GAMMA-RAYS AND NEUTRONS AS A PROBE OF FLARE PROTON SPECTRA: THE SOLAR FLARE OF 11 JUNE 1991

PHILIP P. DUNPHY[1], EDWARD L. CHUPP[2], DAVID L. BERTSCH[3], EDWARD J. SCHNEID[4], STEPHEN R. GOTTESMAN[5] and GOTTFRIED KANBACH[6]

[1]*Space Science Center, University of New Hampshire, Durham, NH 03824, USA*
[2]*Physics Department, University of New Hampshire, Durham, NH 03824, USA*
[3]*Laboratory for High Energy Astrophysics, Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[4]*Northrop Grumman Corporation, Bethpage, NY 11714, USA*
[5]*Northrop Grumman Corporation, Baltimore, MD 21203, USA*
[6]*Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching, Germany*

(Received 10 December 1998; accepted 10 March 1999)

Abstract. The large flare of 11 June 1991 (GOES class X12) was detected by the Total Absorption Shower Counter (TASC) segment of the EGRET gamma-ray telescope on board the Compton Gamma Ray Observatory. Significant gamma-ray emission was observed over the entire energy range to which the TASC was sensitive -1 to 140 MeV. Several phases were identified which showed major changes in the intensity and spectral shape of the flare gamma-rays. Furthermore, a 'delayed' phase during which a response consistent with the detection of energetic neutrons and pion-decay gamma-rays was seen, implying a qualitative change in the spectral shape of the accelerated ion spectrum. The similarity of the characteristics of this delayed phase (pion and energetic neutron production) to those in other large flares hint at a common particle acceleration mechanism.

1. Introduction

The likelihood of the significant production of measurable fluxes of gamma-rays and neutrons in solar flares was investigated by a number of workers, long before the relevant observations were available (e.g., Fireman, 1963; Chupp, 1963; Dolan and Fazio, 1965). The potential value of gamma-ray and neutron measurements as a probe of energetic ions generated in solar flares was pointed out and expected fluxes were calculated in detail by Lingenfelter and Ramaty (1967) and Lingenfelter (1969). These calculations showed that neutrons detected at 1 AU and gamma-rays from pion ($\pi^{\pm}, \pi^{0}$) decay could be directly related to very energetic ions, because of the high threshold kinetic energy required for their production ($\sim$ 300 MeV for both π's and neutrons in $p - p$ reactions and $\sim$ 200 MeV in $p - \alpha$ reactions).

Solar flare neutrons were first detected directly by the SMM spectrometer on 21 June 1980 (Chupp *et al.*, 1982). Evidence of pion-decay gamma-rays from the flare of 3 June 1982 was reported by Forrest *et al.* (1985). Several such satellite-based observations have since been made by SMM (Chupp *et al.*, 1987), GAMMA-1 (Akimov, 1991, 1994a,b), and Comptel (Ryan *et al.*, 1994; Rank *et al.*, 1997).

Solar Physics **187:** 45–57, 1999.

The signature of highly energetic solar neutrons has also been seen by ground-based neutron monitors from a few flares (Debrunner *et al.*, 1983; Smart *et al.*, 1990; Shea *et al.*, 1991; Takahashi *et al.*, 1991; Muraki *et al.*, 1991; Chiba *et al.*, 1992).

In the present paper, we report on an analysis of the response of the EGRET Total Absorption Shower Counter (TASC) on the Compton Gamma Ray Observatory (CGRO) to the solar flare of 11 June 1991. This flare was also observed by the Phebus detector on the GRANAT satellite (Trottet *et al.*, 1993) as well as by detectors on CGRO: COMPTEL (Suleiman, 1995; Rank *et al.*, 1993, 1994, 1996, 1997), OSSE (Murphy *et al.*, 1993), and EGRET (Kanbach *et al.*, 1993; Schneid *et al.*, 1994, 1996). The response of a ground level neutron monitor to this event has also been reported (Muraki *et al.*, 1991). The TASC data presented here contributes unique information on the evolution of the flare proton spectrum above 300 MeV. We argue that the high-energy emission ($>$10 MeV) detected by the TASC in the later stages of the flare is dominated by pion-decay gamma-rays and neutrons. The appearance of this emission marks a significant change, during the course of the flare, in the spectral shape of the protons that interact in the solar atmosphere. This paper is organized as follows: Section 2 describes the capabilities of the EGRET/TASC; Section 3 describes the flare observation and our analysis; Section 4 presents our results.

2. Description of the EGRET/TASC

The EGRET (Energetic Gamma-Ray Experiment Telescope) is a large gamma-ray detector comprising a spark chamber, a NaI(T1) scintillator/calorimeter, and an anticoincidence plastic scintillator dome. EGRET was designed primarily as a telescope to image 20 MeV to 30 GeV gamma-rays from cosmic sources with high sensitivity. The NaI calorimeter, or TASC, is a large ($76\times76\times20$ cm^3) spectrometer which measures the total energy of gamma-rays detected by EGRET. The TASC also has a burst/solar flare mode that records spectra in the energy range of 1 to 200 MeV every 32.75 s independent of the spark chamber and the anticoincidence dome. More information about the EGRET detector system can be found in Hughes *et al.* (1988), Kanbach *et al.* (1988), and Thompson *et al.* (1993).

