EVIDENCE OF ADDITIONAL PRODUCTION OF HIGH ENERGY NEUTRONS DURING THE SOLAR FLARE ON JUNE 4, 1991

A. Struminsky *, M. Matsuoka and K. Takahashi

Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-01, Japan

Abstract

In order to explain the neutron monitor data during the 1991 June 4 X12.0 solar flare we have to consider two long duration ejection periods of high energy neutrons, starting approximately at 03:37 and 04:12 UT. The existence of a second acceleration episode separated by about 30 minutes from the impulsive phase of the flare is supported by the gamma-ray and microwave observations. Assuming that the total number of neutrons in 0.1-3 GeV energy range is proportional to the gamma-line intensity, estimations of neutron spectra can be made during the first production episode where the gamma-ray data are available. But we have to use the similarity between the general trends of microwave and high-energy gamma emission to obtain the neutron spectrum during the second production episode. The spectrum during the first ejection have appeared to be softer than that of the second ejection.

1. Introduction

New exciting observations of solar neutral emissions in wide energy range were made during a number of solar flares in June 1991. The nature of the observed long duration high-energy gamma-ray and neutron emission is still not clear. There are several explanations to this phenomenon. Gamma rays and neutrons are produced in the nuclear interactions between high-energy particles and the ambient solar atmosphere. The charged particles can be impulsively accelerated and then trapped in magnetic loops (Mandzhavidze, & Ramaty 1992), or they can be continuously accelerated for a long time after the initial impulsive phase. Both processes require special physical conditions on the Sun. In the first case the level of plasma turbulence in the coronal part of the loops must be sufficiently low. In the second case the acceleration mechanism should be quite different from that operating in the impulsive phase of the flare. It is also possible that the particles are accelerated in several episodes under

* Also at the P.N. Lebedev Physical Institute, Moscow, Russia.

different physical conditions separated by time intervals during which the particles are mostly trapped (Ramaty, & Mandzhavidze 1993).

The experimental data of solar neutral emission obtained during the 1991 June 4 flare support the existence of two acceleration episodes which occurred under different physical conditions on the Sun and which were separated by about 30 minutes. During this particular solar flare both acceleration episodes were followed by periods of long duration gamma-ray and neutron emissions caused by trapping or continuous acceleration of high energy particles.

2. Experimental Data

On 1991 June 4 a solar x-ray event (X12.0) was observed by GOES-7 from 03:37 to 07:30 UT (Solar Geophysical Data 1991a,b). Its heliocoordinates were N30E70. A number of optical solar flares occurred during that time in the same active region NOAA/USAF 6659. There is some uncertainty in connection between the x-ray event and corresponding optical flare (Solar-Geophysical Data 1991b, Sakurai et al. 1992). The coronal mass ejection from the Sun started at 03:40(44) UT with intensive meter radio emission of type IV. A small solar proton flux was registered by the GOES-7 geostationary satellite about 10 hours after solar flare onset (Solar-Geophysical Data 1991a).

An unusual large enhancement of the NM count rate with at least two hump structure was observed over background from 03:40 to 05:05 UT at Mt. Norikura (N36E138) on 1991 June 4. The hour average atmospheric depth over the Norikura 12NM64 type neutron monitor at that time was 736g/cm^2. The primary analysis of this event was made by Takahashi et al.(1991). The observed enhancement was attributed to solar neutrons. Also the solar neutron event on 1991 June 4 was reported by Muraki et al. (1992), and Chiba et al. (1992). In order to estimate the energy spectrum of the solar neutrons during the first hump, Takahashi et al.(1991) supposed that the neutrons were produced simultaneously on the Sun at 03:41 UT. The obtained solar neutron emissivity spectrum showed an unusual knee near 200MeV with very large neutron intensity at lower energies. So the neutron production was probably extended in time (Mandzhavidze, & Ramaty 1993). The second humps points to a second acceleration episode during this solar flare.

