CGRO GUEST INVESTIGATOR PROGRAM

FINAL REPORT FOR GRANT NAG 5-2420:

"EGRET HIGH ENERGY CAPABILITY" and "MULTIWAVELENGTH FLARE STUDIES"

AND GRANT NAG 5-3518: "SOLAR FLARE PROTON SPECTRA"

Principal Investigator: Dr. Edward L. Chupp

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The study of EGRET/TASC flare data has been funded during phases 3–6 of the CGRO Guest Investigator program. The funding and accomplishments can be summarized as follows:

Phase 3. – Under PI Dr. David L. Bertsch (GSFC) the proposal "Use of EGRET High-Energy Capability to Investigate Energetic Solar Flare Processes" was funded with E. L. Chupp and P. P. Dunphy as Co-Investigators at a level of $15,500 instead of the $22,000 requested (NAG 5-2420).

Under *Phase 3* support the accomplishments were:

UNH was assigned the responsibility to use their accelerator neutron measurements to verify the *TASC* response function and to modify the *TASC* fitting program to include a high energy neutron contribution. Direct accelerator-based measurements by UNH of the energy-dependent efficiencies for detecting neutrons with energies from 36 to 720 MeV in NaI were compared with Monte Carlo TASC calculations. The calculated TASC efficiencies are somewhat lower (by about 20%) than the accelerator results in the energy range 70–300 MeV. The measured energy-loss spectrum for 207 MeV neutron interactions in NaI were compared with the Monte Carlo response for 200 MeV neutrons in the TASC indicating good agreement. Based on this agreement, the simulation was considered to be sufficiently accurate to generate a neutron response library to be used by UNH in modifying the *TASC* fitting program to include a neutron component in the flare spectrun modeling. *TASC* energy-loss data on the 1991 June 11 flare was transferred to UNH.

Phase 4. – Under PI Dr. E. L. Chupp the proposal "Study of High Energy Neutrons and Gamma-Rays Using the *EGRET* /TASC" was funded at a level of $30,000 (Supplement 1) while the level requested for the proposed work was $49,000. Under PI Dr. David L. Bertsch the proposal "Investigation of Energetic Solar Flare Processes Using the High Energy Capabilities of *EGRET*" provided UNH Co-Investigators Chupp and Dunphy with $16,796 of additional funding (Supplement 2) to continue the work started under the phase 3 program instead of the requested amount of $25,000.

Under *Phase 4* the accomplishments were:

The *Phase 3* effort to determine a high energy neutron contribution to the emissions from the 1991 June 11 solar flare was continued. A preliminary upper limit to the neutron fluence (> 50 MeV) from this flare was found by adding a theoretical solar neutron spectrum to the TASC spectral fit program. The result was <27 neutrons cm^{-2} which corresponds to $< 2.2 \times 10^{28}$ neutrons sr^{-1} (> 50 MeV) emitted from the Sun toward the Earth. This is about a factor of 10 less than the neutron emissivity from the 1982 June 3 solar flare. This result was presented by P. P. Dunphy, E. L. Chupp, D. L. Bertsch, E. J. Schneid, and S. Gottesman at the 24th International Cosmic Ray Conference at Rome in September 1995. Subsequently, the *TASC* spectral fitting program has been modified to include components from: γ-ray lines (solar and background), bremsstrahlung, neutral pion decay and high energy neutron interactions.

The next step in the analysis of this event was doing full fits to the *TASC* energy-loss spectra as a function of time. A significant hardening of the solar proton spectrum over time was found for the flare. The results from the analysis were presented at the 188th meeting of the AAS in Madison, WI by P. P. Dunphy *et al.* in June 1996.

Phase 5. – Under PI Dr. E. L. Chupp the proposal "Multiwavelength Studies of October 91 X-Class Solar Flares Observed by EGRET" was funded at a level of $15,000 (Supplement 3) instead of the $52,000 requested.

Under *Phase 5* the accomplishments were:

For the *Phase 5* work, we have gathered a significant amount of correlated data for flares observed by the EGRET/TASC. This includes the TASC spectral data for 5 X–class flares between 1991 October 21 and 1991 November 3, as well as the corresponding response functions which account for the solar angle and the spacecraft mass. Also obtained were: Yohkoh HXT time histories and images for the 1991 October 27 flare, Yohkoh GRS time histories and gamma-ray line spectra for the 1991 October 27 flare, standard GOES x-ray data and NOAA radio reports, Nobeyama radio reports, and Chinese Academy of Sciences Solar-Geophysical Data.

Phase 6. – Under PI Dr. E. L. Chupp the proposal "Characterization of Solar Flare Proton Spectra

Using EGRET/TASC Data" was funded at a level of $25,000 (NAG 5-3518).

Under *Phase 6* the accomplishments were:

The goal of the *Phase 6* program was to apply the analysis technique used successfully with the *EGRET / TASC* energy-loss spectra for the 1991 June 11 flare to data on the remaining X-class flares observed in 1991 June. The first priority was to use the results from fitting the June 11 flare spectra to constrain the flare proton spectral shape and intensity. Our results to date demonstrate that the TASC spectral analysis contributes crucial information on the particle spectrum interacting at the Sun. A paper describing this analysis and its results has been accepted for publication by the journal Solar Physics is attached as Appendix A.

Analysis of nuclear gamma-ray lines from the flare of 1991 October 27 has been completed and a paper based on this work will be presented at the 26th International Cosmic Ray Conference in Salt Lake City, Utah, August 17-25, 1999. A preliminary draft of the paper is attached as Appendix B.

Our findings from the 1991 June 11 flare are compared with other flares with time-extended gamma-ray emission in a paper to be presented at the Centennial Meeting of the American Physical Society in Atlanta, Georgia, March 21-26, 1999. The abstract for this paper is attached as Appendix C.

APPENDIX A

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

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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.

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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 ($\pi^{\pm}$, π^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–α 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.* 1994, 1997). 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(Tl) 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 $\times$ 76 $\times$ 20 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 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 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 ^{3}He/^{1}H 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 32.75s. 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.

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 de–excitation; (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: (1) a theoretical neutron spectrum produced by protons with a power law spectrum in energy (Murphy *et al.* 1987) and (2) a theoretical neutron spectrum produced by protons with a Bessel function spectrum (Murphy *et al.* 1987). These proton (and therefore, neutron) spectral shapes are assumed to be related to different proton acceleration mechanisms (Murphy *et al.* 1987).

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 non–linear multi–parameter 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. 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; Murphy *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 de-excitation 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 s, compared to a value of 70 ± 10 s reported by Trottet *et al.* 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 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), appear 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 (~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.

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Table I
Time Intervals and Hardness Ratio for Flare of 1991 June 11

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	$1.04(\pm 0.05) \times 10^{-2}$

Table II
Fitting Parameters for Flare of 1991 June 11

Parameter	I–1	I–2	Interphase	II
p.l. index	2.08±.07	2.30±.03	2.20±.17	—
p.l. coeff.	0.22±.03	0.54±.03	0.16±.04	**0**
nucl. coeff.	1.36±.07	1.65±.05	< 0.097	0.137±.007
2.2 MeV coeff.	0.067±.004	0.157±.003	0.042±.004	0.0188±.0007
Fe line coeff.	$< 1.4 \times 10^{-3}$	$< 9.2 \times 10^{-4}$	$< 1.8 \times 10^{-3}$	$(1.0 \pm .2) \times 10^{-3}$
pion coeff.	$< 2.3 \times 10^{-5}$	$< 9.0 \times 10^{-6}$	**0**	$(1.55 \pm .13) \times 10^{-5}$
neutron coeff.	**0**	**0**	**0**	**1.55×10^{-5}**

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

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±.002	~ 4.0
I-2	43.5±2.3	57.4±5.7	< 0.044	1.32±0.13	< 0.010	0.023±.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}.

