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Flare γ-ray continuum emission from neutral pion decay

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Abstract

We investigate in detail the production of solar flare gamma ray emission above 10MeV via the interaction of high energy protons with the ambient solar atmosphere. We restrict our considerations to the broad-band gamma ray spectrum resulting from the decay of neutral pions produced in p-H reactions. Thick-target calculations are performed to determine the photon fluences. However, proton transport is not considered. Inferences about the form of the proton spectrum at 10-100MeV have already been drawn from de-excitation gamma ray lines. Our aim is to constrain the proton spectrum at higher energies. Thus the injected proton spectrum is assumed to have the form of a Bessel Function, characteristic of stochastic acceleration models, up to kinetic energies of a few hundred MeV, coupled to a power-law in proton kinetic energy at higher energies. The detailed shape of the gamma ray spectra around 100 MeV is found to have a strong dependence on the spectral index of the power-law and on the turnover energy (from Bessel function to power-law). As would be expected the harder the proton spectrum the wider the 100 MeV feature. The photon spectra are to be compared with observations and used to place limits upon the number of particles accelerated and to constrain acceleration models.

Gamma ray production

We require the production spectrum of γ-ray photons from the decay of secondary π^o produced in p-H collisions in solar flares. This is given by

$$F_{pH}(\varepsilon_\gamma) = \frac{2S}{R^2}\int_{\varepsilon_\gamma+\frac{m_\pi^2}{4\varepsilon_\gamma}}^{\infty}\frac{dE_\pi}{p_\pi}\int_{T_{p,min}}^{\infty} dT_p . j_p(T_p)\int_{T_{p,min}}^{T_p}\frac{d\sigma(T'_p,T_\pi)}{dT_\pi}\frac{T'_p}{K}dT'_p \qquad (1)$$

where the integral over T'_p expresses the total number of pions per unit energy emitted by an average proton in time t, i.e. it allows for the proton spectrum to be modified by thick-target losses as the protons traverse the flaring loop; $j_p(T_p)$ [protons/cm^2/s/GeV] is the incident proton spectrum; $K = 2\pi e^4(m_p/m_e)\Lambda$ (Λ is the Coulomb logarithm relevant to protons); S is the flare area, typically $10^18 cm^2$; R=1AU; E_π/p_π are the total pion energy/momentum; T_p is the proton kinetic energy and $T_{p,min}$ is the minimum kinetic energy required by a proton in the lab. system to produce a pion of kinetic energy T_π. The differential cross-section for the production of a pion with energy T_p is given by

$$\frac{d\sigma(T_p,T_\pi)}{dT_\pi} = \langle\zeta\sigma(T_p)\rangle\frac{dN(T_p,T_\pi)}{dT_\pi} \qquad (2)$$

where $\langle\zeta\sigma(T_p)\rangle$ denotes the inclusive cross-section for the reaction $p+p\rightarrow\pi^o+$ anything and (dN/dT_π) is the normalised production spectrum of secondary π^o . We have ignored contributions from collisions of protons with alpha particles and heavier ions.

Pion production

The production mechanism for π^o from p-p collisions is dependent upon the kinetic energy of the incident protons. Comparison of the various models with accelerator data at various energies show that the production mechanism can be split into three distinct regions (Dermer 1986):

$\underline{T_p < 3GeV}$: Isobar model (Stecker 1970)

- pion production mediated by excitation of the $\Delta(1232)$ isobar which decays into a proton and a neutral pion. The distribution of pions from this decay mechanism is effectively isotropic in the lab. system.

$$\frac{dN}{dT_\pi} = \omega_r(T_p) \int_{m_p+m_{\pi^o}}^{s^{1/2}-m_p} dm_\Delta . B(m_\Delta).f(T_\pi; T_p, m_\Delta) \tag{3}$$

where

w_r is a normalisation factor.
B is the isobar mass distribution given by a Breit-Wigner distribution.
f is the normalised energy spectrum of pions in the laboratory system.
s is the total energy availbale in the centre-of-mass.

