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NEUTRON AND GAMMA RAY PRODUCTION IN THE 1991 JUNE X-CLASS FLARES

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ABSTRACT

We present new calculations of pion radiation and neutron emission from solar flares. We fit the recently reported high energy GAMMA-1 observations with pion radiation produced in a solar flare magnetic loop. We calculate the expected neutron emission in such a loop model and make predictions of the neutron fluences expected from the 1991 June X-class flares.

Neutrons and gamma rays are produced in solar flares by accelerated particles interacting with the ambient solar atmosphere (e.g. Ramaty & Murphy 1987, Hua & Lingenfelter 1987a). Gamma ray continuum, gamma ray lines, and neutrons ranging in energy from tens of MeV to several GeV have been observed (e.g. Chupp et al. 1987; Rieger 1989). A series of X-class flares, accompanied by a variety of gamma ray and neutron signatures, occurred during the first two weeks of June 1991. The gamma ray spectrum observed from one of these flares (June 15) extended to energies in excess of 1 GeV (Akhimov et al. 1991). The comparison of these observations with calculations of solar flare gamma ray emission resulting from pion decay (Mandzhavidze & Ramaty 1992) allows us to derive the number of protons accelerated to energies greater than several hundred MeV and the proton energy spectrum in this energy range. We use this information, as well as information from flares observed previously, to provide estimates of the neutron and 4 - 7 MeV nuclear gamma ray fluences expected from the June 1991 flares. Our neutron study is based on new calculations of anisotropic neutron production and transport in the solar atmosphere.

We perform our calculations in a solar flare magnetic loop model in which the bulk of the nuclear reactions occur in the sub-coronal portions of the loop where the magnetic field decreases with height from the photosphere to the corona (Zweibel & Haber 1983; Hua, Ramaty & Lingenfelter 1989; Gueglenko et al. 1990). We take into account the mirror force in the sub-coronal portions and pitch angle scattering due to plasma turbulence in the coronal portion. We calculate the neutron and gamma ray production by taking into account all the relevant production cross sections as well as the loss mechanisms affecting the primary particles. We also evaluate the attenuation of the emergent radiations due to the interactions of the neutrons and gamma rays with the ambient atmosphere.

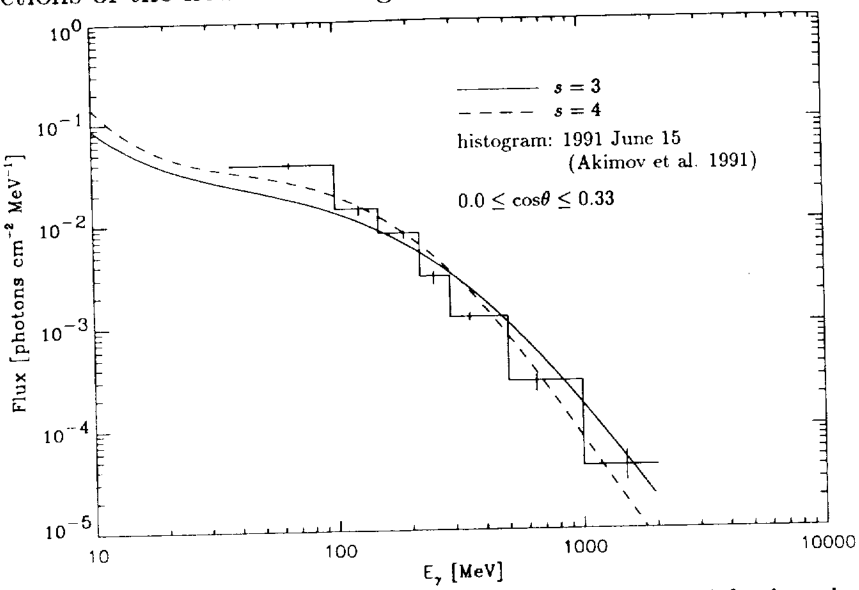

Fig. 1. Observed solar flare gamma ray spectrum fitted with time integrated, directional pion radiation averaged over the indicated range of heliocentric angles. The density in the sub-coronal portions of the loop is assumed to have a constant scale height of 200 km, the coronal portion of the loop has a radius of 10^9 cm, and pitch angle scattering in the corona is ignored. The primary particles have power law spectra with indexes s normalized to $N_p(> 30\text{MeV}) = 1.4 \times 10^{31}$ for $s = 3$ and $N_p(> 30\text{MeV}) = 4.5 \times 10^{32}$ for $s = 4$.