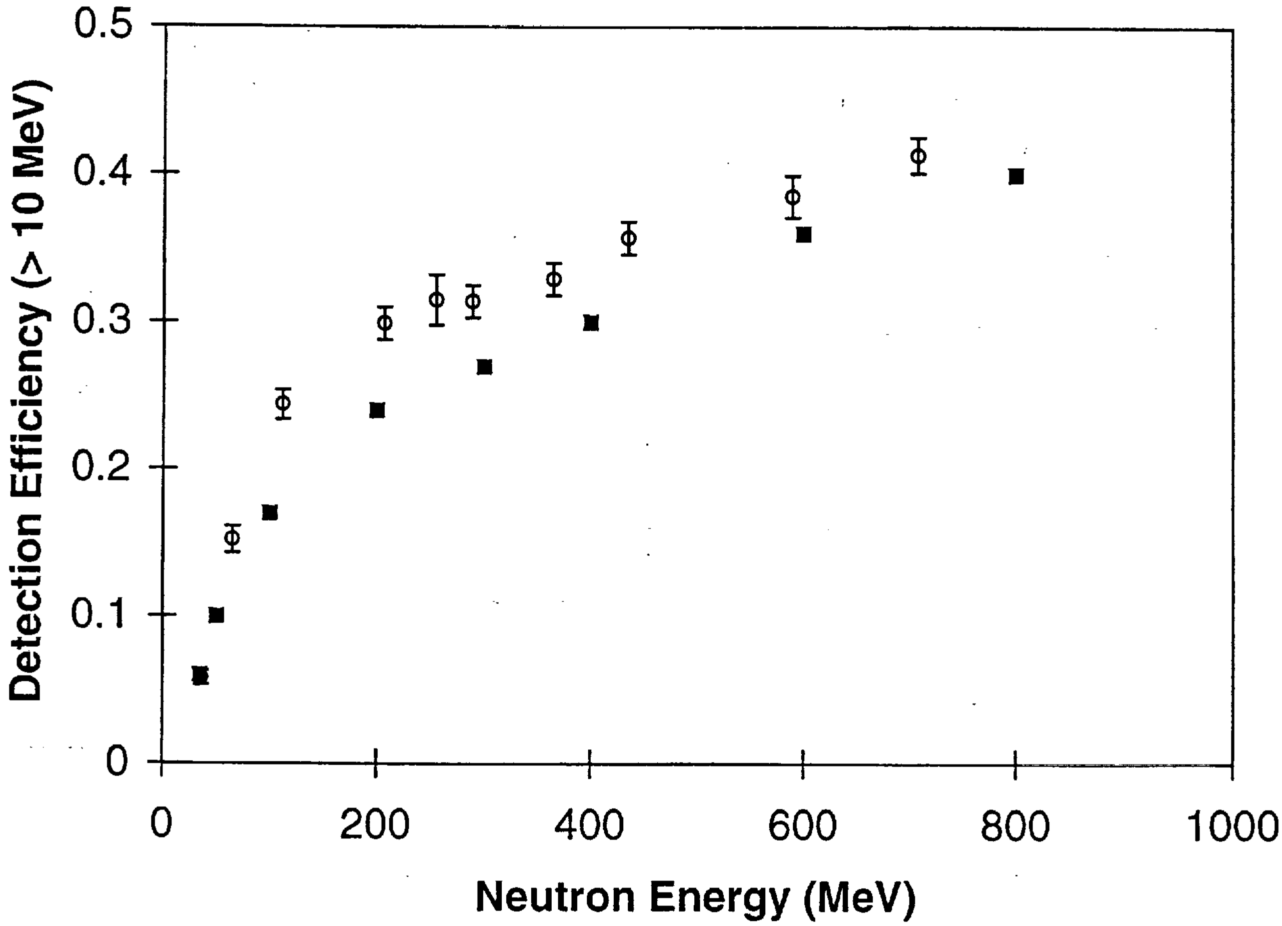
FIGURE CAPTIONS

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.

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.

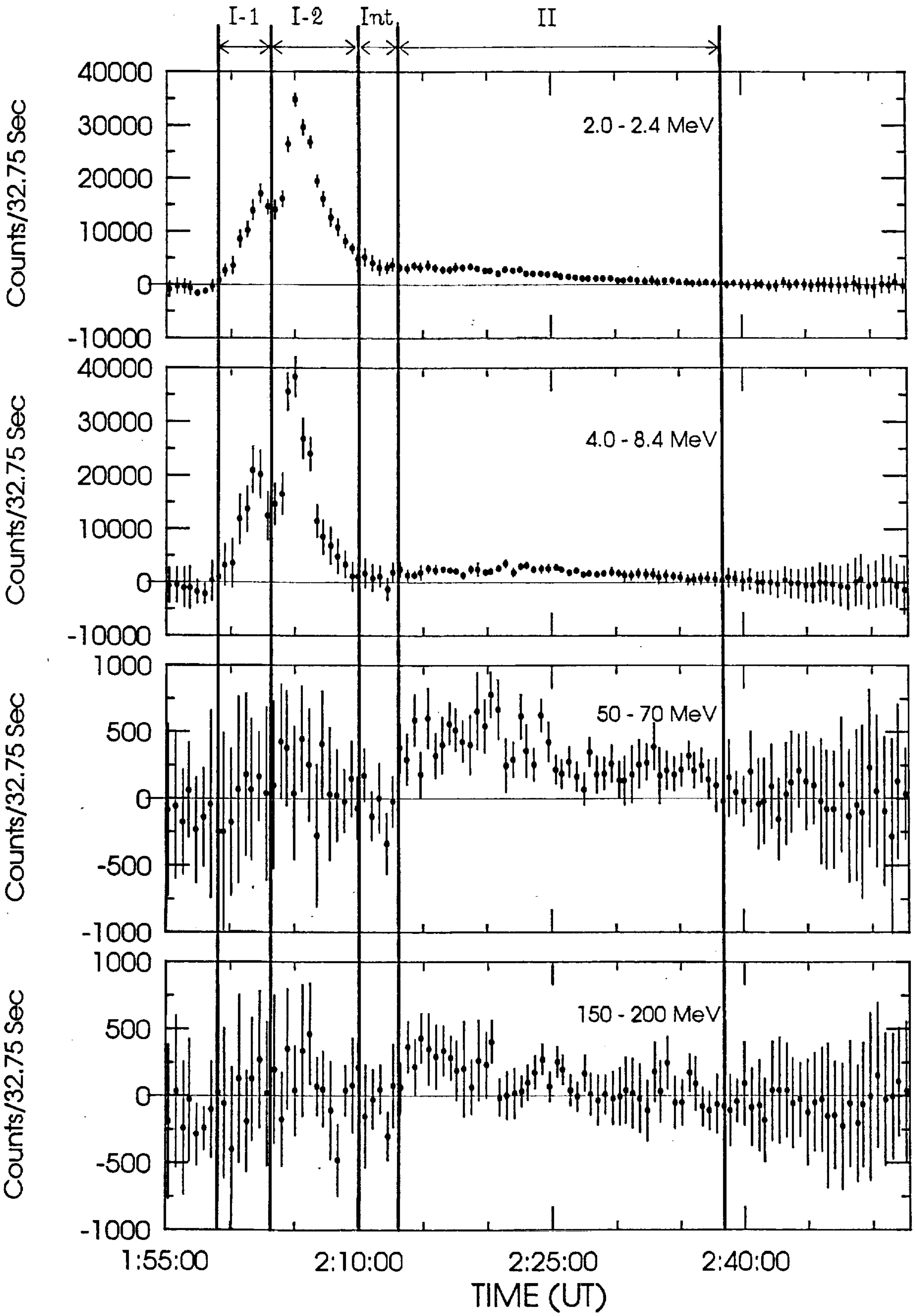
Figure 3. Plots of the energy–loss spectra (background subtracted) observed by the TASC for several time intervals during the 11 June flare. The spectra were fit with a multi–component model spectrum described in the text.

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 3 time periods (I-1, I-2, and II) during the flare of 11 June 1991, and are indicated only for the "horizontal" case.



Detection Efficiency (> 10 MeV)
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
Neutron Energy (MeV)

Figure 1.



I-1
I-2
Int
II
2.0 - 2.4 MeV
4.0 - 8.4 MeV
50 - 70 MeV
150 - 200 MeV
Counts/32.75 Sec
40000
30000
20000
10000
0
-10000
1000
500
-500
-1000
1:55:00
2:10:00
2:25:00
2:40:00
TIME (UT)

Figure 2.