$\underline{T_p > 7GeV}$: Scaling model (Stephens and Badhwar 1981)

- pion production obtained via scaling arguments which imply asymptotic forms for the differential cross-sections

$$\frac{dN}{dT_\pi} = \frac{2\pi p_\pi}{\langle\zeta\sigma(T_p)\rangle} \int_{cos\theta_{max}}^{1} dcos\theta \left(E^* \frac{d^3\sigma^*}{dp^{3*}} \right) \tag{4}$$

where $E^*(d^3\sigma^*/dp^{3*})$ is the invariant cross-section for neutral pion production in p-p collisions (the asterisk denotes centre-of-mass quantities) and $cos\theta_{max}$ may be obtained from kinematic limitations.

$\underline{3GeV < T_p < 7GeV}$:

Between these two limiting energies neither of the above models fit the laboratory data very well and so we follow Dermer (1986) and extrapolate the normalised production spectrum linearly between these two limits.

Incident proton spectrum

Our choice of proton spectrum incident upon the target region is such that we have a Bessel function spectrum, characteristic of stochastic acceleration processes, up to some kinetic energy T_{p0} which is typically of the order of 100MeV since stochastic acceleration is only valid in the non-relativistic regime and a power-law spectrum at higher energies, viz.,

$$j_p(T_p) = A_N K_2[2(3p_p/m_p\alpha T)^{1/2}] \qquad T_p < T_{p0}$$

$$= A_N K_2[2(3p_{p0}/m_p\alpha T)^{1/2}](T_p/T_{p0})^{-\delta} \qquad T_p > T_{p0}$$

where

A_N is a normalisation factor to be determined from comparison with observations .
K_2 is the modified Bessel function (cf. Ramaty and Murphy 1987).
α is the acceleration efficiency.
T is the particle escape time from the acceleration region .
[typical value from fits to observations is $\alpha T = 0.02 - 0.04$]
T_{p0} is the turnover energy from Bessel function to power-law .

Results

In this section we display the form of our spectra for a variation of the spectral parameters, δ (the power-law spectral index) and αT (the hardness of the Bessel function spectrum), for a turnover energy equal to the threshold energy for pion production, $T_{p0} = 280MeV$, and the resulting photon spectra. We have also included the photon spectra obtained from a variation of T_{p0} with $\alpha T = 0.04$ and $\delta = -4$.

