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# Evidence for Extended Neutron and Gamma-Ray Generation During Two Solar Flares

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## ABSTRACT

High energy solar gamma-rays and neutrons were observed by spacecraft experiments during the major solar flares on 24 May 1990 and 15 June 1991. Both these flares were also associated with relativistic solar protons measured by ground-based neutron monitors. The integrated analysis of intensity-time profiles of different radiations and particles during these events gives evidence for extended neutron and gamma-ray generation during these solar flares.



## 1. INTRODUCTION

The identification of a solar gamma-ray burst associated with the detection of high energy solar neutrons by ground-based neutron monitors (Chupp et al.,1987) renewed interest in high energy solar particle acceleration. In the past few years several detectors capable of high energy gamma-ray observations have been launched on a variety of spacecraft such as GAMMA-1, GRANAT, and GRO. Utilizing both ground-based and spacecraft data acquired during two solar flares, we give evidence for extended neutron and gamma-ray generation at the sun.

## 2. SOLAR NEUTRON EVENT OF 24 MAY 1990

### 2.1 Cosmic Ray Measurements

Using data from several North American neutron monitors, Shea et al. (1991) identified the first increase recorded by the Climax, Mexico City and Calgary monitors during the 24 May 1990 relativistic solar proton event as a solar neutron event (see Figure 1). This conclusion was based on the fact that the increase in the cosmic ray intensity was ordered by the apparent air mass along a line of sight through the atmosphere towards the sun and was not ordered by the geomagnetic cutoff rigidity. Shortly after the initial increase was recorded by the above stations, these same stations recorded another increase in cosmic ray intensity which was attributed to the arrival of relativistic solar protons. The increase attributed to the protons was ordered in the expected manner by the geomagnetic cutoff rigidity and the anisotropy along the probable interplanetary magnetic field direction (Pyle et al., 1991; Shea et al., 1991).

The onset of solar neutrons as measured by the Climax, Colorado neutron monitor was in the one minute interval 2049-2050 UT.. Solar neutrons require a minimum of approximately 300 MeV to generate a nuclear cascade capable of being detected above the ambient cosmic ray background recorded by a neutron monitor at mountain altitudes. Since the solar proton event contained protons in excess of 7 GV (6.12 GeV) it is reasonable to assume that solar neutrons of GeV energies were generated during this solar flare.

### 2.2 Solar Emissions

The 1B/X9.3 solar flare associated with this relativistic particle event had an H-alpha onset at 2046 UT and maximum at 2049 UT. The onset of the 1-8 Å soft X-ray flux observed by the GOES-7 spacecraft was at 2045.9 UT with a 2049.5 UT maximum. Figure 2 shows the 10.6-109.5 MeV gamma-ray flux observed on the GRANAT spacecraft (Trottet, private communication). The onset was at ~2047:40 UT and the maximum intensity at ~2048:13 UT. Note that the gamma ray counting rate decreases to ~10% peak intensity about 47 seconds later (2049:00 UT) after which there is an extended tail.

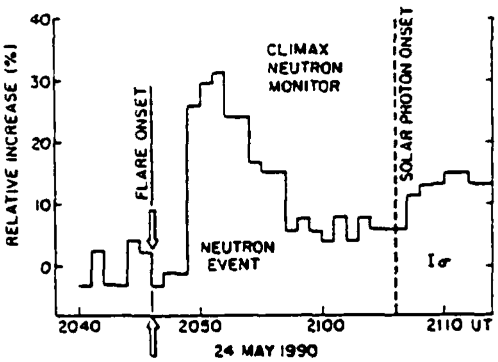


*Figure 1. One-minute averages of the 24 May 1990 solar neutron event observed by the Climax neutron monitor.*

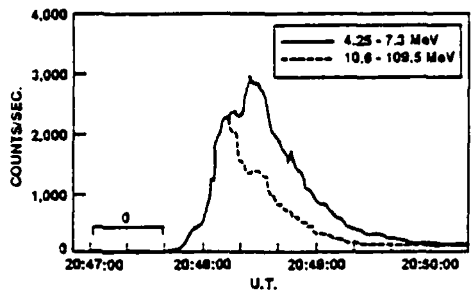


*Figure 2. The 4.25 - 7.3 MeV and the 10.6 - 109.5 MeV gamma-ray flux observed by the GRANAT spacecraft on 24 May 1990.*

## 2.3 Time of Flight Calculations

The earliest arriving gamma rays would have left the sun at 2039.24 UT, the maximum intensity would have been at 2039.79 UT, and those that arrived at the earth at 2049.0 UT (the 10% intensity level) would have left the sun at 2040.58 UT. Assuming that neutrons from 2 GeV to 300 MeV were released from the sun continuously from 2039.79 UT until 2040.58 UT and calculating the time of flight for these particles (which is a function of energy), we find that 2 GeV neutrons would have arrived at 2048.65 UT and the 300 MeV neutrons would have initially arrived at 2052.65 UT. These times are consistent with the initial increases observed by the North American neutron monitors. Assuming that the slower traveling 300 MeV neutrons were still being released at 2040.58 UT, these particles would have arrived at the earth at 2053.43 UT. Any additional neutrons arriving at the earth with energies $\geq$300 MeV would have left the sun after 2040.58 UT (i.e. during the "tail" of the gamma ray emission).

