories toward Earth(where $\tau e^{-\tau}$ is significant). Further assuming the gamma rays produced remain in the same direction of the neutron pion.