According to the primary results of the 2.223 MeV and 4.44 MeV gamma-line observation of the 1991 June 4 Solar flare obtained by OSSE aboard CGRO (Murphy et al. 1993) the nuclear interactions and the resulting gamma-ray emission have continued after the peak of the emission (at about 03:42 UT) for more than 110 minutes. An apparent discontinuity in the gamma-ray intensity may have occurred during satellites. night, 04:05-04:36 UT : the flux started out at higher value in the beginning of second orbit than it was expected from the intensity in the end of the first orbit. The Nobeyama microwave data (17, 35 and 80 GHz) showed a second small hump with a maximum at 04:25 UT during the CGRO night (Enome, & Nakajima 1991). A second maximum was reported by several radio observatories at 04:21(23) UT as well (Solar-Geophysical Data 1991b). The time-profiles of the 2.223 MeV gamma-line intensity and the 17GHz microwave emission are plotted in Fig. 2(Murphy 1993).The strong similarity between the general trends of microwave and high-energy gamma-ray emission was mentioned for the later phase of the 1991 June 15 event and was used to state prolonged acceleration of high energy ions in this flare (Akimov et al. 1993). Approximately the same behavior of gamma and microwave intensity is seen in Fig. 2 during the first CGRO orbit on 1991 June 4. It is possible to fit the gamma-ray intensity time profile roughly by exponentially rising and decaying functions with e-foldings times, 65 sec and 360 sec, and the maximum 2 $photons/(cm^2sec)$ at 03:42 UT, during the first orbit. It seems reasonable to suggest the existence of a second gamma- ray and neutron production during the satellite night-time near the maximum of radio emission. We have assumed the gamma-ray intensity time profile with e-foldings times, 221 sec and 588 sec, and the maximum 0.3 $photons/(cm^2sec)$ at 04:22 UT.

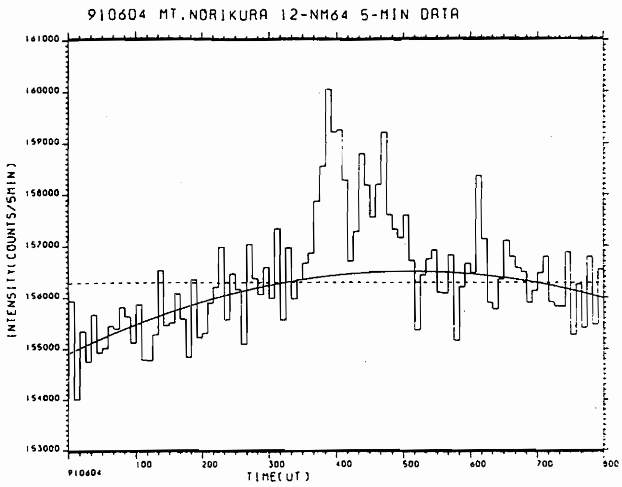

Fig. 1. Norikura NM time-profiles in the morning of 1991 June 4, a count rate for all multiplicities.

3. Model Calculations of Solar Neutron Enhancement at Norikura NM

we express a neutron production on the Sun for each episode as a power law function of neutron energy - E, multiply on the time profile of the 2.223 MeV γ-line intensity at the Earth orbit described above:

$$S(E,T) = N_0(\alpha)E^{-\alpha}F(T), \quad (1)$$

where T is a Sun light delayed time at the Earth orbit. Realy the 2.223 MeV line is delayed by about 100 sec from neutrons, but it doesn't matter taking into account the accuracy of NM measurements and our calculations.

It is possible to fit the neutron monitor enhancement $N(t_1,t_2)$ during the time interval (t_1,t_2) caused by 0.1-3 GeV solar neutrons using equation:

$$N(t_1,t_2) = \int_{t_1}^{t_2}\int_{0.1}^{3} S(E, T - D/c(\beta^{-1}-1))P(E)Y(E)dEdT/D^2, \quad (2)$$

where $P(E)$ is the neutron survival probability, $Y(E)$ is the recently calculated sensitivity of the neutron monitor (Shibata 1992), and D - the Sun-Earth distance.

The best fit analysis of Norikura NM count rates, using a χ^2- test and linear correlation gives us the unknown parameters $\alpha_1 = 3.5, N_{01} = 7.0 \times 10^{23}$ neutrons/s/sr/GeV and $\alpha_2 = 2.25, N_{02} = 6.7 \times 10^{24}$ neutrons/s/sr/GeV for first and second neutron production respectively. Now it is easy to estimate the time integrated directional emissivity at the Sun: $J_1 = 6.3 \times 10^{26}E^{-3.5}$ neutrons/sr/GeV and $J_2 = 1.6 \times 10^{27}E^{-2.25}$ neutrons/sr/GeV.