Because of its large volume and mass, the TASC has a high efficiency for detecting solar flare gamma-rays and neutrons $>$10 MeV. The EGRET, as well as the other detectors aboard CGRO, are not normally pointed at the Sun, except for times of high solar activity when the Sun is chosen as a target of opportunity. Therefore the response of the TASC to solar gamma-rays and neutrons depends on the orientation of CGRO during a particular flare. This response was calculated using a 'mass model' that accounts for the effects of material throughout the CGRO spacecraft. The response calculations for gamma-rays used a standard Monte Carlo code for high-energy gamma-rays, EGS4 (Nelson, 1985). The response to neutrons

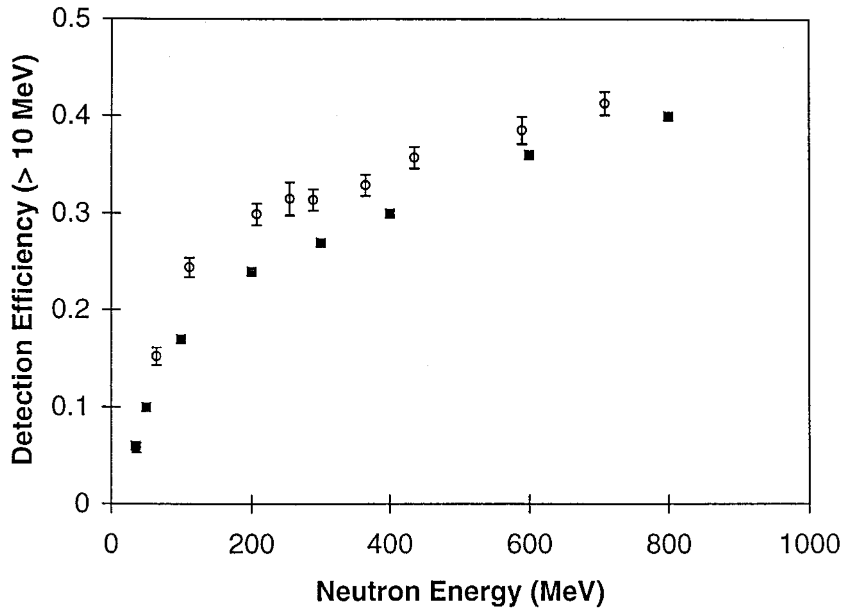

Figure 1. Neutron detection efficiency (energy loss threshold = 10 MeV) plotted versus incident neutron energy for two cases. The solid squares represent EGRET detection efficiencies calculated using a Monte Carlo code. The open circles are efficiencies measured in a tagged neutron beam for a NaI detector of the same thickness.

was calculated with an analogous code for neutrons, CALOR (Jensen, 1990). To check the accuracy of the neutron response code, we have compared the calculated TASC neutron detection efficiency with that of a large NaI (20 cm thick) scintillation detector exposed to a tagged neutron beam (Dunphy *et al.*, 1989). The comparison is plotted in Figure 1 and shows that the efficiency calculated for EGRET deviates at most by 30% from that measured for a detector of the same thickness.

3. Description of the Observations and Analysis

The solar flare of 11 June 1991 was one of a series of flares from active region 6659 that took place during June 1991. Following the occurrence of two GOES X-class flares on 4 June and 6 June, the Sun was declared a ‘target of opportunity’ and the CGRO instruments were pointed at the Sun. As a result, the active region was close to the EGRET pointing axis (zenith angle = 14°) during the 11 June flare. This flare, which was categorized as GOES class X12, was located at 31° N and 17° W in heliocentric coordinates (*Solar Geophysical Data*, 1991).

A number of observations of the 11 June flare in gamma-rays have been reported. Murphy *et al.* (1993) presented preliminary data from OSSE on CGRO that showed an intense (> 100 photons cm^{-2}) neutron-proton capture line fluence at

TABLE I
Time intervals and hardness ratio for flare of 11 June 1991

Phase	Start Time (UT)	End Time (UT)	R(4–8) (s^{-1})	R(30–200) (s^{-1})	R(30– 200)/R(4–8)
I-1	01:59:15	02:03:06	2610 ± 74	1.21 ± 0.84	$4.6(\pm 3.2) \times 10^{-4}$
I-2	02:03:06	02:09:39	3317 ± 52	1.41 ± 0.58	$4.3(\pm 1.8) \times 10^{-4}$
Interphase	02:09:39	02:12:56	269 ± 78	0.61 ± 0.79	–
II	02:12:56	02:40:13	341 ± 12	3.54 ± 0.13	$1.04(\pm 0.05) \times 10^{-2}$

2.223 MeV as well as emission above 10 MeV. Trottet *et al.* (1993) reported measurements of nuclear line radiation using the Phebus detector on GRANAT from which preliminary values of the ion spectral shape and the solar $^3He/^1H$ ratio were derived. Time-extended emission of 2.223 MeV radiation lasting over 5 hours was observed by Comptel on CGRO (Rank *et al.*, 1996). Finally, preliminary analysis of EGRET spark chamber data by Kanbach *et al.* (1993) showed that the 11 June flare had a long-lasting (>8 hours) high-energy component of gamma-ray emission and that this radiation showed spectral evolution to higher energies with time.