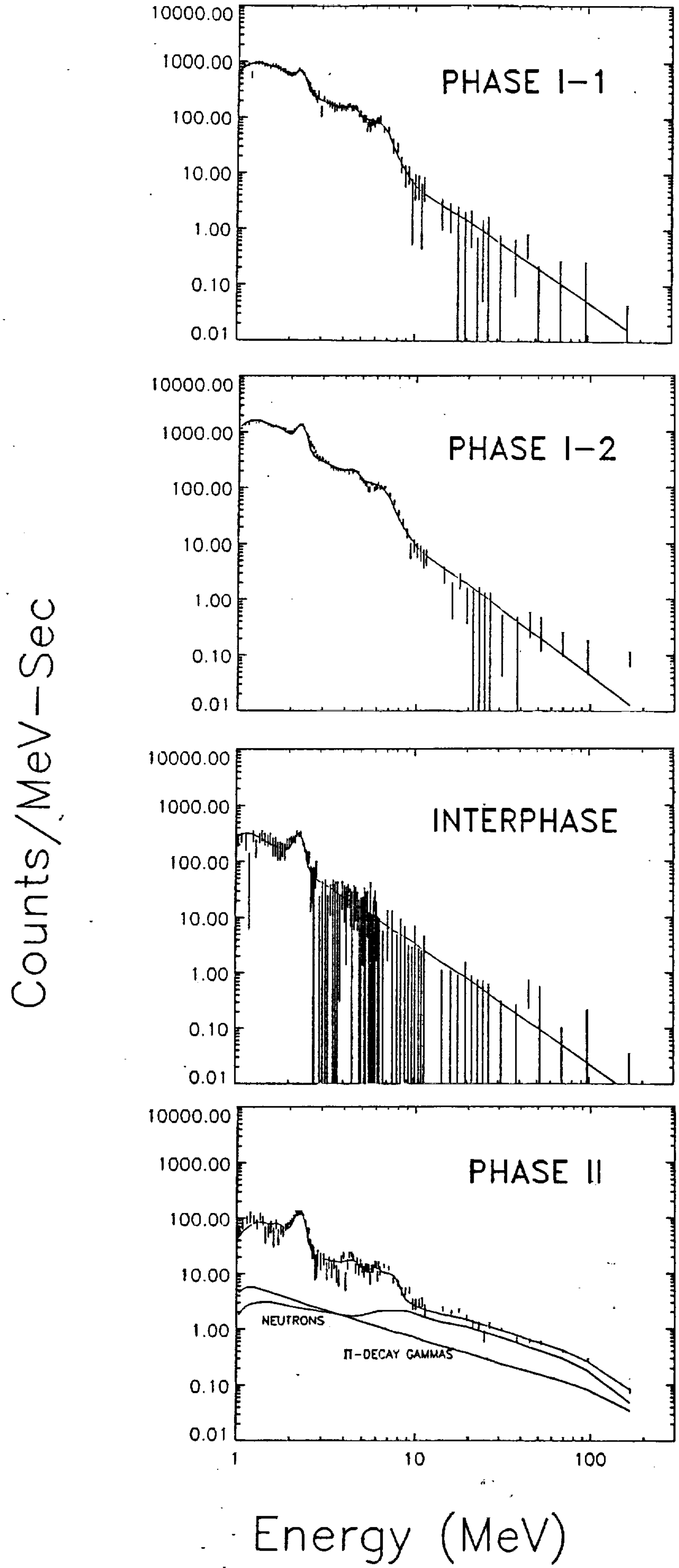
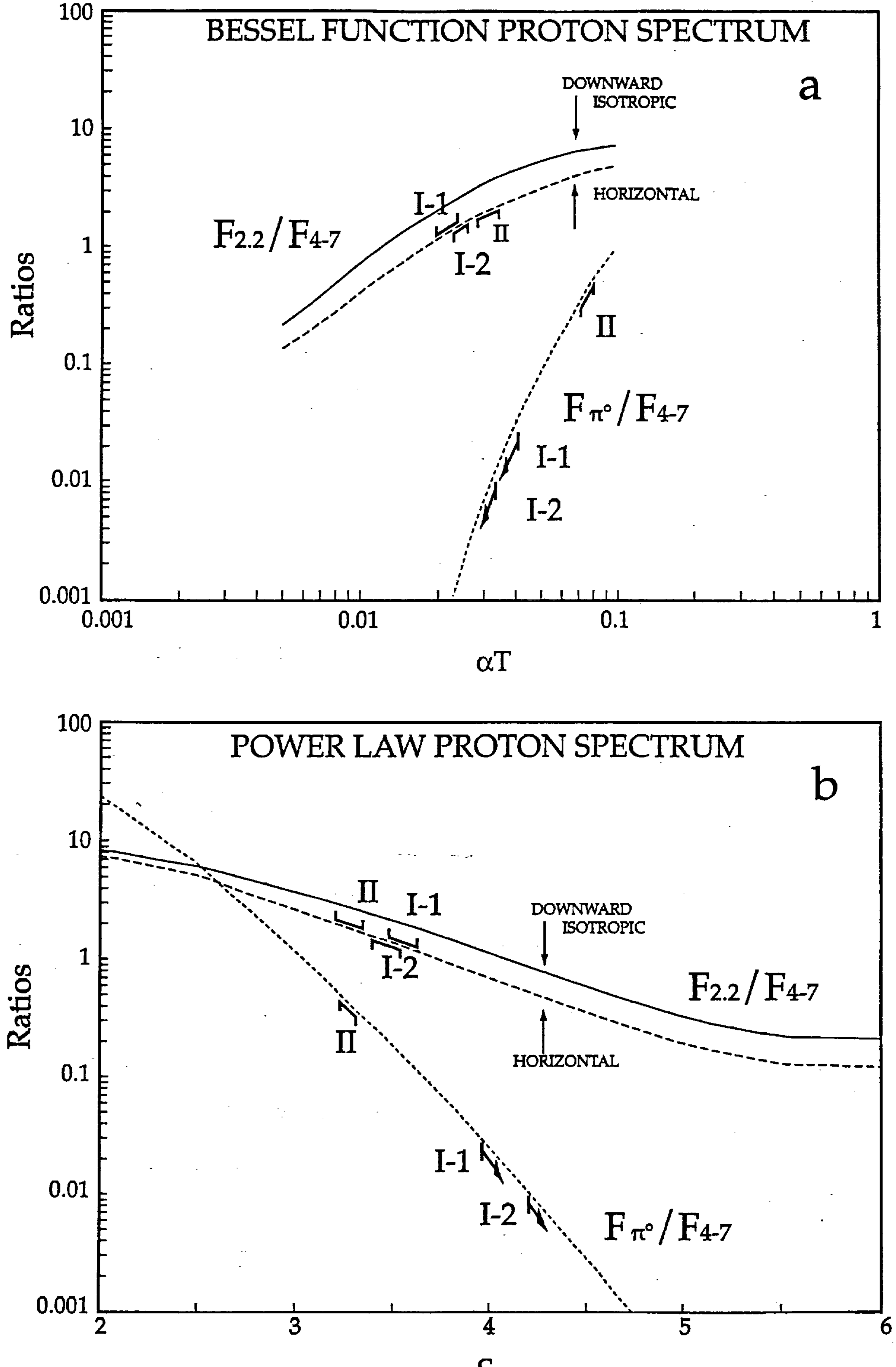

PHASE I-1
PHASE I-2
INTERPHASE
PHASE II
NEUTRONS
Π-DECAY GAMMAS
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
1
10
100
Counts/MeV-Sec
Energy (MeV)

Figure 3.



BESSEL FUNCTION PROTON SPECTRUM
a
DOWNWARD
ISOTROPIC
HORIZONTAL
I-1
I-2
II
F2.2 / F4-7
Fπ° / F4-7
Ratios
αT
100
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
POWER LAW PROTON SPECTRUM
b
II
I-1
I-2
DOWNWARD
ISOTROPIC
HORIZONTAL
F2.2 / F4-7
Fπ° / F4-7
Ratios
S
2
3
4
5
6

Figure 4

Neutron–Capture Gamma–Rays Observed by EGRET from the Flare of 1991 October 27 *

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ABSTRACT

The neutron–capture γ–ray line at 2.223 MeV was observed by the Total Absorption Shower Counter (TASC) section of the EGRET γ–ray telescope on the Compton Gamma Ray Observatory satellite from a solar flare on 1991 October 27. This flare, which produced γ–rays starting around 05:39 UT, was very intense in the energy range dominated by nuclear lines. This radiation was also relatively impulsive compared to other large flares observed by the TASC. The neutron capture γ–ray line at 2.223 MeV is clearly delayed relative to prompt γ–ray line emission in the energy range of 4–8 MeV. We find that the time history of the neutron–capture line at 2.223 MeV can be characterized by a single exponential decay–time of 78 ± 20 s. We use this parameter to constrain the ^{3}He/H ratio at the capture site to a level of $< 5 \times 10^{-5}$ at the 67% confidence level.

INTRODUCTION

A γ–ray of energy 2.223 MeV is produced when deuterium is formed from a proton and a neutron in the exoergic reaction

$$p + n \rightarrow {}^2D + \gamma \quad (1)$$

The neutron–capture line was first observed[1] by the Gamma–Ray Monitor on the OSO–7 satellite during the solar flare of 1972 August 4. Subsequent observations were made by detectors on HEAO–1,[2] HEAO–3,[3] SMM,[4,5] HINOTORI,[6] GRANAT,[8] and CGRO. The 2.223 MeV line can be used to probe conditions in the solar photosphere. In particular, Prince *et al.*[4] and Hua and Lingenfelter[7] used the time history of the line during the large flare of 1982 June 3 to calculate the ^{3}He/H ratio in the solar photosphere. The capture line time history depends on the rate of production of solar neutrons, as well as on

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their rate of capture. The measured time–dependent flux of the 2.223 MeV line can be modeled as (using the notation of Prince *et al.*[4])

$$F_{2.2}(t) = \int_{-\infty}^{t} S(T)R(t,T)dT \tag{2}$$

where $F_{2.2}(t)$ is the observed 2.223 MeV flux, $S(T)$ is the neutron production time history, and $R(t,T)$ is the response function giving the 2.223 MeV photon contribution at time t due to neutrons produced at time T. If the spectral shape of the energetic particles does not change during the flare, the neutron production time history, $S(T)$, is proportional to the flux of prompt nuclear lines produced by the same population of energetic particles.

Then equation (2) becomes

$$F_{2.2}(t) = \int_{-\infty}^{t} k_1 F_\gamma(T)R(t,T)dT \tag{3}$$

where $F_\gamma(T)$ is the observed flux of prompt γ–ray lines, and k_1 is a proportionality constant that relates $F_\gamma(T)$ to the neutron production rate.

Prince *et al.*[4] have shown that the function $R(t,T)$ can be approximated by a single exponential function of the form

$$R(t,T) \approx k_2 \exp(-(t-T)/\tau) \tag{4}$$

. In equation (4), k_2 is a constant that relates flux in the 2.223 MeV line to neutron production at the sun. So the expected flux in the 2.223 MeV line can be rewritten as

$$F_{2.2}(t) = \int_{-\infty}^{t} kF_\gamma(T)\exp(-(t-T)/\tau)dT. \tag{5}$$

The time constant, τ, is essentially the lifetime of the neutron in the capture region. The time constant is determined by[4]

$$\frac{1}{\tau} = \frac{1}{\tau_H} + \frac{1}{\tau_{3He}} + \frac{1}{\tau_d} \tag{6}$$

where $\frac{1}{\tau_H}$, $\frac{1}{\tau_{3He}}$, and $\frac{1}{\tau_d}$ are time constants for neutron capture by hydrogen, neutron capture by ^{3}He, and neutron decay, respectively.

Analysis of the large flare of 1982 June 3 by Prince *et al.*[4] gave a τ of 100 s for the entire flare observation, which lasted more than 1000 s. The best fit τ for the first 150 s was found to be 89 ± 10 s. This τ was used[4] to derive an upper limit on the ^{3}He/H ratio of 3.8×10^{-5} (90% confidence level). Hua and Lingenfelter[7] subsequently used the 1982 June 3 data to more strongly constrain the ^{3}He/H ratio to $(2.3 \pm 1.2) \times 10^{-5}$. Trottet et al.[8] have analyzed data from the flare of 1991 June 11 and report a value of $(3 \pm {}^{2}{}_{1}) \times 10^{-5}$ for the ^{3}He/H ratio. Clearly, better constraints can be put on the ^{3}He/H ratio by studying the decay times of the neutron–capture line from many flares. With this in mind, we report the results from a relevant study of the 1991 October 27 flare.

