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VERY ENERGETIC GAMMA-RAYS FROM THE 3 JUNE 1982 SOLAR FLARE

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ABSTRACT

The Gamma-Ray Spectrometer on the Solar Maximum Mission satellite has recorded high energy gamma-ray and neutron emission from the flare on 3 June 1982. During the 65 sec. impulsive phase the gamma rays >10 MeV contains emissions from both primary electron bremsstrahlung and nuclear pion decay. Hence the impulsive phase acceleration process must produce both primary electrons with energies > 60 MeV and ions >500 MeV. This flare also has a extended emission phase lasting more than 1000 sec which is most easily observed at gamma-ray energies > 10 MeV. After removing the counting rates from the more slowly moving neutrons produced at earlier times, the resulting gamma ray spectrum can be entirely explained by nuclear pion production. We find that >70 % of the pions were produced in the extended emission phase. In contrast, more than 70 % of the high energy primary electron bremsstrahlung and the < 30 MeV ion produced nuclear line emission occured in the 65 sec impulsive phase. This represents the first clear observation of a new acceleration process which produces a electron deficient, very hard ion spectrum extending beyond 1000 MeV.

INTRODUCTION

The flare of 3 June 1982, because of it's large size, location on the solar disk and it's fortuitous time of occurrence, has provided a wealth of observational information on high energy emission from solar flares /1,2,3,4,5,6,7/. In this paper we extend these observation by showing compelling spectral evidence for pion production. We further show that a significant portion of this pion production occurs during a new time extended phase which is most easily observed at these high energies. These observations, together with the observations of high energy neutrons /8,9/ show that this extended phase is distinctly different from that normally observed in the impulsive phase of solar flares.

The Gamma Ray Spectrometer (GRS) on SMM /10/ has a High Energy Monitor (HEM) which is sensitive to both neutrons and gamma rays >10 MeV. The HEM consists of two separate detector planes, a 28 g/cm^2 thick NaI front detector and a 34 g/cm^2 thick CsI back detector. The energy loss spectra from each detector plane are recorded in two separate four channel PHA's covering the energy range 10-100 MeV. The energy loss information from each detector plane for each event are recorded in a matrix array. The data in the matrix array allows us to determine the distribution of events which deposit energy in only the front or back detectors or those which shower and deposit energy in both detectors (called Mixed events). By taking diagonal sums from the matrix array, a five channel pulse height spectrum can be formed with boundaries at 10, 25, 40, 65, 100 and 140 MeV.

Fig. 1 shows three gamma-ray sensitivity curves taken from the Monte Carlo calculations of Cooper et al. /11/. The total sensitivity >10 MeV is shown as curve a and curves b. and c. are for only back detector CsI events or only showering or "Mixed" events. These two curves show that only showering gamma rays > 50 MeV can produce significant response in the Mixed matrix elements. Both lower energy gamma rays and high energy neutrons produce their response in either the front or the back detector elements only. These calculations have been confirmed in orbit using the earth's gamma ray albedo flux /12/.

OBSERVATIONS AND ANALYSIS

The time history of the GRS observations in the hard X-ray energy band, the nuclear line rich 4-8 MeV band and the energy loss bands >25 MeV has been shown before (see Fig 1 in Chupp et al. /7,8/). This data shows that there is continuous emission over the entire flare interval from 11:44 until 12:04 UT with the majority of the total emissions for all energies < 25 MeV being produced within the 11:43 to 11: 44 UT impulsive phase. However, the rates in the energy band > 25 MeV indicate that a significant portion of the total emissions at these energies was observed after 11:44 UT. Earlier it was know that some portion of this excess high energy rate at late times was from energetic neutrons at 1 AU /7/. A better understanding of the HEM's response to both neutrons and gamma rays now allows us to demonstrate that the delayed excess rates at energies > 25 MeV contain a majority of the total nuclear pion production from this flare.

To show GRS's ability to separate high energy neutron from gamma rays we show in Fig. 2 both the total observed rate > 25 MeV (at 16 sec time resolution) and the ratio of observed counts in certain energy loss bands. Fig. 2 curve b is the ratio of counts from showering (ie Mixed) events to those recorded only in the back detector both with energy losses >25 MeV and plotted with a 65 sec time resolution. During the first 65 sec impulsive phase interval this ratio was 0.37$\pm$0.02, a value lower then the 0.58 predicted for pion decay gamma rays. During the impulsive phase this lower ratio is caused by the presence of a relatively steep power law bremsstrahlung spectrum with a index of 3.5 /6/. However the 2nd and 3rd time intervals have a ratio of 0.61$\pm$0.06 and 0.62$\pm$0.04, values which are consistent with that expected from pion gamma rays. The spectrum observed in the second of these two intervals is shown in Fig 3. In this figure the histogram with error bars is the observed spectrum. The two lower continuous curves are the fitted models for neutral pion decay and for the bremsstrahlung from the energetic electrons/positrons from charged pion decay /9,13,14/. It is clear from Fig 3 that the entire observed rate > 10 MeV can be explained by photons from pion decay without any statistically significant contribution from either primary electron bremsstrahlung or from energetic neutrons. However Fig. 2 shows that starting from the 4th interval to the end of the orbit we see that the observed ratio declines to a lower value of ~ 0.1. This decline is caused by the increasing flux of detectable high energy neutrons arriving at the GRS instrument.

