X- and Gamma-Ray Observations of the 15 November 1991 Solar Flare

Dissertation work by

Martina B. Arndt

in collaboration with

A. Connors, J. Lockwood, M. McConnell, R. Suleiman, J. Ryan, C.A. Young

University of New Hampshire

G. Rank, V. Schönfelder

Max Planck Inst. für Extraterrestrische Physik

H. Debrunner

Univ. Bern

K. Bennett, O. Williams, and C. Winkler

SSD/ESTEC

Abstract

This work expands the current understanding of the 15 November 1991 Solar Flare. The flare was a well observed event in radio to gamma-rays and is the first flare to be extensively studied with the benefit of detailed soft and hard X-ray images. In this work, we add data from all four instruments on the Compton Gamma Ray Observatory. Using these data we determined that the accelerated electron spectrum above 170 keV is best fit with a power law with a spectral index of -4.6, while the accelerated proton spectrum above 0.6 MeV is fit with a power law of spectral index -4.5. From this we computed lower limits for the energy content of these particles of $\sim 10^{23}$ ergs (electrons) and $\sim 10^{27}$ ergs (ions above 0.6 MeV). These particles do not have enough energy to produce the white-light emission observed from this event. We computed a time constant of 26 (+20,-15) s for the 2.223 MeV neutron capture line, which is consistent at the 2σ level with the lowest values of ~70 s found for other flares. The mechanism for this short capture time may be better understood after analyses of high energy EGRET data that show potential evidence for pion emission near ~100 MeV.

Dissertation Goals

Add to the extant body of knowledge of the 15 November 1991 solar flare by:

- Analyzing high-energy data from the Compton Gamma Ray Observatory that have been underutilized in previous studies.

- Applying another flare model to explain the most intense high-energy emission from the event.

The Flare

This X1.5 event was a well observed flare in a broad range of wavelengths (c.f. **Table 1**).

Figure 1 shows the flare location in soft X-rays as well as white light contours overlaying hard X-ray footpoints. (Sakao, 1994)

Figure 2 shows time profiles of the event from BATSE (18.5 - 30 keV) and COMPTEL (0.6 - 10 MeV).