FLARE OBSERVATIONS

The flare of interest began at 05:38 UT on 1991 October 27 in soft x–rays (NOAA, Solar Geophysical Data). The flare had an H_α brightness 3B and was an X6–class GOES flare. It was located in active region 6891 with solar coordinates S 13°, E 15° and a heliocentric angle of 23°. The October 27 flare was observed over a range of wavelengths (radio, optical, x–ray, and γ–ray). This flare produced a particulary strong signal in the TASC spectrometer, the most intense of several flares that occurred in October. Figure 1 shows the TASC response in the energy–loss range of 1–10 MeV.

ANALYSIS

To model the behavior of the 2.223 MeV flux as described by equation (5), we need the flux of photons from prompt nuclear lines. In practice, we fit the TASC spectra with a multi–component model source spectrum which is folded through the detector response. The components of the model are: (1) a power–law γ–ray spectrum, (2) the 2.223 MeV γ–ray line, (3) a prompt nuclear γ–ray spectrum, (4) a γ–ray spectrum from activation of Fe nuclear levels by neutron interactions in the spacecraft material, (5) a γ–ray spectrum from pion decay and (6) a spectrum from solar neutrons interacting in the detector.

Figure 2 shows a fit of one of the TASC spectra. The time intervals used for the analysis must be discrete, so equation (5) can be modified to

$$F_{2.2}(t_n) = \sum_{i=1}^{n} \frac{k' F_{4-7}(t_i)\Delta t_i}{\Delta t_n} \int_{t_i-\Delta t_i/2}^{t_i+\Delta t_i/2} \exp(-T/\tau)dT. \qquad (7)$$

where $F_{4-7}(t_i)$ is the flux from nuclear lines in the energy interval 4–7 MeV for a time interval centered on t_i, $F_{2.2}(t_n)$ is the calculated flux in the 2.223 MeV line for a time interval centered on t_n, and k' is the appropriate proportionality constant.

The calculated flux, $F_{2.2}(t_n)$, for each time interval depends on τ and k'. These parameters can be varied to get the best agreement between $F_{2.2}(t_n)$ and the observed flux in the 2.223 MeV line. Figure 3 shows plots of the time histories of the fluxes in the 2.223 MeV line and in the prompt lines (4–7 MeV). The time scale is relative to 05:39:33 UT, the beginning of the time bin during which γ–rays were first detected. Also shown in the figure is a curve representing $F_{2.2}(t_n)$ calculated from equation (7). The values of τ and k' were varied to minimize the sum of the weighted squared residuals between the observed and calculated 2.223 MeV fluxes. An acceptable fit was obtained for a constant k' and τ in equation (7). The "best fit" parameters are $\tau = 78 \pm 20$s and $k' = 1.52 \pm 0.30$, where the uncertainties are at the 67% (1 σ) confidence level. These are the parameters used for calculating the curve in Figure 3.

CONCLUSIONS

Observation of the time history of neutron–capture γ–rays from the solar flare of 1991 October 27 shows that it is consistent with behavior described by equation (9). That is, the instantaneous production of neutrons is proportional to the production of prompt nuclear lines, and the neutron–capture γ–rays are convolved through a single time constant, τ. The time constant that describes the neutron–capture γ–ray time history is 78 ± 20 s (67% confidence level). This agrees with the time constant of 89 ± 10 s for the 1982 June 3 flare[4] and values of 70 ± 10 s and 95 s for the 1991 June 11 flare found by Trottet *et al.*[8] and Dunphy *et al.*,[9] respectively. Simulations have shown that the time behavior is expected to be more complex, with a time "constant," $\tau(t)$, that itself is a function of time.[7,10] However, over a limited time span, a constant τ can be used to approximate the decay.

The time dependence is a function of a number of flare parameters: the proton spectral shape, the proton angular distribution, the flare's heliocentric angle (viewing direction), and the ^{3}He/H ratio. Hua and Lingenfelter[7] have evaluated the effect of these parameters on the time dependence of the 2.223 MeV γ–ray. Using the results of Hua and Lingenfelter[7], we estimate that the time constant for the 1991 October 27 flare implies an upper limit of 5×10^{-5} for the ^{3}He/H ratio at the 67% confidence level. This can be compared with a limit of 3.8×10^{-5} at the 90% confidence level derived by Prince *et al.*[6] and a value of $(2.3 \pm 1.2) \times 10^{-5}$ derived by Hua and Lingenfelter[9], both for the flare of 1982 June 3.

ACKNOWLEDGMENTS

This work was supported in part by NASA grants NAG 5-2420 and NAG 5-3158.

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Figure 1. Response of the TASC in the 1–10 MeV energy–loss band during the flare of 1991 October 27.

Figure 2. TASC energy–loss spectrum during the time interval 05:41:11 – 05:41:44.

Figure 3. The time histories of the observed fluxes in the 2.223 MeV line and in the 4–7 MeV energy range. Also shown is the calculated 2.223 MeV flux, $F_{2.2}(t)$, from equation (7).

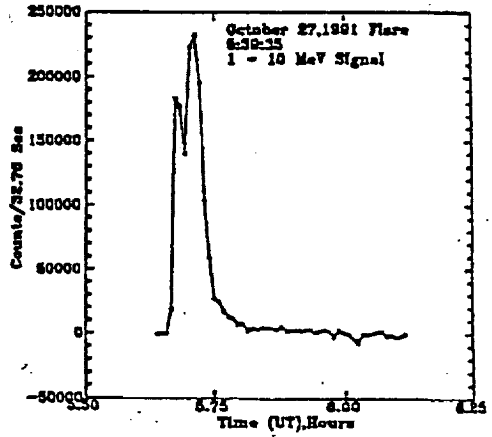

Figure 1.

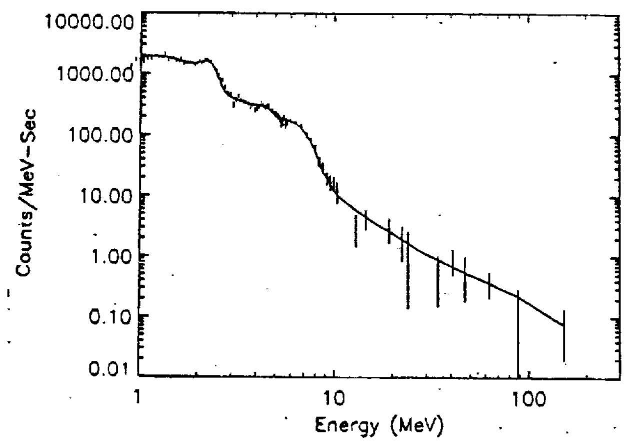

Figure 2.

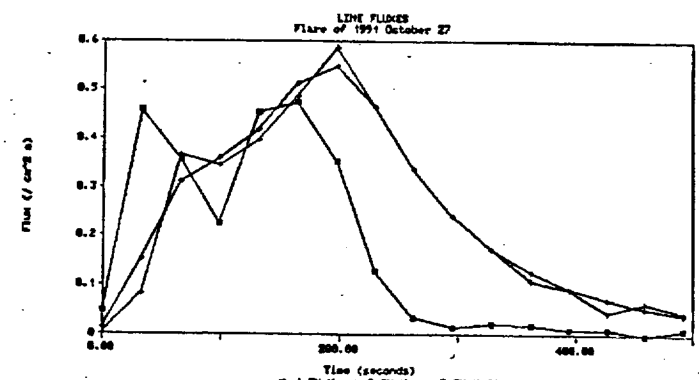

Figure 3.

Abstract Submitted
for the apr99 Meeting of
The American Physical Society

Sorting Category: A.10 (Experimental)

Acceleration of Gamma-ray and Neutron Producing Particles in Impulsive and Long Duration Solar Flares E.L. CHUPP, P.P. DUNPHY, *University of New Hampshire* — A major challenge in high energy solar physics is to identify the mechanism(s) that accelerate ions and electrons to energies as high as 1 GeV with initiation time scales as short as seconds, producing emissions that can extend from minutes to several hours. Therefore, we describe the characteristics of the accelerated particles which produce gamma-ray lines and continua, meson-decay gamma-rays, and high-energy neutrons as deduced from observations of several intense solar flares during solar sunspot cycles 22 and 23. Typically, the events consist of an impulsive gamma-ray burst or bursts lasting minutes, followed by an extended emission lasting up to hours. The extended emission often results from ions accelerated to at least several hundred MeV. Some general scenarios which have been considered to explain these high-energy flare phenomena are: acceleration of ions by 2nd order Fermi acceleration in a closed magnetic loop, acceleration of particles by transient reconnection in magnetic fields at the top of the loop, acceleration of ions at a coronal mass ejection (CME) shock front, and acceleration in a corona stressed by a passing CME. We confront theoretical scenarios with the observations, emphasizing ion acceleration, and mention additional observations and simulations necessary to advance our understanding of acceleration of high energy particles associated with flares.