Figure 2 shows the response of the EGRET/TASC detector to the flare emission over a range of energy losses from 2 to 200 MeV. The net counting rate due to the flare (32.75 s time bins) has been determined by subtracting background measured approximately 24 hours before and after the flare, when the orbital and geomagnetic conditions were similar. A significant flare contribution was present from about 01:59 UT until 02:39 UT. The counting rate profile shows several distinctive features over this time period: two relatively short bursts from 01:59–02:10, an interval of low counting rate from 02:10–02:13, and an extended excess after 02:13. For purposes of analysis, we identify the first interval as phase I, the second as the interphase, and the third as phase II. Phases I and II are similar to ones defined by Mandzhavidze *et al.* (1996) for this flare, as we discuss below. Phase I can be subdivided according to the two bursts into time periods of 01:59–02:03 (phase I-1) and 02:03–02:10 (phase I-2). These time intervals are shown in Figure 2 and listed in Table I. We note that the sharpness of time structure is limited by the TASC time resolution of 32.75 s. The separation of the data into these phases can also be justified directly from a comparison of the 'hardness' of the energy loss spectrum for each phase. To specify the hardness, we compare the TASC counting rate in the energy loss range 30–200 MeV, R(30–200), to the rate in the range 4–8 MeV, $R(4–8)$. These rates and their ratios are shown in Table I. The ratio $R(30–200)/R(4–8)$ is seen to be more than an order of magnitude greater in phase II compared to the bursts of phase I, implying a significant hardening of the parent particle spectra in the later phase of the flare.

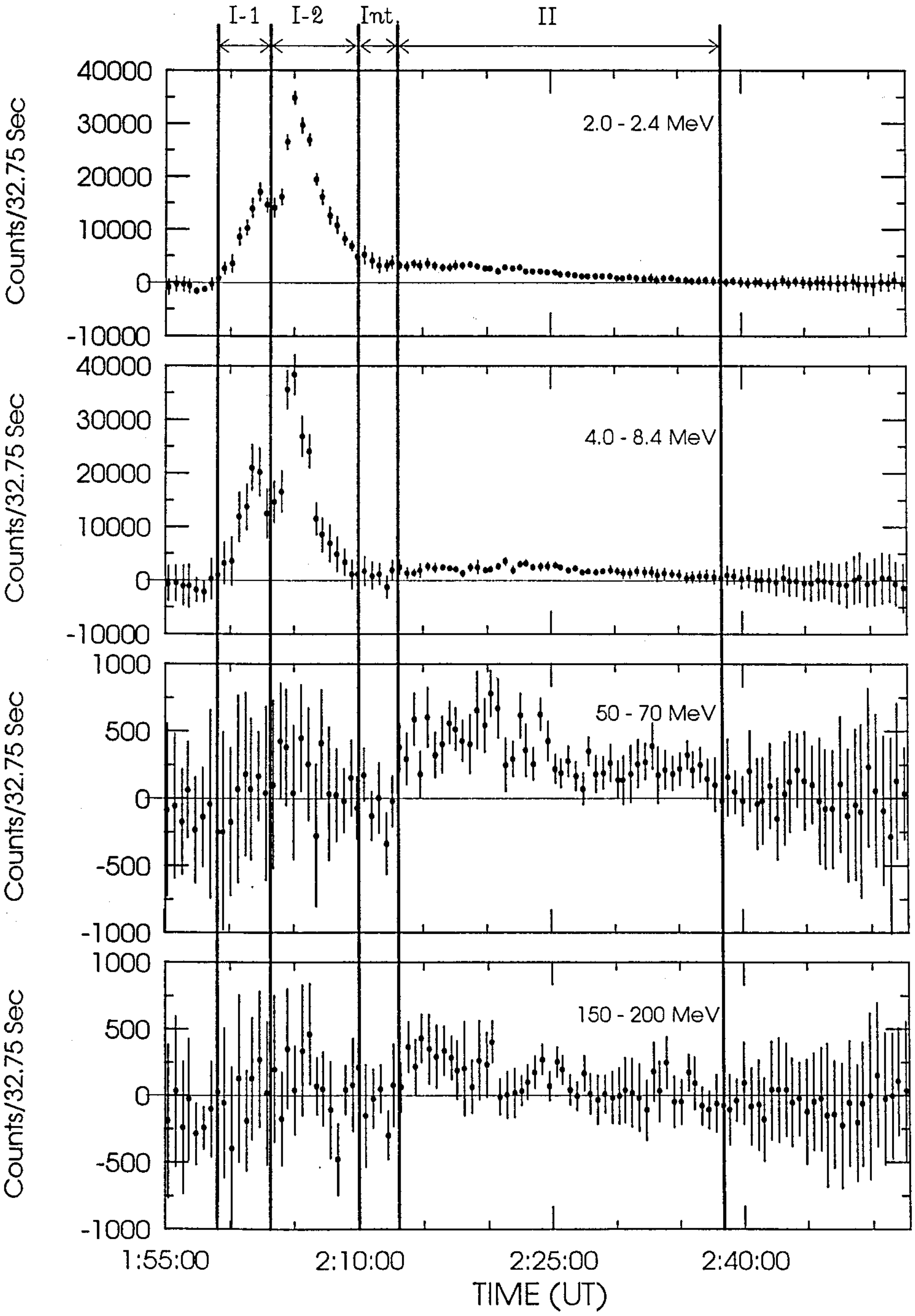

Figure 2. Time history of the response of the TASC during the flare of 11 June 1991 in several energy loss bands. Background has been subtracted. Demarcations of the phases discussed in the text are shown.