To investigate the nature of the gamma ray flux during the latter portion of the extended phase, we show as curve c of Fig 2 the ratio of showering events in the 100 - 140 MeV band to the total showering events > 25 MeV. Note that since this ratio is composed only of showering events it is insensitive to the incident neutron flux. The predicted pion value for this ratio is 0.20. It is clear that the gamma ray flux for the entire extended interval is only consistent with pion gamma rays.

The gamma ray spectral shape from neutral pion decay and charged pion decay bremsstrahlung depends on the nucleon spectrum which produced the pions. Crannell et al. /13/ calculated the shape of the gamma ray spectrum for two different incident proton energies. Using this data we find that the number of pions required to produce a given GRS response can differ by a factor of two depending upon the neutral pion spectral shape used. This is due to the fact that a larger fraction of the gamma ray spectrum extends beyond 200 MeV as the incident proton energy increases (see also Murphy et al./9/). The neutral and charged pion gamma ray models used in Fig. 3 assumed Ep = 560 MeV, an intermediate value. Finally we show in Fig 4 the total GRS observed rate at energies > 10 MeV and it's separation into components from nuclear pion decay gamma rays (curve b.), primary electron bremsstrahlung (curve c.) and high energy neutrons (curve d.). Recall that the high energy neutron rate observed at a time t, must have been produced at a earlier time than the gamma rays observed at time t.

CONCLUSIONS

We have presented the first results of the full GRS energy loss spectrum from gamma rays and neutron from the flare of 3 June 1982. We have demonstrated the ability of the HEM to separate gamma ray and neutron events. During the 65 sec duration impulsive phase of this flare we find evidence for a steep power law (index = 3.5) photon spectrum produced by primary electrons requiring the impulsive acceleration of electrons to near 100 MeV in time scales less than 10 sec. A full spectral analysis > 10 Mev as well as the presence of significant flux > 100 MeV also requires the production of neutral pions within this interval. This requires the acceleration of ion to > 500 MeV within the same time scales.

The observed rates early in the extended phase are clearly produced by a large flux of nuclear pion decay gamma rays. At later times in this extended phase the rates from pion gamma rays were augmented by those from high energy neutrons arriving at 1 AU. This pion production continued until S/C sunset at 12:10 UT. Using a neutral pion gamma ray decay spectrum model expected for Ep = 560 MeV we find the model dependent total observed neutral pion gamma ray yield for this flare of 55 photons/cm^2. Of this total > 70% were produced after 11:43UT, during the extended emission phase. This interpretation is entirely consistent with the observed 0.511 MeV line distribution /2/, a portion of which is produced by the decay of positively charged pions /9,14/. This extended production of pions is also required to explain the time history of the neutron flux at 1 AU observed by both GRS and the Jungfraujock Neutron Monitor /3,7,9,10/.

However this distribution of pion production appears to be at odds with the distribution of prompt nuclear gamma ray lines and the low energy neutrons responsible for the observed 2.22 MeV gamma ray line /1/. More than 70 % of the production of these two products of low energy ion nuclear reactions occured in the 65 sec impulsive phase.

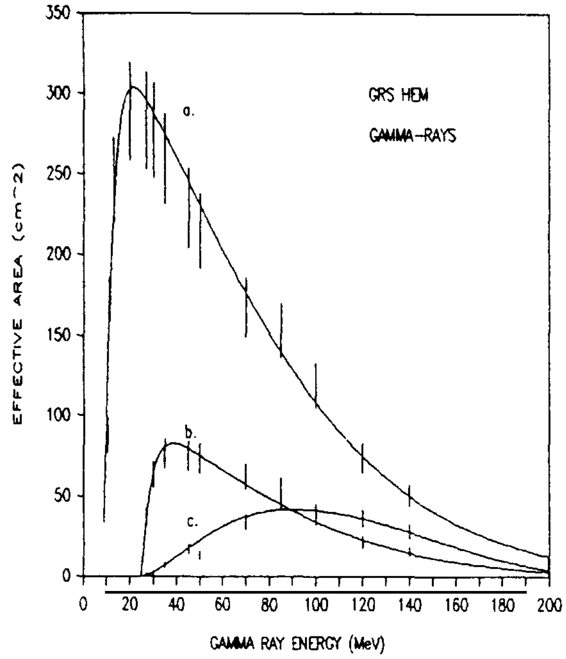

Fig. 1 - The GRS HEM gamma ray effective area for a. total events > 10 MeV, b. back CsI detector >25 MeV and c. showering or Mixed events >25 MeV.