[ ] Prefer Oral Session
[X] Prefer Poster Session

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Date submitted: January 12, 1999

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CGRO GUEST INVESTIGATOR PROGRAM

FINAL REPORT FOR GRANT NAG 5-2420:

"EGRET HIGH ENERGY CAPABILITY" and "MULTIWAVELENGTH FLARE STUDIES"

AND GRANT NAG 5-3518: "SOLAR FLARE PROTON SPECTRA"

Principal Investigator: Dr. Edward L. Chupp

Period Covered by Report: 11/15/96 – 11/15/98

Space Science Center, University of New Hampshire, Durham NH 03824

The study of EGRET/TASC flare data has been funded during phases 3–6 of the CGRO Guest Investigator program. The funding and accomplishments can be summarized as follows:

Phase 3. – Under PI Dr. David L. Bertsch (GSFC) the proposal "Use of EGRET High-Energy Capability to Investigate Energetic Solar Flare Processes" was funded with E. L. Chupp and P. P. Dunphy as Co-Investigators at a level of $15,500 instead of the $22,000 requested (NAG 5-2420).

Under *Phase 3* support the accomplishments were:

UNH was assigned the responsibility to use their accelerator neutron measurements to verify the *TASC* response function and to modify the *TASC* fitting program to include a high energy neutron contribution. Direct accelerator-based measurements by UNH of the energy-dependent efficiencies for detecting neutrons with energies from 36 to 720 MeV in NaI were compared with Monte Carlo TASC calculations. The calculated TASC efficiencies are somewhat lower (by about 20%) than the accelerator results in the energy range 70–300 MeV. The measured energy-loss spectrum for 207 MeV neutron interactions in NaI were compared with the Monte Carlo response for 200 MeV neutrons in the TASC indicating good agreement. Based on this agreement, the simulation was considered to be sufficiently accurate to generate a neutron response library to be used by UNH in modifying the *TASC* fitting program to include a neutron component in the flare spectrun modeling. *TASC* energy-loss data on the 1991 June 11 flare was transferred to UNH.

Phase 4. – Under PI Dr. E. L. Chupp the proposal "Study of High Energy Neutrons and Gamma-Rays Using the *EGRET* /TASC" was funded at a level of $30,000 (Supplement 1) while the level requested for the proposed work was $49,000. Under PI Dr. David L. Bertsch the proposal "Investigation of Energetic Solar Flare Processes Using the High Energy Capabilities of *EGRET*" provided UNH Co-Investigators Chupp and Dunphy with $16,796 of additional funding (Supplement 2) to continue the work started under the phase 3 program instead of the requested amount of $25,000.

Under *Phase 4* the accomplishments were:

The *Phase 3* effort to determine a high energy neutron contribution to the emissions from the 1991 June 11 solar flare was continued. A preliminary upper limit to the neutron fluence (> 50 MeV) from this flare was found by adding a theoretical solar neutron spectrum to the TASC spectral fit program. The result was <27 neutrons cm^{-2} which corresponds to $< 2.2 \times 10^{28}$ neutrons sr^{-1} (> 50 MeV) emitted from the Sun toward the Earth. This is about a factor of 10 less than the neutron emissivity from the 1982 June 3 solar flare. This result was presented by P. P. Dunphy, E. L. Chupp, D. L. Bertsch, E. J. Schneid, and S. Gottesman at the 24th International Cosmic Ray Conference at Rome in September 1995. Subsequently, the *TASC* spectral fitting program has been modified to include components from: γ-ray lines (solar and background), bremsstrahlung, neutral pion decay and high energy neutron interactions.

The next step in the analysis of this event was doing full fits to the *TASC* energy-loss spectra as a function of time. A significant hardening of the solar proton spectrum over time was found for the flare. The results from the analysis were presented at the 188th meeting of the AAS in Madison, WI by P. P. Dunphy *et al.* in June 1996.

Phase 5. – Under PI Dr. E. L. Chupp the proposal "Multiwavelength Studies of October 91 X-Class Solar Flares Observed by EGRET" was funded at a level of $15,000 (Supplement 3) instead of the $52,000 requested.

Under *Phase 5* the accomplishments were:

For the *Phase 5* work, we have gathered a significant amount of correlated data for flares observed by the EGRET/TASC. This includes the TASC spectral data for 5 X–class flares between 1991 October 21 and 1991 November 3, as well as the corresponding response functions which account for the solar angle and the spacecraft mass. Also obtained were: Yohkoh HXT time histories and images for the 1991 October 27 flare, Yohkoh GRS time histories and gamma-ray line spectra for the 1991 October 27 flare, standard GOES x-ray data and NOAA radio reports, Nobeyama radio reports, and Chinese Academy of Sciences Solar-Geophysical Data.

Phase 6. – Under PI Dr. E. L. Chupp the proposal "Characterization of Solar Flare Proton Spectra

Using EGRET/TASC Data" was funded at a level of $25,000 (NAG 5-3518).

Under *Phase 6* the accomplishments were:

The goal of the *Phase 6* program was to apply the analysis technique used successfully with the *EGRET / TASC* energy-loss spectra for the 1991 June 11 flare to data on the remaining X-class flares observed in 1991 June. The first priority was to use the results from fitting the June 11 flare spectra to constrain the flare proton spectral shape and intensity. Our results to date demonstrate that the TASC spectral analysis contributes crucial information on the particle spectrum interacting at the Sun. A paper describing this analysis and its results has been accepted for publication by the journal Solar Physics is attached as Appendix A.

Analysis of nuclear gamma-ray lines from the flare of 1991 October 27 has been completed and a paper based on this work will be presented at the 26th International Cosmic Ray Conference in Salt Lake City, Utah, August 17-25, 1999. A preliminary draft of the paper is attached as Appendix B.

Our findings from the 1991 June 11 flare are compared with other flares with time-extended gamma-ray emission in a paper to be presented at the Centennial Meeting of the American Physical Society in Atlanta, Georgia, March 21-26, 1999. The abstract for this paper is attached as Appendix C.

APPENDIX A

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

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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.

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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 ($\pi^{\pm}$, π^{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–α 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.* 1994, 1997). 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(Tl) 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 × 76 × 20 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 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 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 32.75s. 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.

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 de–excitation; (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: (1) a theoretical neutron spectrum produced by protons with a power law spectrum in energy (Murphy *et al.* 1987) and (2) a theoretical neutron spectrum produced by protons with a Bessel function spectrum (Murphy *et al.* 1987). These proton (and therefore, neutron) spectral shapes are assumed to be related to different proton acceleration mechanisms (Murphy *et al.* 1987).

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 non–linear multi–parameter 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. 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; Murphy *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 de-excitation 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 s, compared to a value of 70 ± 10 s reported by Trottet *et al.* 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 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), appear 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 (~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.

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Table I
Time Intervals and Hardness Ratio for Flare of 1991 June 11

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	$1.04(\pm 0.05) \times 10^{-2}$

Table II
Fitting Parameters for Flare of 1991 June 11

Parameter	I–1	I–2	Interphase	II
p.l. index	2.08±.07	2.30±.03	2.20±.17	—
p.l. coeff.	0.22±.03	0.54±.03	0.16±.04	**0**
nucl. coeff.	1.36±.07	1.65±.05	< 0.097	0.137±.007
2.2 MeV coeff.	0.067±.004	0.157±.003	0.042±.004	0.0188±.0007
Fe line coeff.	$< 1.4 \times 10^{-3}$	$< 9.2 \times 10^{-4}$	$< 1.8 \times 10^{-3}$	$(1.0 \pm .2) \times 10^{-3}$
pion coeff.	$< 2.3 \times 10^{-5}$	$< 9.0 \times 10^{-6}$	**0**	$(1.55 \pm .13) \times 10^{-5}$
neutron coeff.	**0**	**0**	**0**	**1.55×10^{-5}**

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

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±.002	~ 4.0
I-2	43.5±2.3	57.4±5.7	< 0.044	1.32±0.13	< 0.010	0.023±.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}.

FIGURE CAPTIONS

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.

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.

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.

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 3 time periods (I-1, I-2, and II) during the flare of 11 June 1991, and are indicated only for the "horizontal" case.