To specify the details of the spectral changes with time, we fit the energy loss spectrum for each phase with a multi-component model gamma-ray and neutron spectrum. There are five gamma-ray components: (1) a power law in energy, assumed to be due to electron bremsstrahlung; (2) a line spectrum from nuclear deexcitation; (3) a line at 2.223 MeV from neutron capture by protons; (4) a spectrum (dominated by lines at $\sim$ 7.6 MeV) from excitation of Fe nuclear levels by neutron interactions in the spacecraft material; and (5) a broad 'line' peaking at 67 MeV from π^0 decay plus a continuum due to bremsstrahlung from electrons and positrons from charged pion decay. For the neutron spectrum, two types of spectral shapes are used (Murphy *et al.*, 1987): (1) a theoretical neutron spectrum produced by protons with a power-law spectrum in energy and (2) a theoretical neutron spectrum produced by protons with a Bessel function spectrum. These proton (and therefore, neutron) spectral shapes are assumed to be related to different proton acceleration mechanisms.

The components of the model are folded through the gamma-ray and neutron response functions described above and fit to the observed energy-loss spectra using a standard Levenberg–Marquardt nonlinear multiparameter iterative fitting routine (Press *et al.*, 1989). The results of the fitting procedure are shown in Figure 3. Taking each phase in turn, we point out a number of features. The spectra from the two bursts during phase I are quite similar, with a power-law continuum, a significant contribution from the nuclear line de-excitation component (apparent mainly in the energy range 4–8 MeV), and a strong neutron-capture line at 2.2 MeV. During this phase, there is no significant contribution from pion-decay gamma-rays, solar neutrons, or Fe activation. In fact, these components were omitted from the phase I fits shown in Figure 3. The fit to the interphase has only two significant components: a power-law continuum and the 2.2 MeV neutron-capture line. Again, no pion-decay or neutron component is used in the fit for the interphase. Finally, the fit to the phase II spectrum indicates a significant pion-decay and neutron component but no significant power-law component. Otherwise, this phase II fit requires all of the gamma-ray components listed above. Unfortunately, the response of the EGRET/TASC is very similar for both pion-decay gamma-ray spectra and high-energy neutron spectra, so determination of independent pion-decay and neutron spectra is not possible. Therefore, we have used combinations of pion-decay and neutron spectra based on theoretical calculations (Murphy and Ramaty, 1985). The best-fit parameters and associated uncertainties for each of the phases are listed in Table II. In the following section, we discuss the implications of the differences between the spectra.

4. Results and Discussion

One of the most obvious features of the evolution of the high-energy emission from this flare is the clear hardening of the detected spectrum between phases I and II.

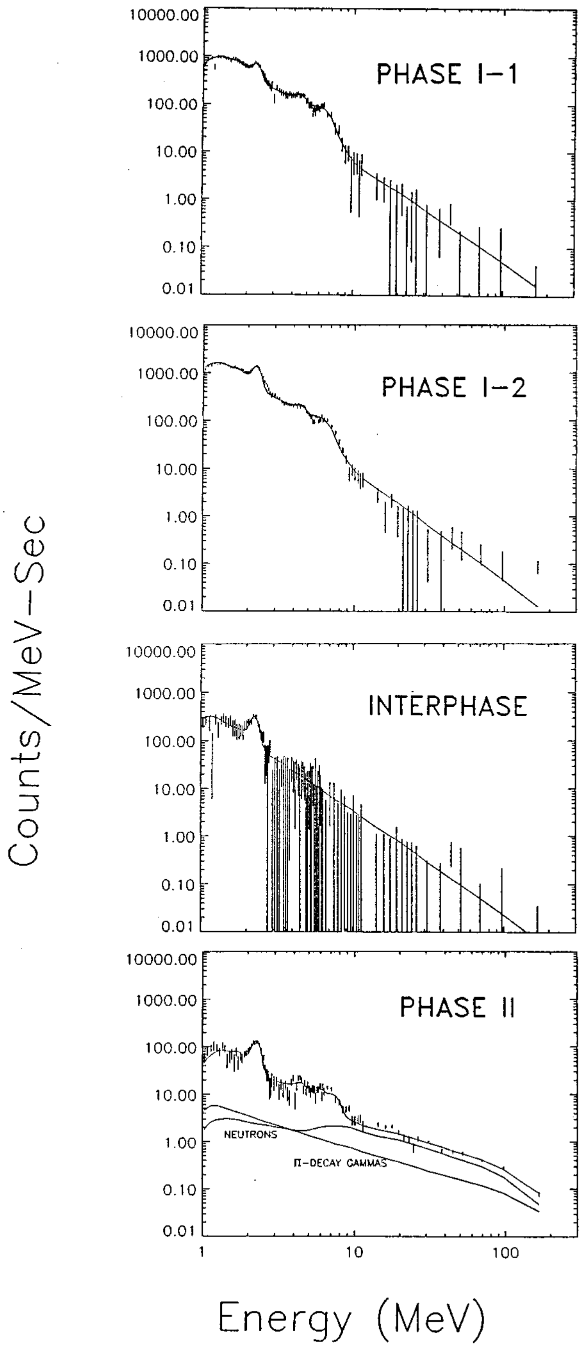

Figure 3. Plots of the energy-loss spectra (background subtracted) observed by the TASC for several time intervals during the 11 June flare. The spectra were fit with a multi-component model spectrum described in the text.