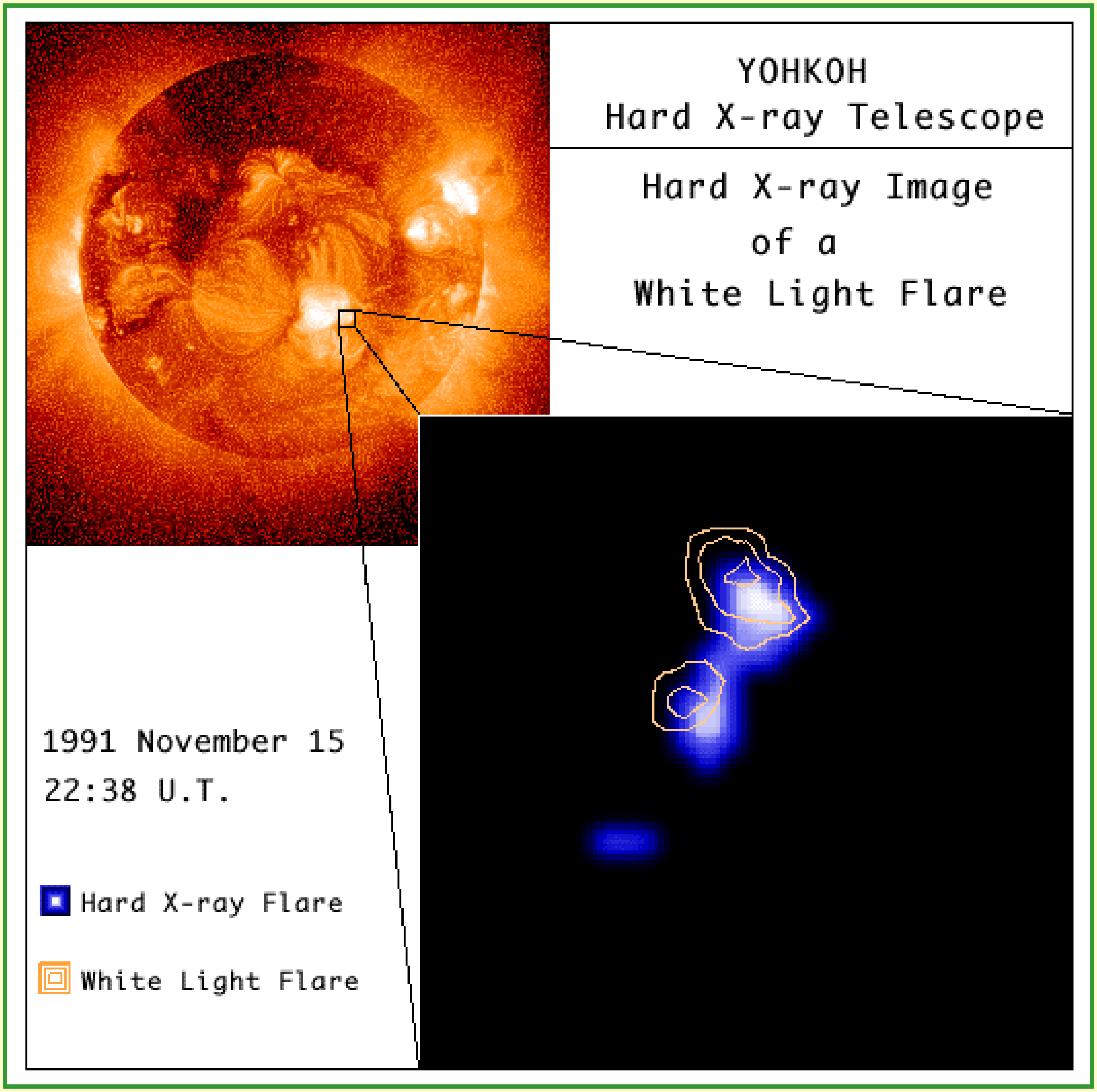


Figure 1: Images in soft X-rays (top) as well as hard X-rays and white light (bottom) of the 15 November 1991 solar flare (Sakao, 1994). The hard X-rays and white light are footpoint emission.

Energy	Observatory	Type of Data
Radio:		
2.7, 8.8, 15.4 GHz	Learmonth Observatory [8] Palehua Observatory [8]	Fluxes
1, 2, 3.75, 9.4 GHz	Tokoyawa Observatory [1]	Contour Plots, degree of polarization and radio flux(t)
17, 35, 80 GHz	Nobeyama Observatory [1]	Contour Plots, degree of polarization and radio flux (t)
Visible		
	Yohkoh, SXT Aspect Camera [8, 11, 17, 19, 24]	Images, time profiles
Hα (λ = 6562.8 Å)	Mees Solar Observatory [5, 11, 15]	Images
Ca II K-line (λ = 3934 Å)	Mees Solar Observatory [1]	
Hard X-Rays:		
1.5 – 24.8 keV	GOES [26]	Flux (t)
14 - 93 keV	Yohkoh, HXT [1, 6, 7, 10, 15-18, 23]	Images, time profiles
20 – 600 keV	Yohkoh, HXS [9, 10, 12-14 21, 22]	Spectra, time profiles
25 keV – 10 MeV (4 Channel)	CGRO, BATSE [2]	Time profiles
25 keV – 10 MeV (16 Channel)	CGRO, BATSE [2]	Spectra, time profiles
0.1 – 2.0 MeV	PVO [9]	Spectra
15-150 keV	ULYSSES [3, 9, 10, 14]	Spectra, time profiles
Soft X-Rays		
Ca XIX (λ = 3.1769 Å)	Yohkoh, BCS [5, 6, 15]	Spectra
	Yohkoh, SXT [1, 11, 14-15]	Images
Gamma Rays:		
0.6 - 10 MeV (Burst Mode)	CGRO, COMPTEL	Spectra, time profiles
0.05 – 10 MeV	CGRO, OSSE	Spectra, time profiles
0.2 – 100 MeV	Yohkoh, GRS [4, 10, 12, 14, 20]	Spectra, time profiles
Other:		
Magnetograph	MSO [5, 11]	Vector Magnetograms

Table 1: Summary of 15 November 1991 solar flare observations sorted by energy, observatory and observation type. Superscripts refer to articles that utilize these data. [1]Sakao, 1994; [2]Aschwanden et al. 1996a,b, 1998; [3]Kane et al. 1993a,b; [4]Yoshimori et. al, 1992; [5]Canfield et al. 1992; [6]Culhane et al. 1993; [7]Inda-Koide et al. 1995; [8]Hudson et al. 1992; [9]McTiernan et al. 1994; [10]Kane et al. 1998; [11]Canfield et al. 1998; [12]Kotov et al. 1996; [13]Yoshimori et al. 1994; [14]Kane et al. 1993b; [15]Wülser et al 1994;[16]Sakao et al. 1998; [17]Sakao et al. 1992; [18]Sakao et al. 1994; [19]Matthews et al. 1998 ; [20]Kawabata et al. 1994a,b; [21]Yoshimori et al. 1996; [22]Yoshimori et al. 1993; [23]Takakura et al. 1995; [24]Sylwester et al. 2000.