We first consider the high energy gamma ray emission resulting from pion decay. The neutral pions decay into gamma rays directly, while the charged pions decay (via muons) into positrons and electrons which produce gamma rays by bremsstrahlung and annihilation in flight (Murphy, Dermer & Ramaty 1987). Calculations of pion radiation in a magnetic loop model have recently been carried out by Mandzhavidze & Ramaty (1992). In Figure 1 we show their results, extended to 2 GeV and fitted to the high energy gamma ray spectrum observed (Akimov et al. 1991) from the 1991 June 15 flare (location: N33, W69; heliocentric angle cosine $\cos\theta = 0.30$). The calculated spectra, representing angle integrated averages over $0 < \cos\theta < 1/3$, are for power law proton and α particle spectra with spectral index s and no pitch angle scattering in the corona. The normalization to the data requires that the total number of protons above 300 MeV (the effective pion production threshold) be 1.4×10^{29} and 4.5×10^{29} for $s = 3$ and $s = 4$ respectively. As can be seen from Figure 1, the spectrum for $s = 4$ provides a somewhat better fit to the data than that for $s = 3$, although neither the $s = 4$ nor the $s = 3$ curves can account for the observed emission below 100 MeV. It is possible that some of this emission is bremsstrahlung from primary electrons. It is also possible that the spectrum of the interacting protons varies during the course of the flare, as was the case for the 1982 June 3 flare (see Mandzhavidze & Ramaty 1992).

To calculate the neutron and nuclear deexcitation line fluences it is necessary to extrapolate the proton and α particle spectra to lower energies. The above normalizations for the 1991 June 15 flare yield $N_p(> 30\text{MeV}) = 1.4 \times 10^{31}$ for $s = 3$ and $N_p(> 30\text{MeV}) = 4.5 \times 10^{32}$ for $s = 4$. These values of $N_p(> 30\text{MeV})$ are very similar to those derived (Murphy & Ramaty 1984; Hua & Lingenfelter 1987a) from 4 - 7 MeV deexcitation line and neutron observations of a dozen previous flares seen with SMM and other experiments.