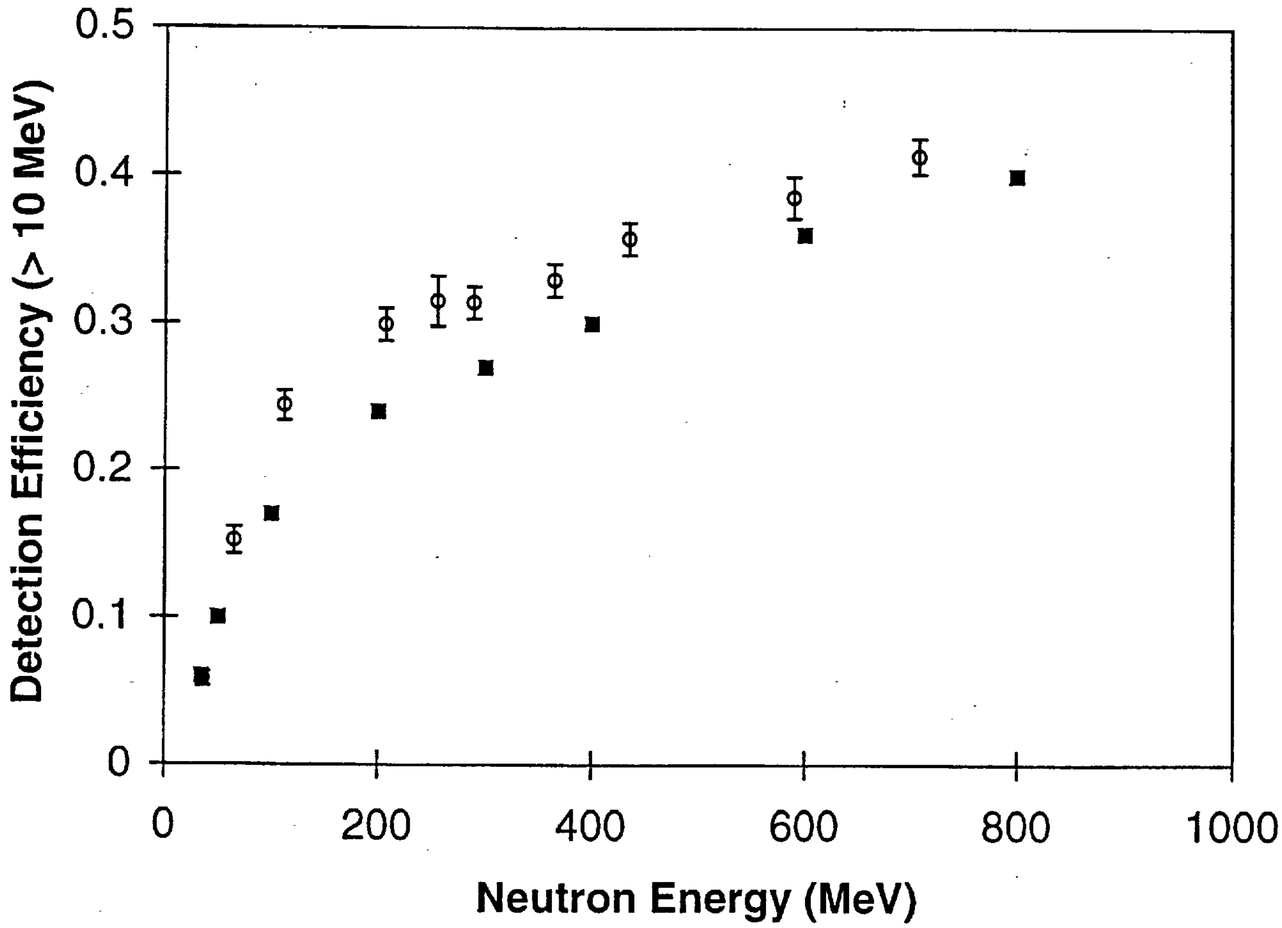

0.5
0.4
0.3
0.2
0.1
0
Detection Efficiency (> 10 MeV)
0
200
400
600
800
1000
Neutron Energy (MeV)

Figure 1.

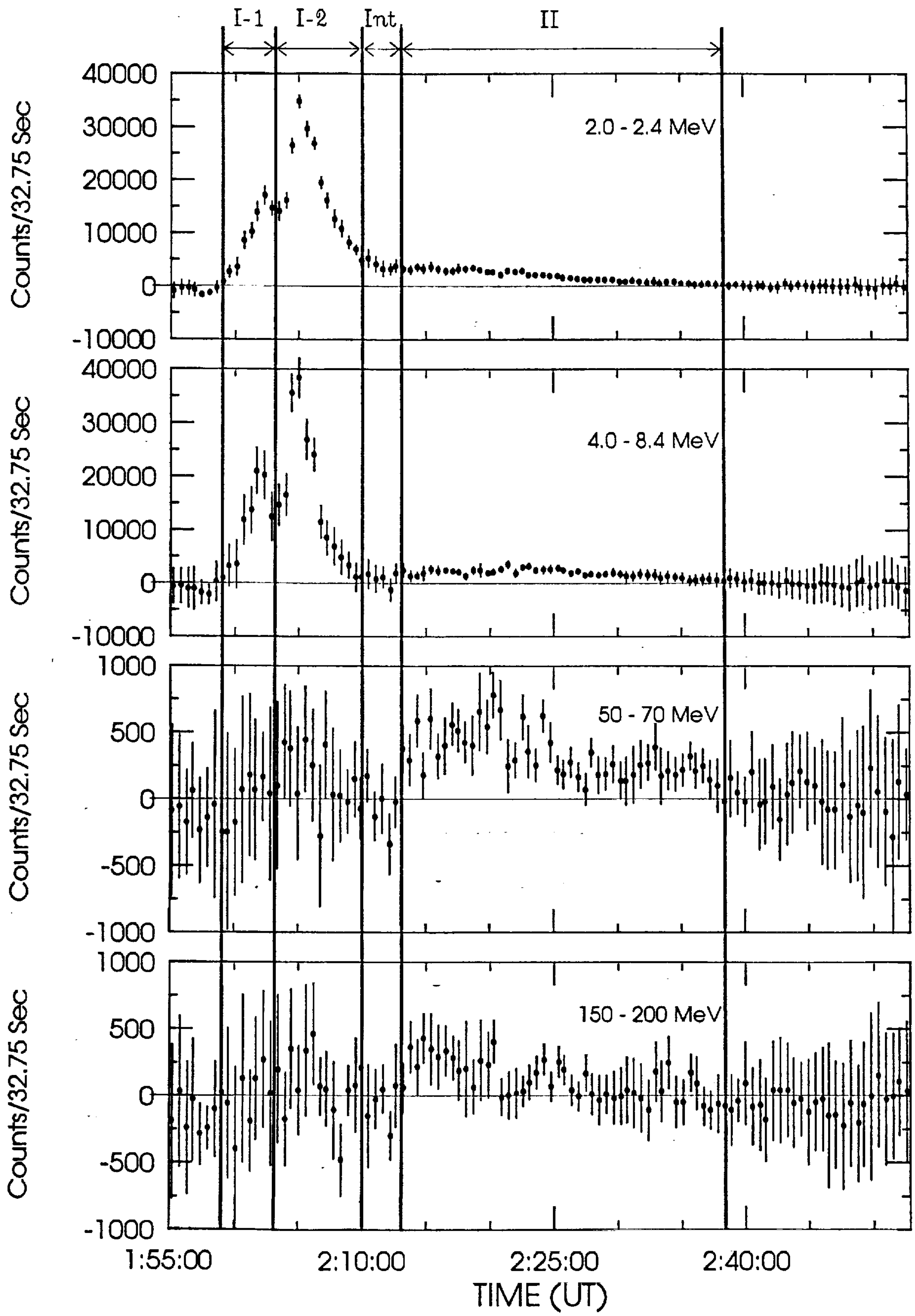
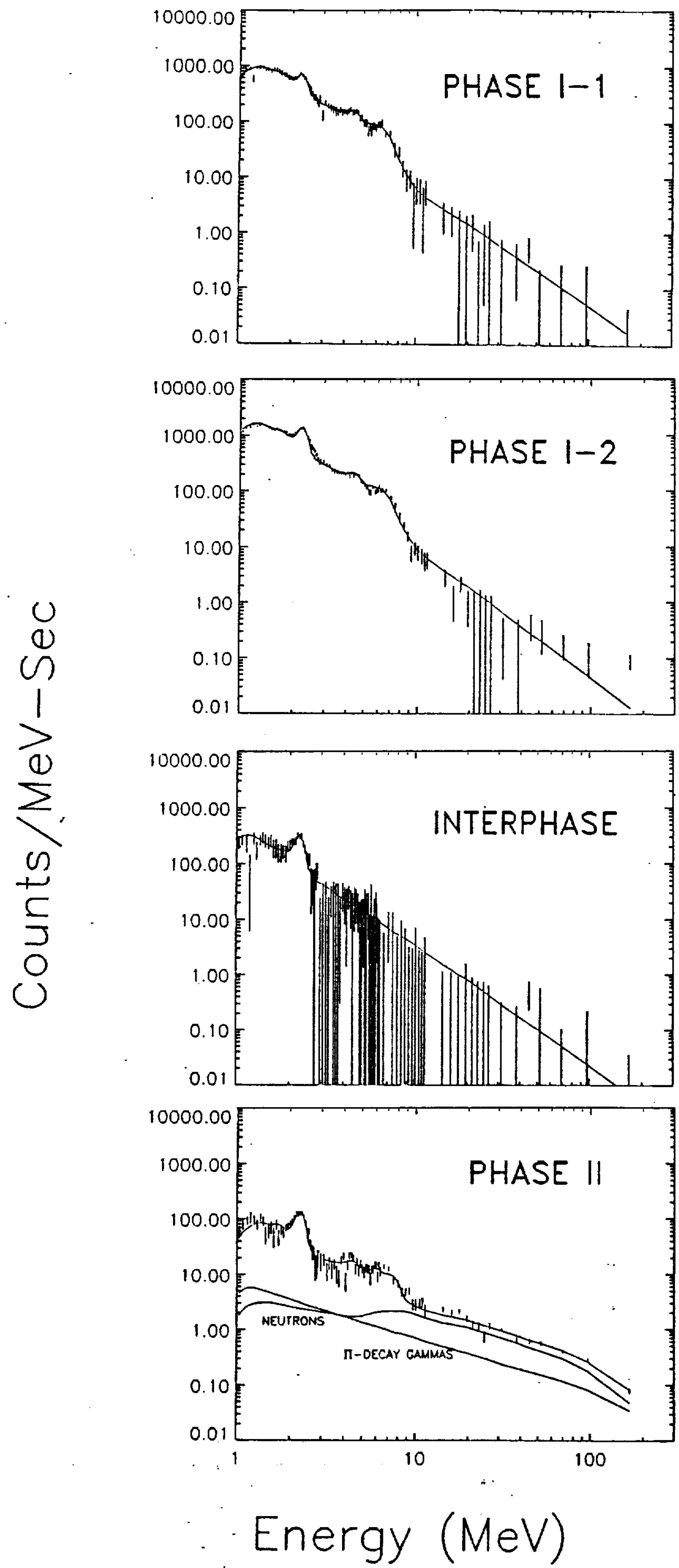

I-1
I-2
Int
II
2.0 - 2.4 MeV
4.0 - 8.4 MeV
50 - 70 MeV
150 - 200 MeV
Counts/32.75 Sec
40000
30000
20000
10000
0
-10000
1000
500
-500
-1000
1:55:00
2:10:00
2:25:00
2:40:00
TIME (UT)

Figure 2.