TABLE II

Fitting parameters for flare of 11 June 1991

Parameter	I-1	I-2	Interphase	II
p.l. index	2.08 ± 0.07	2.30 ± 0.03	2.20 ± 0.17	–
p.l. coeff.	0.22 ± 0.03	0.54 ± 0.03	0.16 ± 0.04	0
nucl. coeff.	1.36 ± 0.07	1.65 ± 0.05	< 0.097	0.137 ± 0.007
2.2 MeV coeff.	0.067 ± 0.004	0.157 ± 0.003	0.042 ± 0.004	0.0188 ± 0.0007
Fe line coeff.	$< 1.4 \times 10^{-3}$	$< 9.2 \times 10^{-4}$	$< 1.8 \times 10^{-3}$	$(1.0 \pm 0.2) \times 10^{-3}$
pion coeff.	$< 2.3 \times 10^{-5}$	$< 9.0 \times 10^{-6}$	0	$(1.55 \pm 0.13) \times 10^{-5}$
neutron coeff.	0	0	0	1.55×10^{-5}

Note: Upper limits are 1σ. Values in bold print were held fixed.

This can be seen both in the spectral hardness ratios in Table I and in the change in spectral shape in Figure 3, where an intensification in the spectrum above 10 MeV occurs during phase II. In our fitting model, this implies a flux of solar neutrons and pion-decay gamma-rays which were not present earlier. Mandzhavidze *et al.* (1996) have already pointed out the change in spectral shape. In fact, the change in shape is more radical than their analysis would imply. Since spectral analysis of the TASC data was beyond the scope of their paper, they had assumed that the emission detected > 10 MeV in phase I was due to pion decay. The present spectral analysis indicates that this energy range is actually dominated by electron bremsstrahlung in phase I. Thus the change in spectral shape from phase I to phase II is largely due to the appearance of a new pion-decay component. This, in turn, is due to the hardening of the ion spectrum that produces the nuclear lines and the pion-decay emission. Furthermore, we see a significant contribution from neutrons in the TASC response above 10 MeV during phase II. This affects the derived fluence of the pion-decay emission and, therefore, the proton spectral shape that is inferred from that fluence.

The virtual disappearance during the interphase of nuclear lines that are a signature of ion interactions imply that the phase I and phase II emissions are, to some extent, independent. This could mean that the ion acceleration mechanisms or the sites of the acceleration are different. The presence of a strong 2.2 MeV neutron-capture line during the interphase is not inconsistent with a decrease in ion interactions, since neutron capture line emission is expected to be delayed with respect to the prompt de-excitation lines (Prince *et al.*, 1983; Hua and Lingenfelter, 1987; Trottet *et al.*, 1993) produced in phase I.

Using the best-fit neutron and gamma-ray spectral parameters obtained from each phase of the flare, fluences for various components can be calculated, and these are listed in Table III. These fluences can be applied to appropriate solar gamma-ray and neutron production models (e.g., Murphy and Ramaty, 1985; Mur-

TABLE III
Fluences and proton spectral parameters

Phase	F_{4-7}	$F_{2.2}$	F_{π^0}	$F_{2.2}/F_{4-7}$	F_{π^0}/F_{4-7}	αT	S
I-1	21.7 ± 1.8	26.0 ± 2.6	< 0.063	1.20 ± 0.12	< 0.029	0.020 ± 0.002	~ 4.0
I-2	43.5 ± 2.3	57.4 ± 5.7	< 0.044	1.32 ± 0.13	< 0.010	0.023 ± 0.002	~ 4.0
II	13.1 ± 0.8	23.8 ± 2.4	5.13 ± 0.43	1.82 ± 0.18	0.39 ± 0.06	–	3.35 ± 0.10

Note: Upper limits are 1σ. Fluence units are cm^{-2}.

phy *et al.*, 1987; Ramaty *et al.*, 1993) to constrain the flare proton spectrum. In particular, the relative fluences of the 2.2 MeV line ($F_{2.2}$), the nuclear line emission in the range 4–7 MeV (F_{4-7}), and π^0-decay gamma-rays (F_{π^0}) can be used to constrain the energy spectrum of solar protons that produce these emissions. Because the 2.2 MeV line emission is delayed relative to the prompt 4–7 MeV deexcitation lines, we have modeled the 2.2 MeV time history, using the technique of Prince *et al.* (1983), to get the appropriate relationship between the 2.2 MeV and 4 –7 MeV fluences. This method gives a neutron–proton 'capture time' of 95 ± 40 s during phase I, compared to a value of 70 ± 10 s reported by Trottet *et al.* (1993) for this flare. We also note that the ratio $F_{2.2}/F_{4-7}$ of 1.26 ± 0.08 averaged over phase I is consistent with the value of 1.25 ± 0.12 found by Trottet *et al.* (1993) using data from Phebus for phase I, but higher than the values 0.80 ± 0.12 and 1.24 ± 0.12 found by Rank *et al.* (1996) from Comptel data for phases I and II, respectively.