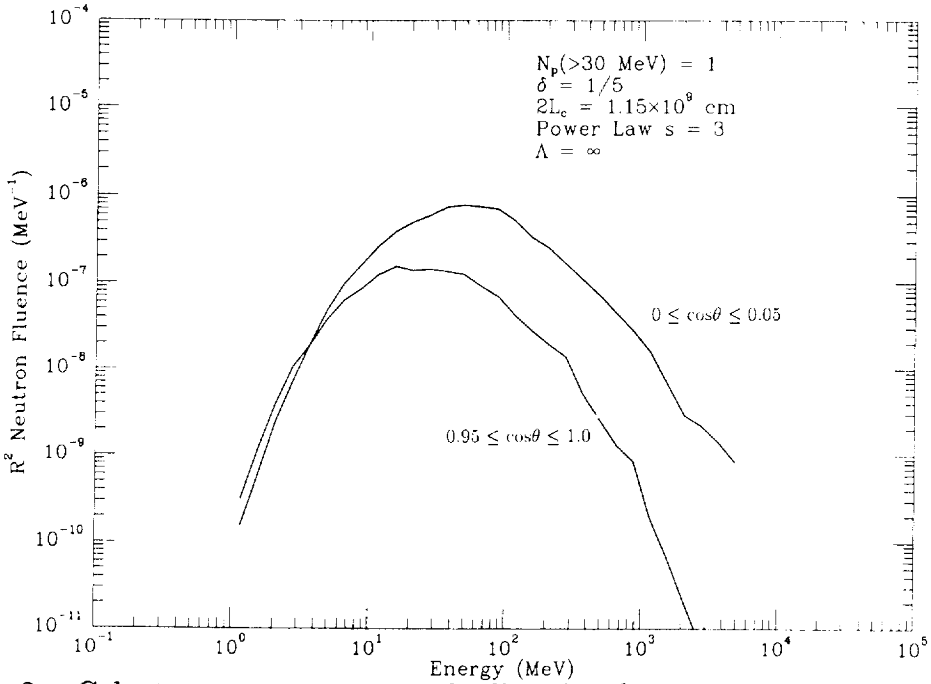

Fig. 2. Calculated time integrated, directional neutron spectra at Earth. The primary particles have power law spectra with indexes s; θ is the heliocentric angle at the flare site, δ is the convergence parameter of the sub-coronal magnetic field, $2L_c$ is the loop length, and Λ is the pitch angle scattering diffusion mean free path (see Hua et al. 1989 for details).

We turn now to the neutron calculations. Using the loop model described in detail by Hua et al. (1989) and updating the nuclear data given in Murphy et al. (1987) and Hua & Lingenfelter (1987a), we have carried out new calculations of neutron production. Then using the neutron transport code developed by Hua & Lingenfelter (1987b), we have calculated the time dependence, angular distribution and energy spectrum of the neutrons escaping from the Sun. In Figures 2, 3, 4 and 5 we show time integrated directional neutron energy spectra at Earth for power law proton and α particle spectra at the Sun ($s = 3$ and $s = 4$) normalized to $N_p(> 30\text{MeV}) = 1$. The parameter δ defines the convergence of the magnetic flux tube and $2L_c$ is the total length of the loop. For $\delta = 1/5$ the magnetic field increases by a factor of 10 from the corona to the photosphere. In Figures 2 and 4 there is no pitch angle scattering ($\Lambda = \infty$), whereas in Figures 3 and 5 the pitch angle scattering rate is close to saturation ($\Lambda = 4.6 \times 10^{10}$ cm). In this case the particles are isotropized in the corona on a time scale comparable to their transit time along the loop. The quantity Λ is the pitch angle scattering mean free path, which can be related to the energy density in the turbulent plasma waves (see Miller & Ramaty 1989). The net effect of saturated pitch angle scattering is to cause the particles to interact in the loss cone rather than near their mirror points. This moves the interaction region deeper into the atmosphere and causes the angular distribution of the interacting particles to be more downward peaked than in the case of no pitch angle scattering when their distribution peaks at directions tangential to the photosphere (for a mean loop magnetic field which is radial in the photosphere). The two curves in each figure correspond to averages over the indicated ranges of heliocentric angle cosines.