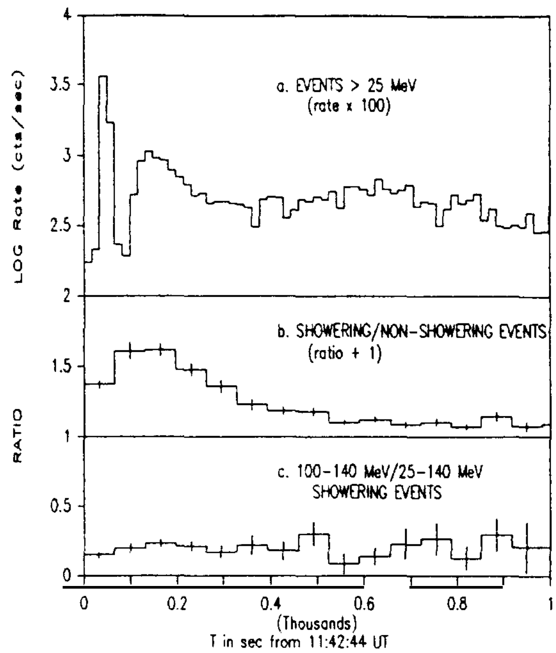

Fig 2. The observed time history for a. the total events > 25 MeV, and the ratio of b. showering to non-showering and c. showering 100-140 MeV to showering > 25 MeV.

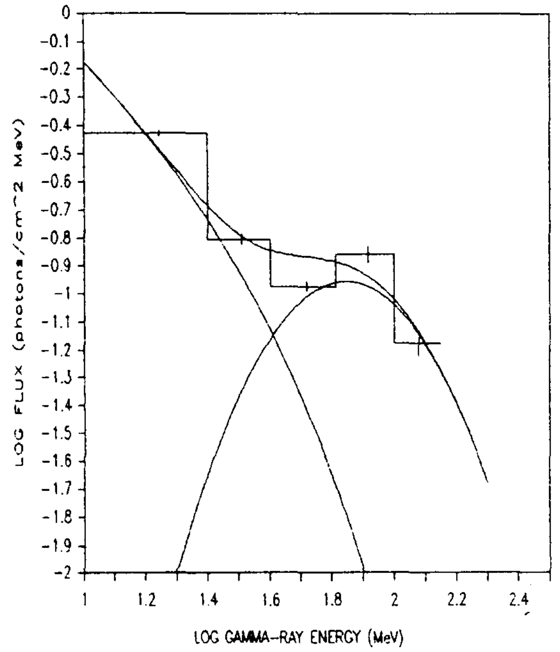

Fig. 3 - The pion gamma ray spectrum in the interval 11:44:55 to 11:46:00 UT.

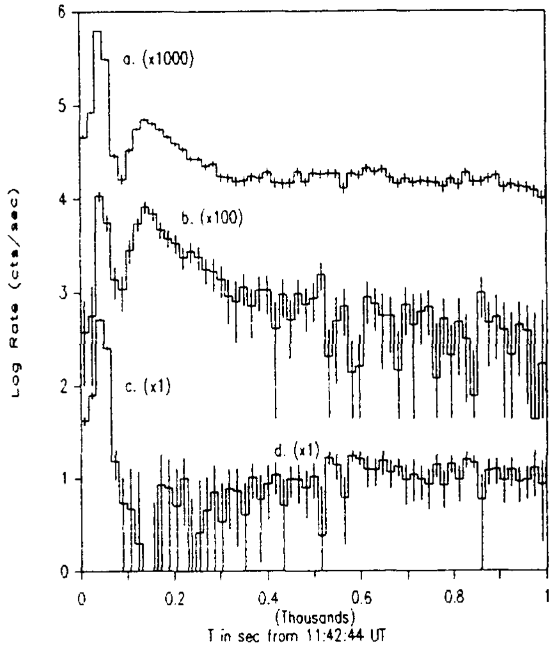

Fig 4. - The total observed rate > 10 MeV a. and it's components from b. pions, c. primary electron bremsstrahlung and d. energetic solar neutrons.

These observations require a different ion spectra in each phase. The impulsive phase acceleration process produced both electrons and ions in a process similar to that observed in all GRS flare events. During the extended phase, however, a different process occured which was inefficient in accelerating electrons but did produce a very hard spectrum of ions. It appears that this new acceleration process can be most easily observed at gamma ray energies > 10 MeV.

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