In Figure 4, we plot the relevant ratios, $F_{2.2}/F_{4-7}$ and F_{π^0}/F_{4-7}, as a function of proton spectral shape, based on calculations by Ramaty *et al.* (1993) and Ramaty (personal communication). Two forms of proton spectral shapes are presented: a Bessel-function shape characterized by parameter αT in panel a, and a power-law shape characterized by (negative) index S in panel b. In both panels of Figure 4, the calculated ratio $F_{2.2}/F_{4-7}$ is shown for two directional distributions of the energetic protons. One assumes an isotropic distribution in the downward hemisphere into the solar photosphere ('downward isotropic') and the second assumes a fan-beam distribution that is at an angle of 89° with respect to the downward radius vector ('horizontal'). The composition of both the accelerated particles and the ambient medium is taken to be the photospheric composition, 'comp 1' in Ramaty *et al.* (1993). For both the Bessel-function spectrum and the power-law spectrum, the measured ratios are plotted for the 'horizontal' case. Using the 'downward isotropic' case would cause the implied spectrum to be 'softer'. Taking the data and theoretical curves at face value leads to the following conclusions: (1) the phase I data are consistent with Bessel-function proton spectra ($\alpha T = 0.022 \pm 0.003$ for the horizontal case and 0.015 ± 0.002 for the downward isotropic case); (2) the phase I data are also consistent with power-law spectra (index $S \sim 4.0$) for the

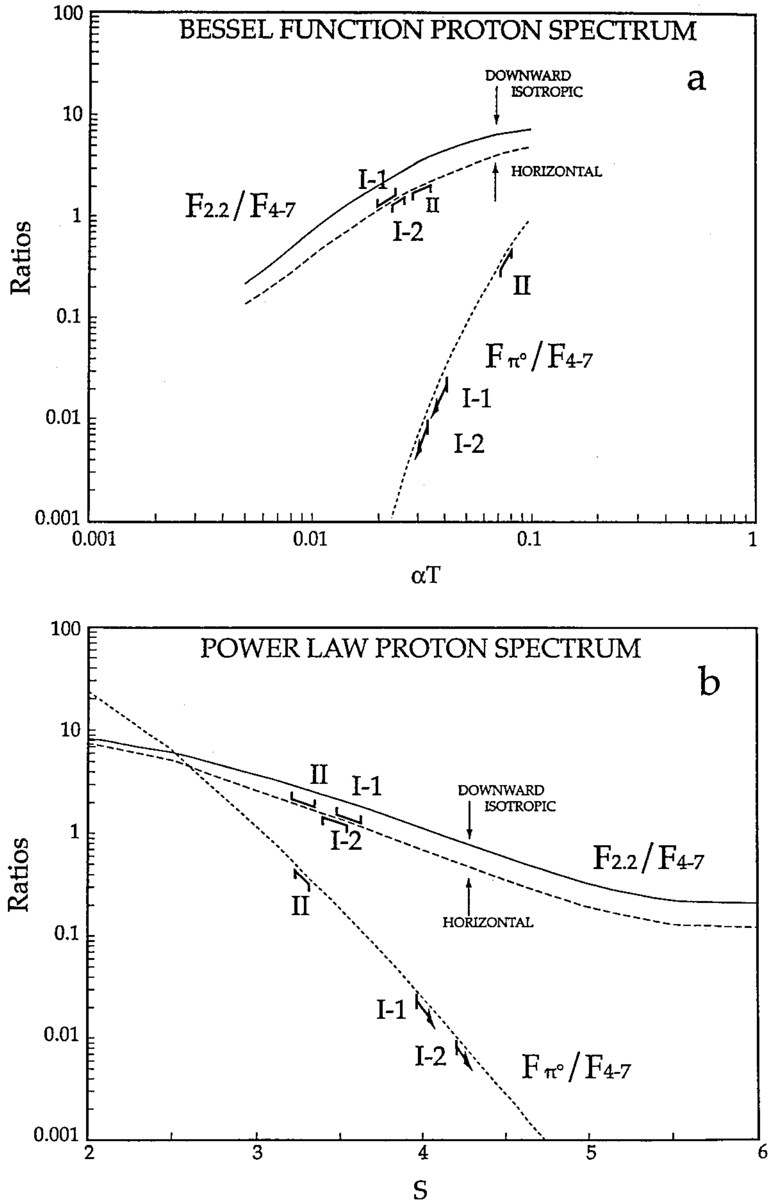

Figure 4. The fluence ratios $F_{2.2}/F_{4-7}$ and F_{π^0}/F_{4-7} are plotted for two proton spectral shapes: (a) a Bessel function in energy characterized by parameter αT and (b) a power law in energy with index $-S$. The curves are theoretical values based on calculations by Ramaty *et al.* (1993) and Ramaty (private communication). The ratio $F_{2.2}/F_{4-7}$ is plotted for both 'horizontal' and 'downward isotropic' proton distributions (see text). The labeled sections correspond to the values observed for three time periods (I-1, I-2, and II) during the flare of 11 June 1991, and are indicated only for the 'horizontal' case.

downward isotropic case, especially if a slight softening of the spectra above about 100 MeV is allowed; (3) the phase II data are consistent with a single power law ($S = 3.35 \pm 0.10$), with a horizontal distribution favored over a downward isotropic distribution; (4) the phase II data are inconsistent with a Bessel-function spectrum. For any model, the phase II spectrum is significantly harder than the phase I spectra. This evolution in ion spectral shape from a relatively soft (possibly Bessel-function) spectrum to a harder power-law spectrum is reminiscent of the flare of 3 June 1982. In that case, Murphy *et al.* (1987) argued that the initial burst of gamma-rays (and neutrons) was due to ion acceleration by a 2nd-order Fermi process, while the time-extended emission was caused by shock acceleration.