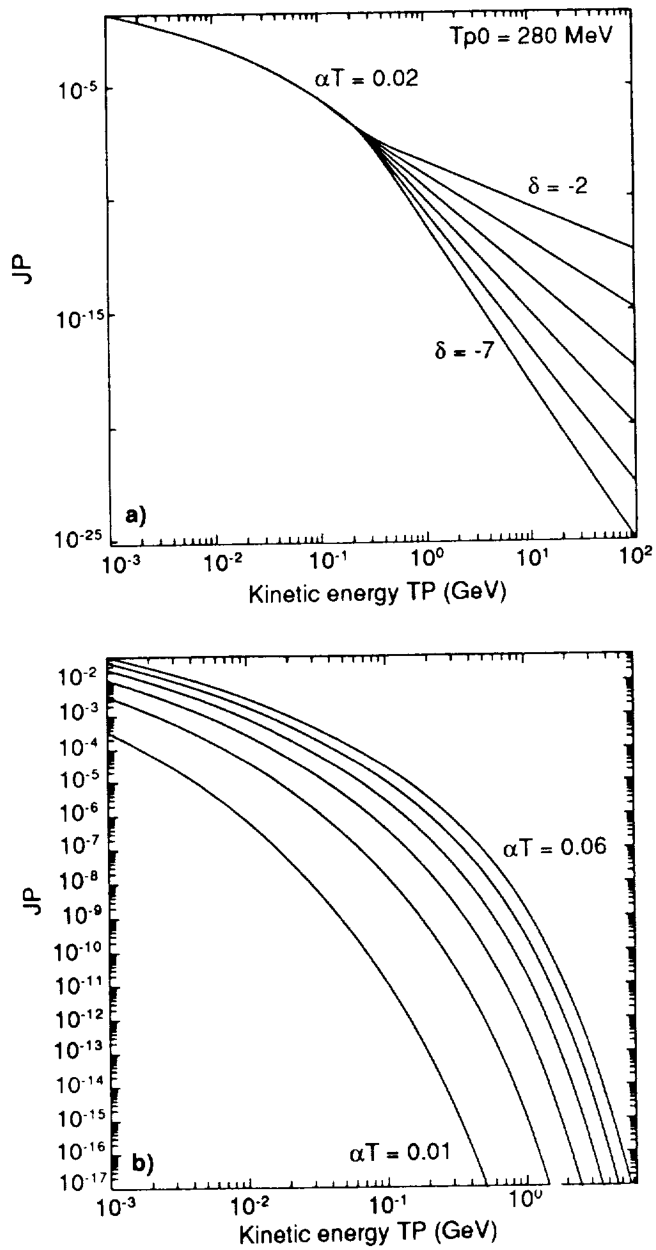

Figure 1: Injected proton spectra, J_p(protons/GeV/cm^2/s) **a)** Bessel function with $\alpha T = 0.02$ for $T_p < 280MeV$ (pion production threshold) and power-law of spectral index δ at higher energies. **b)** Bessel function spectra with range of spectral hardness αT (as a with turnover energy = ∞).