## 2.4 Discussion of 24 May 1990 Event

From Figure 1 it is clear that the cosmic ray intensity was above the "pre-increase" background at Climax until the solar proton event commenced. The one-minute data from the neutron monitor at Mt. Wellington, Australia, show that the solar proton event commenced no earlier than 2103 UT. Therefore the increase recorded bv the Climax neutron monitor between 2054.0 UT and 2103 UT can be attributed to solar neutrons that were generated by the sun as late as 2050.1 UT - approximately 9.5 minutes after the main gamma ray emission (i.e during the "tail" of the gamma ray emission).

## 3. HIGH ENERGY SOLAR GAMMA RAY EVENT OF 15 JUNE 1991

The importance 3B solar flare associated with this high energy gamma ray event had an H-alpha onset at 0810 UT and reached maximum intensity at 0821 UT. The onset of the 1-8 Å soft X-ray flux was at 0810 UT; maximum intensity of X12 was reached at 0821 UT. The soft X-ray event lasted ~10 hours. We calculate (Kovaltsov, al., 1993) the temperature and emission measure of the thermal source of soft X-ray emission deduced from observations in the 1-8 Å and 0.5-4 Å bands at the maximum are $\geq 10^7$ K and $5 \times 10^{51}$ $cm^{-3}$. An hour later these values were $10^7$ K and $10^{51}$ $cm^{-3}$.

The flare radio emission observed in centimeter and decimeter wavelengths indicated an impulsive phase (0812-0827 UT) and a subsequent $IV_{dm}$ and $IV_u$ type burst lasting until about 1000 UT. The meter radio emission of type II had an onset at about 0816 UT in the impulsive phase of the flare and its duration was about 20 minutes.

The flare was also observed by the COMPTEL instrument aboard GRO which detected gamma-rays in the 0.8-30 MeV energy band and 10-100 MeV neutrons (McConnell et al., 1992). Because the GRO spacecraft was in eclipse during the onset of the flare, the COMPTEL observations were not until the late stages of the flare from 0859 until 0937 UT. The "GAMMA-1" telescope observed 50-4000 MeV gamma-ray emission from 0837 UT until 0902 UT (Akimov et al. 1991). The observations began at satellite sunrise at 0837:22 UT and were interrupted at ~0902 by satellite entry into the South Atlantic Anomaly. During the observing time there was no significant variation in the observed gamma-ray spectrum; the spectrum between 250-2000 MeV was similar to a power law.

The observed spectral shape of the gamma-ray emission was considered by Akimov et al. (1991) as indicative of $\pi^0$-decay gamma-rays. We have used this hypothesis for calculations of pion generation in the solar atmosphere (Kocharov, L., et al. 1991; Kovaltsov et al., 1993). If the primary proton spectrum is a power law with index of -3 to -4 and the total number of protons above 1 GeV is equal to $\sim 10^{29}$, then the calculated spectrum agrees with the observed spectrum above 250 MeV. The power law shape of the gamma-ray spectrum up to energies above 1 GeV indicates that the maximum energy in the primary proton spectrum would be at least 10 GeV.

The flare of 15 June 1991 was characterized by a continuous generation of electromagnetic and corpuscular emissions which had a complicated multi-impulsive structure. The time profiles of centimeter radio emission (2950 and 9100 MHz) had three principal peaks at 0815 - 0825 UT, 0830 - 0840 UT and 0855 - 0930 UT. The first peak lasted for ten minutes and corresponds to the impulsive phase of the flare; the remaining peaks correspond to the extended phase. The increase in emission in the centimeter band during the extended phase corresponds to maxima in the decimeter emission (950 MHz). The centimeter radio emission can be interpreted as a synchrotron emission of electrons with energy $\geq 1$ MeV. The decimeter emission is caused by plasma mechanisms of radio emission and follows multi-impulsive energy release processes during the extended phase of the flare.