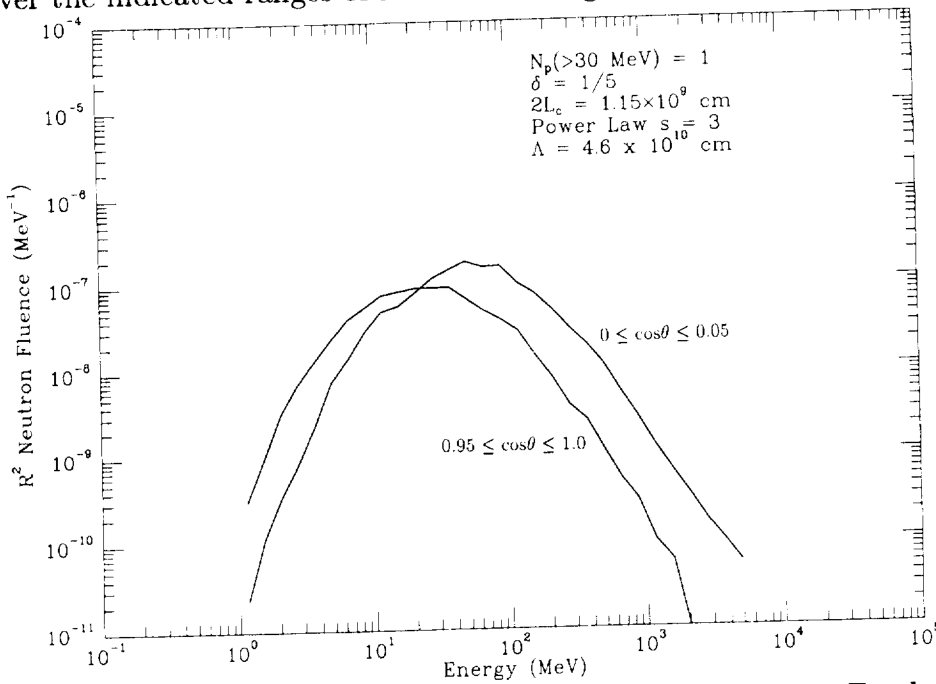

Fig. 3. Calculated time integrated, directional neutron spectra at Earth (see caption to Fig. 2)

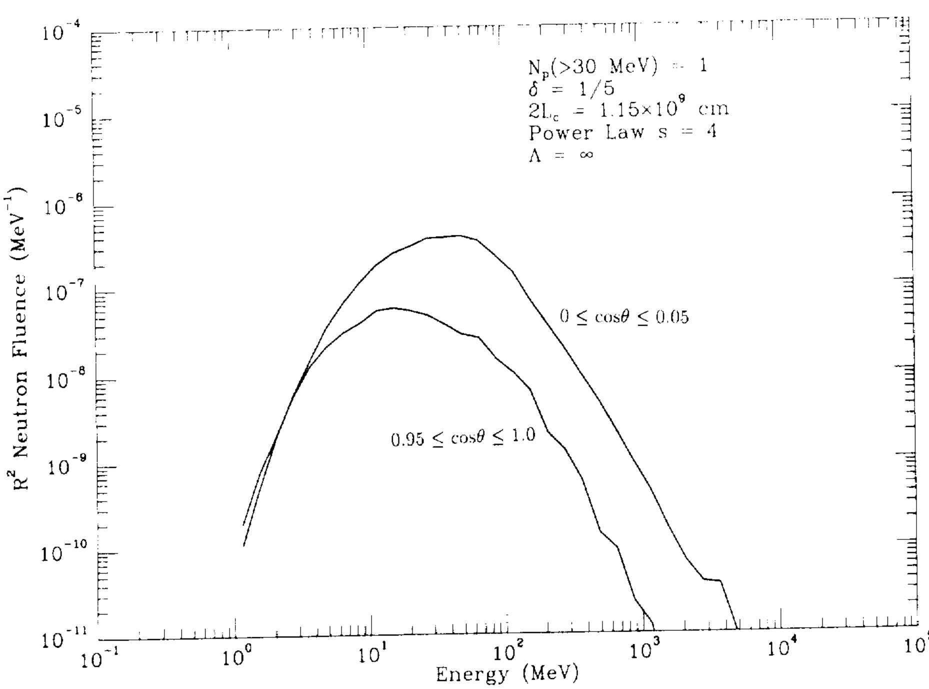

Fig. 4. Calculated time integrated, directional neutron spectra at Earth (see caption to Fig. 2).

We see that the differential neutron spectra at Earth reach their maxima in the energy range from about 10 to 100 MeV, owing to the combined effects of the decreasing neutron production spectra and increasing neutron survival probability with increasing energy. Neutron emission from solar flares is quite anisotropic, the anisotropy being most pronounced at high energies and when there is no pitch angle scattering. In general, the neutron emission from limb flares is larger than from flares at disk center, except at low energies where the neutron fluence from limb flares is attenuated during transit in the solar atmosphere. By causing the neutrons to be produced deeper in the atmosphere, pitch angle scattering increases the attenuation and hence decreases the anisotropy. In fact, as can be seen from Figures 3 and 5, the neutron emission is significantly limb darkened at low energies ($\lesssim$ 10 MeV).