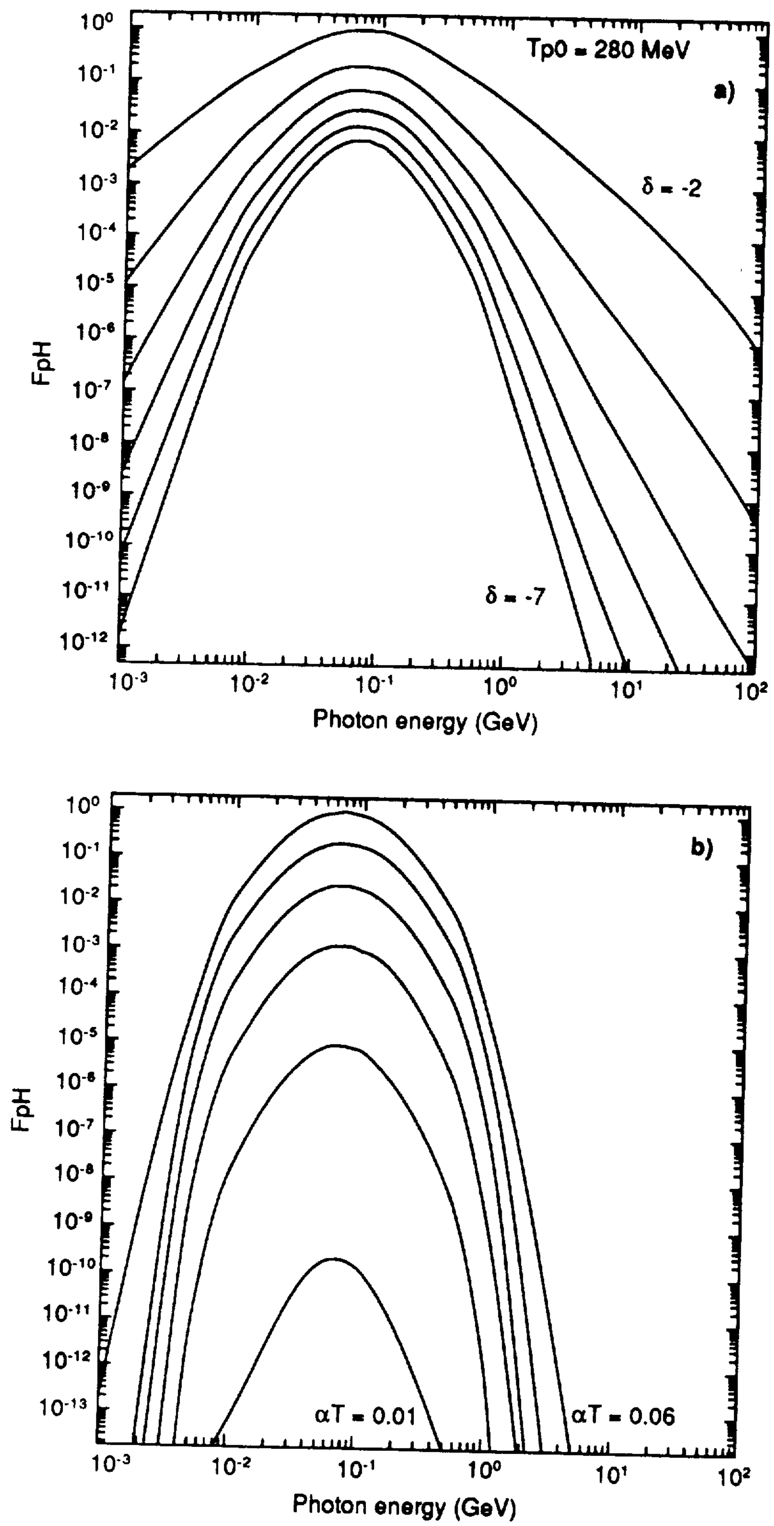

Figure 2: Gamma-ray spectra, FpH (photons/GeV/cm^2/s) resulting from the proton spectra shown in Figures 1. **a)** Bessel function/power-law spectra. **b)** Bessel function spectra.

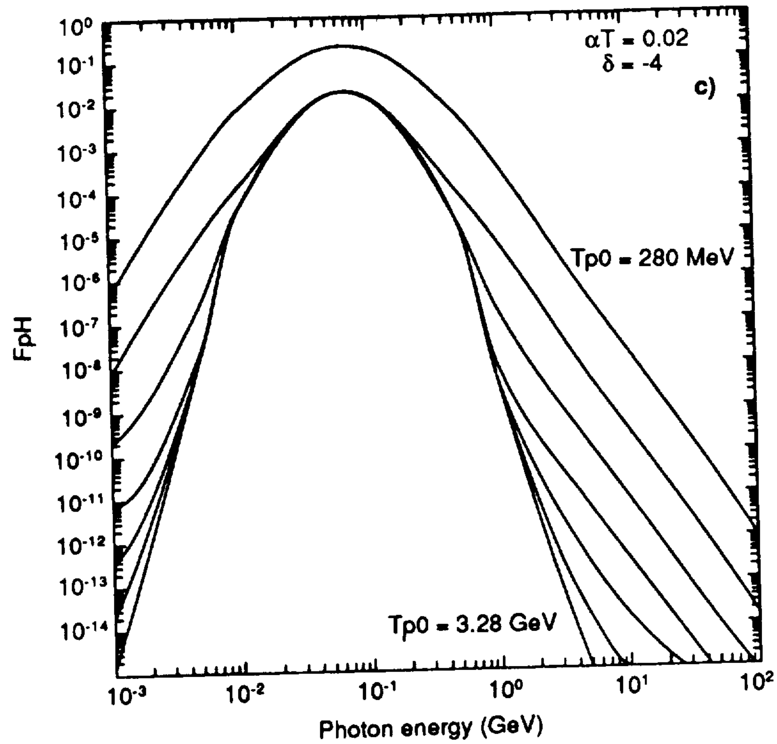

Figure 2c: Gamma-ray spectra, FpH (photons/GeV/cm^2/s) resulting from proton spectra similar to those of Figure 1a with a fixed $\delta = -4$ and $\alpha T = 0.02$ and the turnover energy T_{p0} allowed to vary.

Discussion and Conclusions

Our theoretical calculations show that the detailed structure of the 70MeV feature depends strongly upon the form of the accelerated proton spectrum at energies from 100MeV to a few GeV. The harder the proton spectra the wider the pion decay feature as one would expect. However, until a detailed comparison of our results are made with observation our conclusions are limited. There are a few observations which demonstrate a strong (possibly dominant) pion emission at energies of around 100MeV. Events such as the SMM event of June 3 1982 (studied in detail by Murphy et al. 1987) and possibly a couple of events from 1989 (Rieger - private communication) allow us some evidence for a neutral pion decay feature flattening the spectrum at ~70MeV. We intend to investigate these observations in more detail. Solar observations by the TASC spectrometer on The Compton Observatory should hopefully provide many more such data.

References

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