In Figure 3 we show overlapping of the time profiles of the 9100 MHz radio emission and the gamma-ray radiation observed at GAMMA-1 and GRO. One can see that the time profiles in the centimeter band coincide with the gamma-rays nuclear lines and the emission resulting from $\pi^0$-decay.

We have analyzed the onsets of the particle flux at five energy ranges observed on the IMP-8 spacecraft. When these onsets are plotted as a function of $1/\beta$ ($\beta$ being the particle speed) as shown in Figure 4, we obtain a consistent initial release time which corresponds to the second peak (0830 - 0840 UT) in the centimeter radio emission. For this event we calculate that the number of escaping protons above 30 MeV exceeded the number of protons required to produced the nuclear gamma-ray lines.

## 4. DISCUSSION AND SUMMARY

There are two possibilities to explain these long duration gamma-ray emissions and the injection of particles into the interplanetary medium. The first is continuous acceleration of particles during solar flares. The second is impulsive acceleration followed by continuous trapping of energetic protons in a magnetic arch (e.g. Gueglenko et al., 1990).

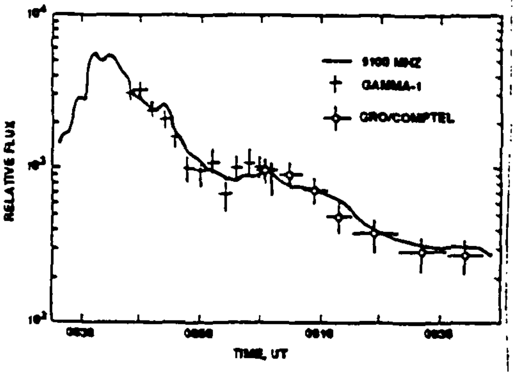


*Figure 3. Composite of the overlapping time profiles of the 9100 MHz radio emission and gamma-ray emission observed by GAMMA-1 and GRO on 15 June 1991.*

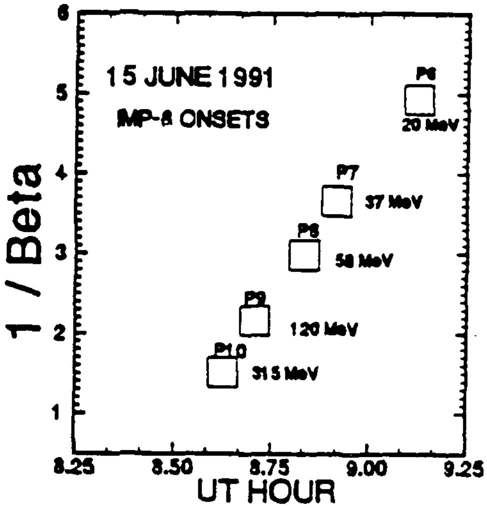


*Figure 4. Onset times observed by the IMP-8 satellite for 5 differential energy channels. These data are plotted as 1/β of the center energy of each measurement interval.*

Figure 3 illustrates the time-coincident radio emission and gamma-ray emission profiles even though the energy losses and trapping time of particles producing those kinds of emission are significantly different. The emission measure in soft X-rays (EM $\sim 10^{51}$ $cm^{-3}$) requires plasma densities to be $n > 10^{11}$ $cm^{-3}$. At such densities the deceleration time of electrons and protons generating nuclear gamma-ray lines is small as compared to the observed duration of emission. That is why we consider it to be evidence of a continuous and simultaneous acceleration of protons and electrons in a wide range of energies. It is significant that the continuous acceleration does not coincide in time with the Type II radio emission which had an onset time during the impulsive phase. In our opinion it indicates continuous acceleration of particles in the extended phase.

## ACKNOWLEDGEMENT

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## REFERENCES

Akimov, V.V. et al. 1991, Proc. 22nd ICRC, Dublin, 3, 73.
Chupp, E.L., et al.: 1987, Astrophys. J., 318, 913.
Gueglenko, V.G., et al., :1990, Solar Phys. 125, 91.
Kocharov, L.G.. et al.: 1991, in "Nuclear Astrophysics", Phys.-Tech.Inst., St.Peterburg, 5.
Kovaltsov, G.A., et al.:1993, Izv. RAN, ser.fiz. 57, N2 in press (in Russian)
McConnell, M., et al.,: 1992, Report at "Recent Advance in High Energy Astronomy, Toulouse, France.
Pelaez et al.: 1992, Solar Phys., 140, 121.
Pyle, K.R., Shea, M.A., and Smart, D.F.: 1991, 22nd ICRC Conf. Proc., 3, 57.
Shea, M.A., Smart, D.F., and Pyle, K.R.: 1991, Geophys. Res. Letters, 18, 1655.