We conclude by noting a more general similarity of the high-energy time history of this flare with other large flares. In particular, the presence of an initial impulsive phase (phase I here), followed by a 'delayed' or 'extended' phase with a harder ion spectrum (phase II here), appears to be the rule rather than the exception for the largest X-class flares detected by SMM, CGRO, and GAMMA-1 (Dunphy and Chupp, 1994; Akimov *et al.*, 1991, 1994a, 1994b; Ryan *et al.*, 1994; Rieger, 1996). It is already known that electrons ($>$1 MeV) and ions ($>$100 MeV) can be accelerated together over short time scales ($\sim$ 1 s) (Forrest and Chupp, 1983; Kane *et al.*, 1986) and particle acceleration models that describe the impulsive burst behavior typical of phase I have been addressed. Models that explain particle acceleration and/or trapping with emphasis on ions which would be appropriate to the phase II emission reported here have also been put forward (Ryan and Lee 1991; Kocharov *et al.*, 1993; Guglenko *et al.*, 1990; Mandzhavidze *et al.*, 1996). Given the commonness of extended phase emission, models which do not depend on unusual or special conditions at the flare site should be favored.

Acknowledgements

The authors acknowledge helpful comments and unpublished calculations from R. Ramaty. They also gratefully acknowledge support from NASA through grants NAG 5-2420 and NAG 5-3518 (UNH) and contract NAS 5-31210 (Northrop Grumman).

References

Akimov, V. V. *et al.*: 1991, *Proc. 22nd Int. Cosmic Ray Conf., Dublin* **3**, 73.

Akimov, V. V., Leikov, N. G., Belov, A. V., Chertok, I. M., Kurt, V. G., Magun, A., and Melnikov, V. F.: 1994a, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 106.

Akimov, V. V., Leikov, N. G., Kurt, V. G., and Chertok, I. M.: 1994b, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 130.

Chiba, N. *et al.*: 1992, *Astroparticle Phys.* **1**, 27.

Chupp, E. L.: 1963, in W. N. Hess (ed.), *AAS-NASA Symposium on the Physics of Solar Flares*, NASA SP-50, p. 445.

Chupp, E. L., Forrest, D. J., Ryan, J. M., Heslin, J., Reppin, C., Pinkau, K., Kanbach, G., Rieger, E., and Share, G.: 1982, *Astrophys. J.* **263**, L95.

Chupp, E. L., Debrunner, H., Flückiger, E., Forrest, D. J., Golliez, F., Kanbach, G., Vestrand, W. T., Cooper, J., and Share, G.: 1987, *Astrophys. J.* **318**, 913.

Debrunner, H., Flückiger, E., Chupp, E. L., and Forrest, D. J.: 1983, *Proc. 18th Int. Cosmic. Ray Conf.* **4**, 75.

Dolan, J. F. and Fazio, G. G.: 1965, *Rev. Geophys.* **3**, 319.

Dunphy, P. P., and Chupp, E. L.: 1994, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 112.

Dunphy, P. P., Chupp, E. L., Popecki, M., Forrest, D. J., Lopiano, D., Shima, T., Spinka, H., Glass, G., Burleson, G., and Beddo, M.: 1989, *Experimental Astrophys.* **2**, 233.

Fireman, E. L.: 1963, in W. N. Hess (ed.), *AAS-NASA Symposium on the Physics of Solar Flares*, NASA SP-50, p. 279.

Forrest, D. J. and Chupp, E. L.: 1983, *Nature* **305**, 291.

Forrest, D. J., Vestrand, W. T., Chupp, E. L., Rieger, E., Cooper, J., and Share, G. H.: 1985, *Proc. 19th Int. Cosmic. Ray Conf.* **4**, 146.

Guglenko, V. G., Efimov, Yu. E., Kocharov, G. E., Kovaltsov, G. A., Mandzhavidze, N. Z., Terekhov, M. M., and Kochaov, L. G.: 1990, *Astrophys. J.* **73**, 209.

Hua, X.-M. and Lingenfelter, R. E.: 1987, *Astrophys. J.* **323**, 779.

Hughes, E. B. *et al.*: 1988, *IEEE Trans. Nucl. Sci.* **NS-27**, 364.

Jensen, C. M.: 1990, *CALOR/VAX Users Manual*, Applied Science Corporation, Landover, MD.

Kanbach, G. *et al.*: 1988, *Space Sci. Rev.* **49**, 69.

Kanbach, G. *et al.*: 1993, *Astron. Astrophys. Suppl. Ser.* **97**, 349.

Kane, S. R. *et al.*: 1986, *Astrophys. J.* **300**, L95.

Kocharov, G. E., *et al.*: 1993, *Proc. 23rd Int. Cosmic Ray Conf.* **3**, 123.

Lingenfelter, R. E.: 1969, *Solar Phys.* **8**, 341.

Lingenfelter, R. E. and Ramaty, R.: 1967, in B. S. P. Shen (ed.), *High-Energy Nuclear Reactions in Astrophysics*, W. A. Benjamin, Inc., New York, p. 99.

