GAMMA RAY EMISSION FROM A SOLAR FLARE OBSERVED ALSO AS A GROUND LEVEL EVENT

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Abstract

The Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite recorded strong emissions from a solar flare on 1982 December 7, near the west limb, which was also a medium sized Ground Level Event (GLE). The spectrum showed several gamma-ray lines. The time integrated flux (fluence) of the carbon and oxygen lines between 4 and 8 MeV was about 160 Photons/cm^2.

Assuming, that the spectral form of the particles measured in space and by neutron monitors and the spectral form of the particles which caused the gamma-rays was the same, the computed photon fluence above 25 MeV (resulting from pion decay) is larger by more than an order of magnitude than the fluence measured by the GRS. Implications of this result are discussed.

Introduction. Information about the acceleration of charged particles during solar flares can be obtained by directly measuring the spectrum of the charged particles escaping into interplanetary space and indirectly by the analysis of the flares' gamma ray spectrum resulting from the particles which loose their energy in the solar atmosphere. Many flares, for which both sources of information are available, show similar spectral parameters, so that it is commonly assumed that both particle populations originate from the same acceleration process /1/, /2/. However, we have to bear in mind, that for these events either the particle data or the measurements of the gamma rays are limited in energy range.

The flare of December 7, 1982 is exceptional in this respect, because it was observed by satellite particle detectors, and as a ground level event, which means, that protons with energies of at least 500 MeV have been created and it was recorded in space by the SMM gamma ray spectrometer, which is sensitive to photon energies of up to 140 MeV.

In this paper we present the gamma ray flux measurements in the nuclear energy band from 4 - 8 MeV and above 10 MeV and estimate the flux above 25 MeV, which we should observe, if the spectral form of the directly measured particles and of the particles, which caused the gamma rays, was the same.

Observations. The flare, which originated from McMath region 23453 (S19 W86), was classified 1B in H_α, beginning at 2341 UT and reaching its maximum at 2351 UT. According to measurements of the GOES-satellites the maximum intensity in the 1 - 8 Å band was X 2.8 at 2354 UT (Solar Geophysical Data, prompt. rep., No 461/1). The flare was accompanied by strong micro wave and radio emissions, the micro wave flux exceeding the radio flux by more than an order of magnitude. The dynamic spectrum at radio wavelengths shows two intense type II bursts, one beginning at ~ 2343 UT and the other at ~ 2358 UT (Kosugi, private communication).

Particle detectors, which were close to the earth, showed an impulsive increase of their count rate after the flare. This event was recorded by the world wide neutron monitor network. Listed in Figure 2 is the count rate versus time of the

Kerguelen neutron monitor (49.92°S/70.22°E; cut-off rigidity 1.19 GV), where the maximum response to the high energy solar particles was observed. The time profile exhibits a rapid increase to the maximum value of ~ 55 % and a quick decay (~ 180 min) to the background rate. This time history indicates, that 1.) the propagation of the particles was nearly scatterfree between the sun and the earth and 2.) the flare particles at the sun had relatively easy access to the footpoint of the magnetic field line connecting the sun and the earth /3/.

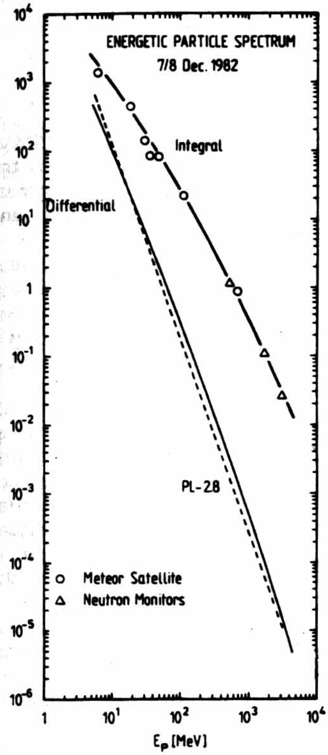

Fig. 1. Energetic Particle Spectrum observed after the flare of Dec. 7, 1982. Full Line: fit to data. Dashed Line: power law approximation.