4. Conclusions

Long duration neutron production, lasting for about 30 minutes, occurred twice during the 1991 June 4 flare with maximum intensity at 03:42 and 04:22 UT. This long duration production may have been caused by the trapping or continuous acceleration of high energy particles. There neutrons were observed by the Norikura NM. The spectrum of neutrons was considerably harder during the second long duration production episode. Whether or not each neutron production corresponds to a separate acceleration episodes of different nature is still not clear.

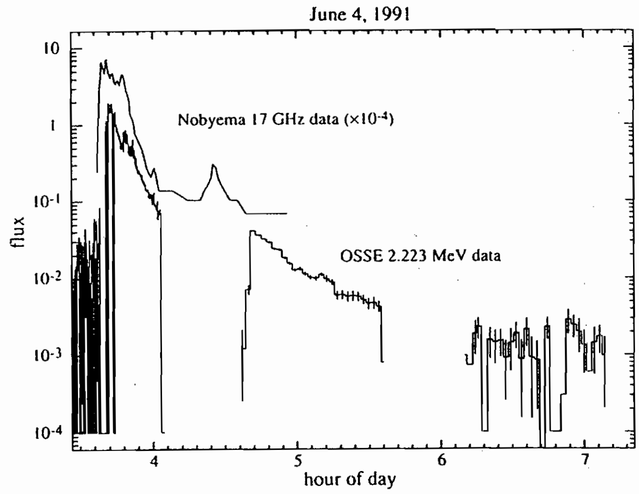

Fig. 2. Combination of 2.223 MeV gamma-line intensity as observed by OSSE CGRO and 17 GHz microwave intensity in the same scale (Murphy 1993). The flux units are photons/cm^2 sec and 10^{-22} W/m^2 Hz for microwave intensity.

Acknowledgments: The Norikura NM is under the guidance of the staff of Norikura Observatory attached to the Institute for Cosmic Ray Research (ICRR), the University of Tokyo. The authors acknowledge the ICRR for this work. The authors thank Profs S. Enome and H. Nakajima for providing the Nobeyama microwave data; Dr. R. Murphy for providing Fig. 2.; Ms E. Sakamoto for the data processing; Drs, V. Akimov, M. Kodama, T. Kohno, N. Mandzavidze, R. Ramaty for critical and valuable discussions. AS is supported by the fellowship of the Science and Technology Agency of Japan.

References

1. Akimov, V., Belov, A., Chertok, I., Kurt, V., Leikov, N., Magun, A., & Melnikov, V., 1993, *23rd ICRC* **3**, 941.
2. Chiba, N., et al., 1992, *Astroparticle Physics* **1**, 27.
3. Enome, S., & Nakajima, H., 1991, *private communication.*
4. Mandzhavidze, N., & Ramaty, R., 1992, *AP. J.*, **396**, L111
5. Mandzhavidze, N., & Ramaty, R., 1993, *Nuclear Physics*, **B33**, 141
6. Muraki, Y., et al., 1992, *AP. J.*, **400**, L75.
7. Murphy, R., et al., 1993, *23rd ICRC*, **3**, 99.
8. Murphy, R., 1993, *private communication.*
9. Ramaty, R., & Mandzhavidze, N., in *High Energy solar Phenomena eds. Ryan J. M. and Vestrand W. T.*, in press 1993.
10. Sakurai, T., et al., 1992, *publ. Astro. Soc. Japan*, **44**, L7.
11. *Solar-Geophysical Data*, 1991a, **563**, part 1.
12. *Solar-Geophysical Data*, 1991b, **568**, part 2.
13. Shibata, S., 1992, *Proceedings of the Csmic-Ray Research section of Nagoya University*, **33**, 1, 3(in Japanese), *JGR* in press 1994.
14. Takahashi, K., Sakamoto, E., Matsuoka, M., Nishi, K., Yamada, Y., Shimoda, S., Shikata, T., & Wada, M., 1991, *Proceedings of 22nd ICRC* **3**, 37.