PHASE I-1
PHASE I-2
INTERPHASE
PHASE II
NEUTRONS
Π-DECAY GAMMAS
10000.00
1000.00
100.00
10.00
1.00
0.10
0.01
1
10
100
Counts/MeV-Sec
Energy (MeV)

Figure 3.

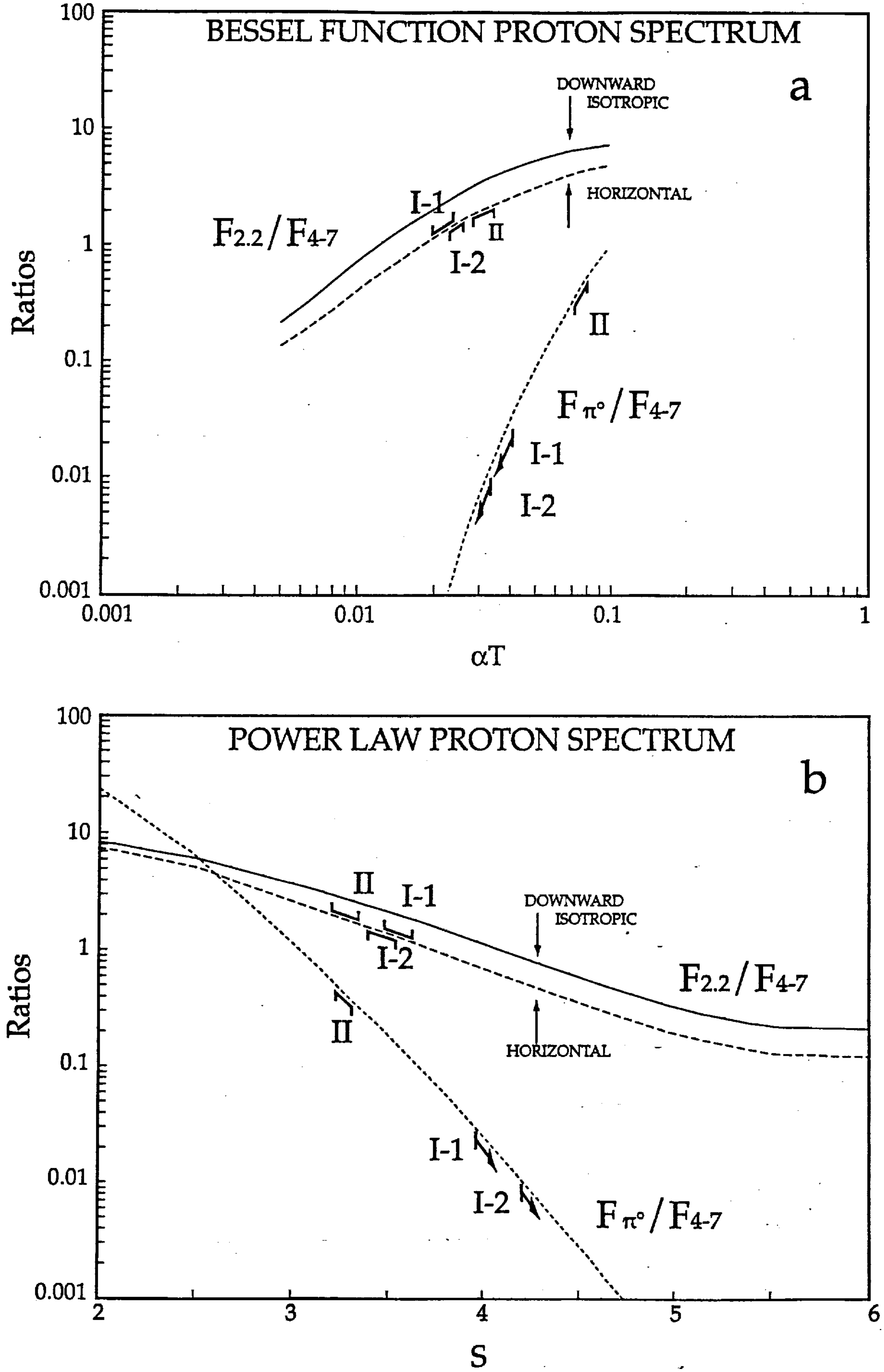

BESSEL FUNCTION PROTON SPECTRUM
a
DOWNWARD
ISOTROPIC
HORIZONTAL
I-1
I-2
II
$F_{2.2}/F_{4\text{-}7}$
$F_{\pi^\circ}/F_{4\text{-}7}$
Ratios
αT
100
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
POWER LAW PROTON SPECTRUM
b
DOWNWARD
ISOTROPIC
HORIZONTAL
II
I-1
I-2
$F_{2.2}/F_{4\text{-}7}$
$F_{\pi^\circ}/F_{4\text{-}7}$
Ratios
S
100
10
1
0.1
0.01
0.001
2
3
4
5
6

Figure 4

APPENDIX B

Neutron–Capture Gamma–Rays Observed by EGRET from the Flare of 1991 October 27 *

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ABSTRACT

The neutron–capture γ–ray line at 2.223 MeV was observed by the Total Absorption Shower Counter (TASC) section of the EGRET γ–ray telescope on the Compton Gamma Ray Observatory satellite from a solar flare on 1991 October 27. This flare, which produced γ–rays starting around 05:39 UT, was very intense in the energy range dominated by nuclear lines. This radiation was also relatively impulsive compared to other large flares observed by the TASC. The neutron capture γ–ray line at 2.223 MeV is clearly delayed relative to prompt γ–ray line emission in the energy range of 4–8 MeV. We find that the time history of the neutron–capture line at 2.223 MeV can be characterized by a single exponential decay–time of 78 ± 20 s. We use this parameter to constrain the ^{3}He/H ratio at the capture site to a level of $< 5 \times 10^{-5}$ at the 67% confidence level.

INTRODUCTION

A γ–ray of energy 2.223 MeV is produced when deuterium is formed from a proton and a neutron in the exoergic reaction

$$p + n \rightarrow {}^2D + \gamma \qquad (1)$$

The neutron–capture line was first observed[1] by the Gamma–Ray Monitor on the OSO–7 satellite during the solar flare of 1972 August 4. Subsequent observations were made by detectors on HEAO–1,[2] HEAO–3,[3] SMM,[4,5] HINOTORI,[6] GRANAT,[8] and CGRO. The 2.223 MeV line can be used to probe conditions in the solar photosphere. In particular, Prince *et al.*[4] and Hua and Lingenfelter[7] used the time history of the line during the large flare of 1982 June 3 to calculate the ^{3}He/H ratio in the solar photosphere. The capture line time history depends on the rate of production of solar neutrons, as well as on

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their rate of capture. The measured time–dependent flux of the 2.223 MeV line can be modeled as (using the notation of Prince *et al.*[4])

$$F_{2.2}(t) = \int_{-\infty}^{t} S(T)R(t,T)dT \tag{2}$$

where $F_{2.2}(t)$ is the observed 2.223 MeV flux, $S(T)$ is the neutron production time history, and $R(t,T)$ is the response function giving the 2.223 MeV photon contribution at time t due to neutrons produced at time T. If the spectral shape of the energetic particles does not change during the flare, the neutron production time history, $S(T)$, is proportional to the flux of prompt nuclear lines produced by the same population of energetic particles.

Then equation (2) becomes

$$F_{2.2}(t) = \int_{-\infty}^{t} k_1 F_\gamma(T)R(t,T)dT \tag{3}$$

where $F_\gamma(T)$ is the observed flux of prompt γ–ray lines, and k_1 is a proportionality constant that relates $F_\gamma(T)$ to the neutron production rate.

Prince *et al.*[4] have shown that the function $R(t,T)$ can be approximated by a single exponential function of the form

$$R(t,T) \approx k_2 \exp(-(t-T)/\tau) \tag{4}$$

. In equation (4), k_2 is a constant that relates flux in the 2.223 MeV line to neutron production at the sun. So the expected flux in the 2.223 MeV line can be rewritten as

$$F_{2.2}(t) = \int_{-\infty}^{t} kF_\gamma(T)\exp(-(t-T)/\tau)dT. \tag{5}$$

The time constant, τ, is essentially the lifetime of the neutron in the capture region. The time constant is determined by[4]

$$\frac{1}{\tau} = \frac{1}{\tau_H} + \frac{1}{\tau_{^3He}} + \frac{1}{\tau_d} \tag{6}$$

where $\frac{1}{\tau_H}$, $\frac{1}{\tau_{^3He}}$, and $\frac{1}{\tau_d}$ are time constants for neutron capture by hydrogen, neutron capture by ^{3}He, and neutron decay, respectively.