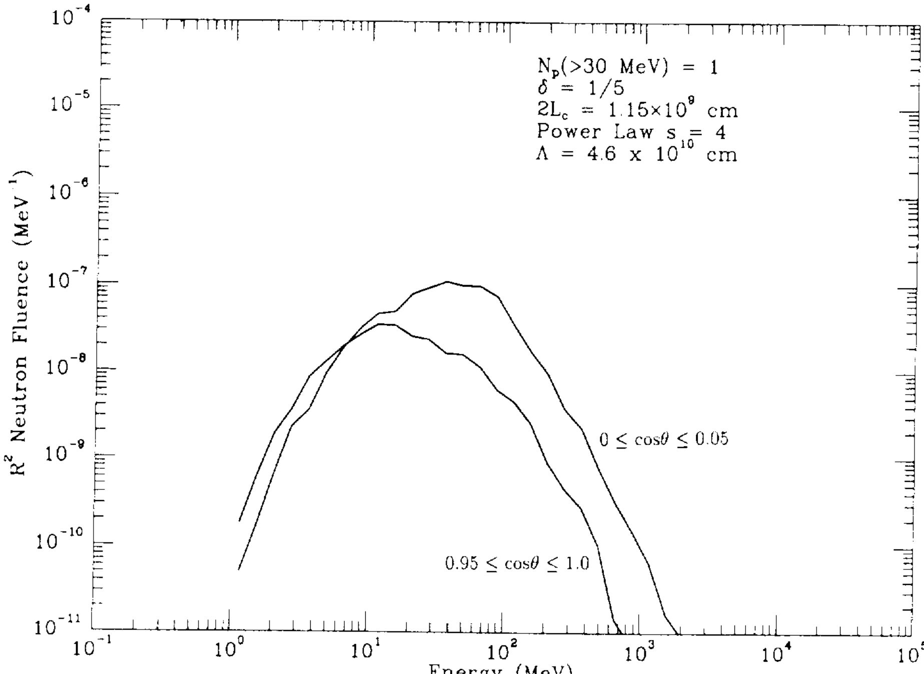

Fig. 5. Calculated time integrated, directional neutron spectra at Earth (see caption to Fig. 2).

To better assess the expected neutron fluxes from large (class X) flares, we show in Table 1 energy integrated neutron fluences in two energy bands for a fixed normalization ($N_p(>30\text{MeV}) = 5 \times 10^{32}$), for limb and disk-center flares, and for the cases of no pitch angle scattering and saturated scattering. Also shown in Table 1 are nuclear deexcitation line fluences derived from the calculations of Murphy & Ramaty (1984). This line emission is essentially isotropic and unattenuated, even in the case of saturated pitch angle scattering (Hua et al. 1989). We see that the neutron fluences above 100 MeV are very strongly limb brightened, especially when there is no pitch angle scattering. With pitch angle scattering the limb brightening is less pronounced, although it is still quite strong above 100 MeV. There is also limb brightening below 100 MeV (we expect limb darkening only below about 10 MeV), although with saturated pitch angle scattering and the flatter primary particle spectrum ($s = 3$), the limb brightening amounts to only a factor of 2.

Given that the normalization assumed in Table 1 is typical of the X-class flares of June 1991, the neutron fluences shown in this Table should be representative of the expected neutron fluxes. The detailed modeling of these flares, however, must await the release of all the available data, including deexcitation line emission, 2.223 and 0.511 MeV line emission, neutrons, and gamma ray emission from pion decay and primary electron bremsstrahlung.

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TABLE 1

Nuclear deexcitation and neutron fluences at Earth for the case of no pitch angle scattering in the coronal portion of the loop (no pas) and saturated pitch angle scattering (pas). The normalization is $N_p(> 30\text{MeV}) = 5 \times 10^{32}$.

	s = 3		s = 4	
Φ_{4-7} (ph/cm^2)	62		132	
	$\Phi_n(< 100$ MeV) (n/cm^2)			
	no pas	pas	no pas	pas
Limb	138	28	63	18
Disk	22	13	6.7	3.3
	$\Phi_n(> 100$ MeV) (n/cm^2)			
	no pas	pas	no pas	pas
Limb	250	41	33	7.1
Disk	14	6.5	2.2	0.9

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