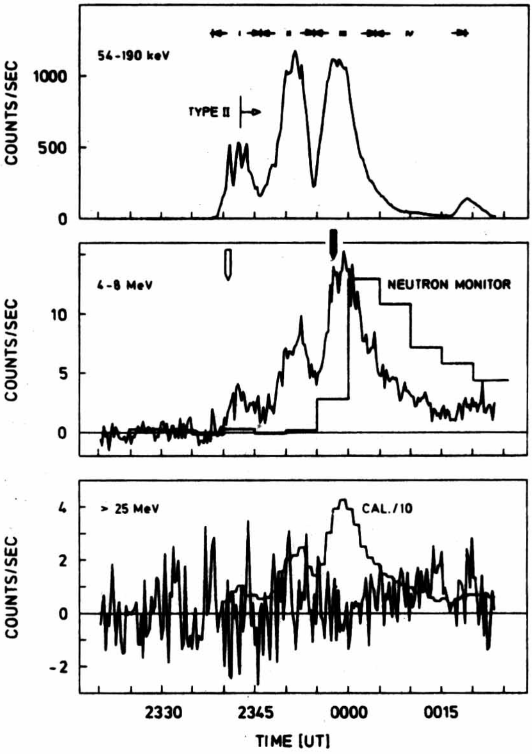

Fig. 2. Time history of the flare of Dec. 7, 1982 in hard X- and gamma-rays. The histogram in panel B is a short period of the Kerguelen neutron monitor record.

In Figure 1 the integral particle energy spectrum as deduced from the Soviet Meteor satellite /4/ and from neutron monitors is shown, covering almost three decades in energy. There is very good agreement in the overlapping energy interval around 1 GeV. The measurement points are fitted by an analytical function with the form $F(E) = 3.9 \cdot 10^{10} \exp(-E^{0.08}/0.07)$, (with E in MeV), which has a slope of 1.5 and 2.1 at lower and higher energies, respectively. Shown is also the energy derivative of this functional form.

Figure 2 shows the time profile of the flare recorded by the gamma ray spectrometer (sensitivity range 0.3 MeV to 140 MeV) on board of the Solar Maximum Mission satellite in the energy band 4 - 8 MeV, which contains the carbon and oxygen lines, and above 25 MeV with a time resolution of 16.384 sec, subtracted for background. For reference we list the emission in the energy range from 54 - 190 keV which is measured by one of two X-ray detectors attached to the spectrometer. The emission at high energy X-rays and in the 4 - 8 MeV band lasts for more than 30 minutes showing a gradual rise and fall in three major pulses, however, a dominant impulsive burst of short duration ($\lesssim$ 1 min) is missing. The event belongs to the class, which is named "gradual" /5/. The emission above 25 MeV, ignoring the big scatter, does not follow the time history of the 4 - 8 MeV band. It is low, when the latter reaches the highest values during the third burst and increases towards the end of the flare. The full arrow indicates the release time at the sun (+ 8 min 20 sec, light travel time sun-earth) of a 1 GeV particle recorded by the Kerguelen neutron monitor at 2400 UT, assuming scatterfree propagation on a nominal 1.17 AU Archimedian spiral (solar wind speed $\sim$ 400 km/sec; Pilipp, private communication). Shown by an open arrow is the time of the first significant microwave peak at 17 GHz (Kosugi, private communication).