Analysis of the large flare of 1982 June 3 by Prince *et al.*[4] gave a τ of 100 s for the entire flare observation, which lasted more than 1000 s. The best fit τ for the first 150 s was found to be 89 ± 10 s. This τ was used[4] to derive an upper limit on the ^{3}He/H ratio of 3.8×10^{-5} (90% confidence level). Hua and Lingenfelter[7] subsequently used the 1982 June 3 data to more strongly constrain the ^{3}He/H ratio to $(2.3 \pm 1.2) \times 10^{-5}$. Trottet et al.[8] have analyzed data from the flare of 1991 June 11 and report a value of $(3 \pm {}^2{}_1) \times 10^{-5}$ for the ^{3}He/H ratio. Clearly, better constraints can be put on the ^{3}He/H ratio by studying the decay times of the neutron–capture line from many flares. With this in mind, we report the results from a relevant study of the 1991 October 27 flare.

FLARE OBSERVATIONS

The flare of interest began at 05:38 UT on 1991 October 27 in soft x–rays (NOAA, Solar Geophysical Data). The flare had an H_α brightness 3B and was an X6–class GOES flare. It was located in active region 6891 with solar coordinates S 13°, E 15° and a heliocentric angle of 23°. The October 27 flare was observed over a range of wavelengths (radio, optical, x–ray, and γ–ray). This flare produced a particulary strong signal in the TASC spectrometer, the most intense of several flares that occurred in October. Figure 1 shows the TASC response in the energy–loss range of 1–10 MeV.

ANALYSIS

To model the behavior of the 2.223 MeV flux as described by equation (5), we need the flux of photons from prompt nuclear lines. In practice, we fit the TASC spectra with a multi–component model source spectrum which is folded through the detector response. The components of the model are: (1) a power–law γ–ray spectrum, (2) the 2.223 MeV γ–ray line, (3) a prompt nuclear γ–ray spectrum, (4) a γ–ray spectrum from activation of Fe nuclear levels by neutron interactions in the spacecraft material, (5) a γ–ray spectrum from pion decay and (6) a spectrum from solar neutrons interacting in the detector.

Figure 2 shows a fit of one of the TASC spectra. The time intervals used for the analysis must be discrete, so equation (5) can be modified to

$$F_{2.2}(t_n) = \sum_{i=1}^{n} \frac{k' F_{4-7}(t_i)\Delta t_i}{\Delta t_n} \int_{t_i-\Delta t_i/2}^{t_i+\Delta t_i/2} \exp(-T/\tau)dT. \qquad (7)$$

where $F_{4-7}(t_i)$ is the flux from nuclear lines in the energy interval 4–7 MeV for a time interval centered on t_i, $F_{2.2}(t_n)$ is the calculated flux in the 2.223 MeV line for a time interval centered on t_n, and k' is the appropriate proportionality constant.

The calculated flux, $F_{2.2}(t_n)$, for each time interval depends on τ and k'. These parameters can be varied to get the best agreement between $F_{2.2}(t_n)$ and the observed flux in the 2.223 MeV line. Figure 3 shows plots of the time histories of the fluxes in the 2.223 MeV line and in the prompt lines (4–7 MeV). The time scale is relative to 05:39:33 UT, the beginning of the time bin during which γ–rays were first detected. Also shown in the figure is a curve representing $F_{2.2}(t_n)$ calculated from equation (7). The values of τ and k' were varied to minimize the sum of the weighted squared residuals between the observed and calculated 2.223 MeV fluxes. An acceptable fit was obtained for a constant k' and τ in equation (7). The "best fit" parameters are $\tau = 78 \pm 20$s and $k' = 1.52 \pm 0.30$, where the uncertainties are at the 67% (1 σ) confidence level. These are the parameters used for calculating the curve in Figure 3.

CONCLUSIONS

Observation of the time history of neutron–capture γ–rays from the solar flare of 1991 October 27 shows that it is consistent with behavior described by equation (9). That is, the instantaneous production of neutrons is proportional to the production of prompt nuclear lines, and the neutron–capture γ–rays are convolved through a single time constant, τ. The time constant that describes the neutron–capture γ–ray time history is 78 ± 20 s (67% confidence level). This agrees with the time constant of 89 ± 10 s for the 1982 June 3 flare[4] and values of 70 ± 10 s and 95 s for the 1991 June 11 flare found by Trottet *et al.*[8] and Dunphy *et al.*,[9] respectively. Simulations have shown that the time behavior is expected to be more complex, with a time "constant," $\tau(t)$, that itself is a function of time.[7,10] However, over a limited time span, a constant τ can be used to approximate the decay.

The time dependence is a function of a number of flare parameters: the proton spectral shape, the proton angular distribution, the flare's heliocentric angle (viewing direction), and the $^3He/H$ ratio. Hua and Lingenfelter[7] have evaluated the effect of these parameters on the time dependence of the 2.223 MeV γ–ray. Using the results of Hua and Lingenfelter[7], we estimate that the time constant for the 1991 October 27 flare implies an upper limit of 5×10^{-5} for the $^3He/H$ ratio at the 67% confidence level. This can be compared with a limit of 3.8×10^{-5} at the 90% confidence level derived by Prince *et al.*[6] and a value of $(2.3 \pm 1.2) \times 10^{-5}$ derived by Hua and Lingenfelter[9], both for the flare of 1982 June 3.

ACKNOWLEDGMENTS

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Figure 1. Response of the TASC in the 1–10 MeV energy–loss band during the flare of 1991 October 27.

Figure 2. TASC energy–loss spectrum during the time interval 05:41:11 – 05:41:44.

Figure 3. The time histories of the observed fluxes in the 2.223 MeV line and in the 4–7 MeV energy range. Also shown is the calculated 2.223 MeV flux, $F_{2.2}(t)$, from equation (7).

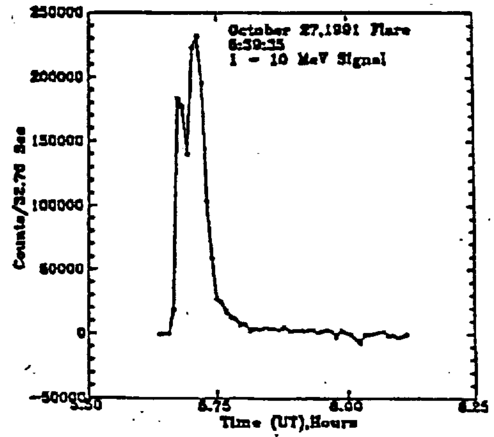

Figure 1.

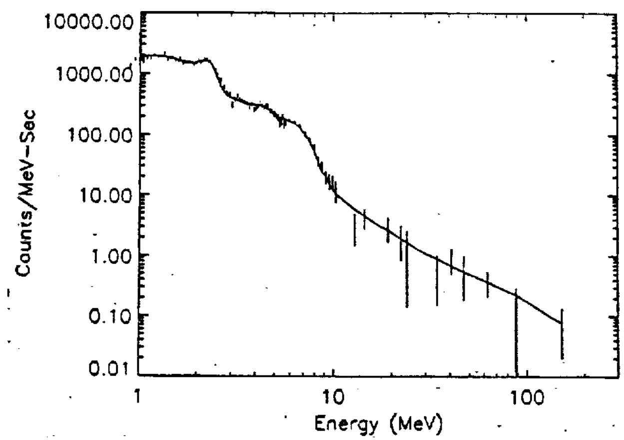

Figure 2.

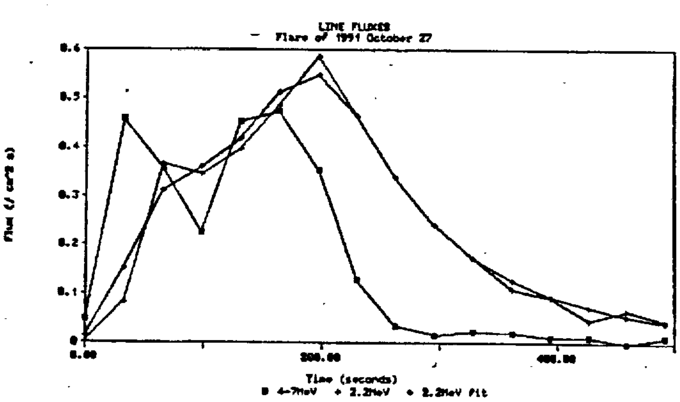

Figure 3.

APPENDIX C

Abstract Submitted
for the apr99 Meeting of
The American Physical Society

Sorting Category: A.10 (Experimental)

Acceleration of Gamma-ray and Neutron Producing Particles in Impulsive and Long Duration Solar Flares E.L. CHUPP, P.P. DUNPHY, *University of New Hampshire* — A major challenge in high energy solar physics is to identify the mechanism(s) that accelerate ions and electrons to energies as high as 1 GeV with initiation time scales as short as seconds, producing emissions that can extend from minutes to several hours. Therefore, we describe the characteristics of the accelerated particles which produce gamma-ray lines and continua, meson-decay gamma-rays, and high-energy neutrons as deduced from observations of several intense solar flares during solar sunspot cycles 22 and 23. Typically, the events consist of an impulsive gamma-ray burst or bursts lasting minutes, followed by an extended emission lasting up to hours. The extended emission often results from ions accelerated to at least several hundred MeV. Some general scenarios which have been considered to explain these high-energy flare phenomena are: acceleration of ions by 2nd order Fermi acceleration in a closed magnetic loop, acceleration of particles by transient reconnection in magnetic fields at the top of the loop, acceleration of ions at a coronal mass ejection (CME) shock front, and acceleration in a corona stressed by a passing CME. We confront theoretical scenarios with the observations, emphasizing ion acceleration, and mention additional observations and simulations necessary to advance our understanding of acceleration of high energy particles associated with flares.

☐ Prefer Oral Session
☒ Prefer Poster Session

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