Mandzhavidze, N. and Ramaty, R.: 1992, *Astrophys. J.* **389**, 739.

Mandzhavidze, N. and Ramaty, R.: 1993, *Nuclear Physics B. Proc. Suppl.* **33**, 141.

Mandzhavidze, N., Ramaty, R., Bertsch, D. L., and Schneid, E. J.: 1996, in R. Ramaty, N. Mandzhavidze, and X.-M. Hua (eds.), *High Energy Solar Physics*, AIP, New York, p. 225.

Muraki, Y *et al.*: 1991, *Proc. 22nd Int. Cosmic Ray Conf.* **3**, 49.

Murphy, R. J. and Ramaty, R.: 1985, *Adv. Space Res.* **4**(7), 127.

Murphy, R. J., Dermer, C. D., and Ramaty, R.: 1987, *Astrophys. J. Suppl.* **63**, 721.

Murphy, R. J., Share, G. H., Grove, J. E., Johnson, W. N., Kinzer, R. L., Kroeger, R. A., Kurfess, J. D., Strickman, M. S., Matz, S. M., Grabelsky, D. A., Purcell, W. R., Ulmer, M. P., Cameron, R. A., Jung, G. V., Jensen, C. M., Vestrand, W. T., and Forrest, D. J.: 1993, in M. Friedlander, N. Gehrels, and D. J. Macomb (eds.), *Compton Gamma Ray Observatory*, AIP, New York, p. 619.

Nelson, W. R.: 1981, *The EGS4 Code System*, SLAC-265, Stanford Linear Accelerator Center.

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T.: 1989, *Numerical Recipes: The Art of Scientific Computing*, FORTRAN Version, Cambridge University Press, Cambridge, p. 524.

Prince, T. A., Forrest, D. J., Chupp, E. L., Kanbach, G., and Share, G. H.: 1983, *Proc. 18th Int. Cosmic Ray Conf.* **4**, 79.

Ramaty, R., Mandzhavidze, N., Kozlovsky, B., and Skibo, J. G.: 1993, *Adv. Space Res.* **13**(9), 275.

Rank, G., Diehl, R., Lichti, G. G., Schönfelder, V., Varendorff, M., Swanenburg, B. N., Forrest, D., Macri, J., McConnell, M., Ryan, J., Hanlon, L., and Winkler, C.: 1993, in M. Friedlander, N. Gehrels, and D. J. Macomb (eds.), *Compton Gamma Ray Observatory*, AIP, New York, p. 661.

Rank, G., Diehl, R., Lichti, G. G., Schönfelder, V., Varendorff, M., Swanenburg, B. N., van Dijk, R., Forrest, D., Macri, J., McConnell, M., Loomis, M., Ryan, J., Bennett, K., and Winkler, C.: 1994, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 100.

Rank, G. *et al.*: 1996, in R. Ramaty, N. Mandzhavidze, and X.-M. Hua (eds.), *High Energy Solar Physics*, AIP, New York, p. 219.

Rank, G., Debrunner, H., Lockwood, J., McConnell, M., Ryan, J., and Schönfelder, V.: 1997, *Proc. 25th Int. Cosmic Ray Conf.* **1**, 5.

Rieger, E.: 1996, in R. Ramaty, N. Mandzhavidze, and X.-M. Hua (eds.), *High Energy Solar Physics*, AIP, New York, p. 194.

Ryan, J. M., and Lee, M. A.: 1991, *Astrophys. J.* **368**, 316.

Ryan, J. M., Forrest, D., Lockwood. J., Loomis, M., McConnell, M., Morris, D., Webber, W., Bennett, K., Hanlon, L., Winkler, C., Debrunner, H., Rank, G., Schönfelder, V., and Swanenburg, B. N.: 1994, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 89.

Schneid, E. J., Brazier, K. T. S., Kanbach. G., von Montigny, C., Mayer-Hasselwander, H. A., Bertsch, D. L., Fichtel, C. E., Hartman, R. C., Hunter, S. D., Thompson, D. J., Dingus, B. L., Sreekumar, P., Lin, Y. C., Michelson, P. F., Nolan, P. L., Kniffen, D. A., and Mattox, J. R.: 1994, in J. M. Ryan and W. T. Vestrand (eds.), *High-Energy Solar Phenomena*, AIP, New York, p. 94.

Schneid, E. J., *et al.*: 1996, *Astron. Astrophys. Suppl. Ser.* **120**, 299.

Shea, M. A., Smart, D. F., and Pyle, K. R.: 1991, *Geophys. Res. Letters* **18**, 1655.

Smart, D. F. *et al.*: 1990, *Astrophys. J. Suppl.* **73**, 269.

Solar-Geophysical Data: 1991, Comprehensive Reports, December 1991, Number 568, Part II, p. 104.

Suleiman, R. M.: 1995, M.S. Thesis, Physics Department, University of New Hampshire, Durham, NH.

Takahashi, K. *et al.*: 1991, *Proc. 22nd Int. Cosmic Ray Conf.* **3**, 37.

Thompson, D. J. *et al.*: 1993, *Astrophys. J. Suppl. Ser.* **86**, 629.

Trottet, G., Vilmer, N., Barat, C., Dezalay, J. P., Talon, R., Sunyaev. R., Kuznetsov, A., and Terekhov, O.: 1993, *Astron. Astrophys. Suppl. Ser.* **97**, 337.