Table 1 contains the measured photon fluxes at different energy bands, integrated over the time intervals, which are marked also in Fig. 2. The 4 - 8 MeV flux (column 2) is the excess over a power law extrapolation from lower energies. To calculate the photon flux above 10 MeV we used the effective area obtained by a Monte Carlo calculation /6/. The limits of the fluences are statistical 1σ - errors. In column 5 we computed the $>$ 25 MeV photon flux originating from the decay of neutral pions, assuming, that the spectral form of the energetic particles and of the particles, which caused the gamma rays was the same. For simplicity we used a power law with an exponent of - 2.8 (dashed line in Figure 1) instead of the true functional form. The yield ratio between the number of neutral pions and the number of 4 - 8 MeV photons is 1.47 /1/. The photon flux is calculated for isotropic conditions which is an idealization, because in reality the high energy particles will have a preferred direction of motion, leading to anisotropic emission. One can show, however, that for sunward moving particles the value is reduced only insignificantly, because the flare is observed close to the limb /8/. If, on the other hand, the particles move tangentially to the solar surface, mirroring in the converging magnetic field, the intensity will be higher for a flare close to the limb, compared to isotropic conditions.

Table 1

Measured and Calculated Fluxes (photons/cm^2)

	Times UT	Measured			Cal. /1/
		F(4-8 MeV)	F(10-25 MeV)	F($>$25 MeV)	F($>$25 MeV)
I	23:38:13 - 23:45:52	11.0 ± 0.9	1.2 ± 0.7	-1.6 ± 1.2	32
II	23:45:52 - 23:54:19	31.8 ± 1.0	3.1 ± 0.8	3.2 ± 1.4	94
III	23:54:19 - 00:04:09	71.3 ± 1.1	2.9 ± 0.7	1 ± 1.2	210
IV	00:04:09 - 00:18:38	32.6 ± 0.9	3.3 ± 0.7	7.6 ± 1.2	96
V	23:38:13 - 00:23:33	156.0 ± 2.0	10.7 ± 1.5	13 ± 2.6	459

3. Discussion. The flux above 10 MeV, recorded by our spectrometer, may have three different sources, 1.) high energy primary electrons, which radiate via bremsstrahlung, 2.) decay of charged and neutral pions and 3.) high energy neutrons, which escaped from the sun, reaching the detector before they disintegrate. If we extrapolate the bremsstrahlung component, which appears as a power law with exponent 3 between 0.3 and 1 MeV /7/ to energies above 10 MeV, we get a significant contribution to the signal of the 10 - 25 MeV energy band, but above 25 MeV it can be neglected. This energy band, however, may contain a contribution from high energy neutrons, which we did not attempt to separate out. The flux listed in Table 1 is clearly an upper limit for the number of charged and neutral pions. Moreover, in our calculation of the flux above 25 MeV we only took the contribution of neutral pions, so that the comparison of the measured and calculated flux (column 4 and 5) is a conservative one.

Columns 4 and 5 show, that the calculated flux exceeds the measured one by more than an order of magnitude, independent of the time interval, over which it is taken. To make this discrepancy apparent, we have calculated the > 25 MeV flux, modelled after the 4 - 8 MeV time history. This time profile divided by 10 is shown in panel C of Figure 2. Further, it is evident, that the observed emission above 25 MeV does not reflect the time history of the ground level event. Even down to the highest time resolution of 2 sec we do not find a significant excess in the >25 MeV energy band, where the photons of decayed pions show up, which could be interpreted as the moment, the GLE-particles have been created.

4. Conclusion. The determination of the spectral parameters and time history of the flare by the measurement of gamma rays and by the observation of particles released into space, allows two alternative explanations: 1.) If the propagation and escape of the accelerated particles depend on energy, then both particle populations can originate from one acceleration process. This, however, puts narrow limits on the escape and propagation conditions for the particles. 2.) If the propagation and escape of the accelerated particles is energy independent, then different acceleration processes are required to explain the data (see for inst. /9/, /10/).

Regardless of these two alternatives we can state that the coincidence in time of the soft particle population, deduced from the gamma ray measurements, and of the hard particle population observed with detectors in space and with neutron monitors, argues against a first- and second phase scenario.

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