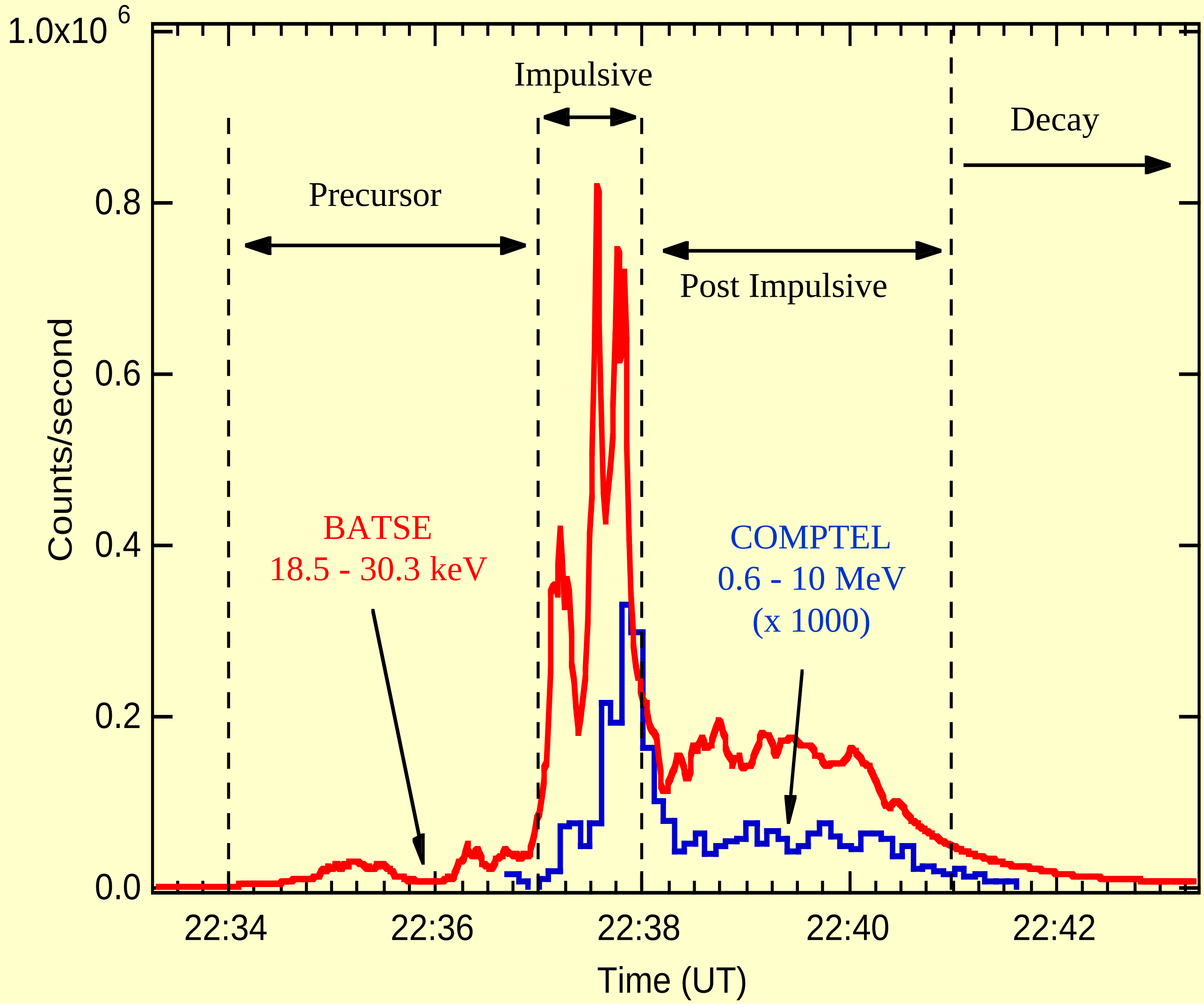


Figure 2: Lightcurves of the 15 November 1991 event from BATSE and COMPTEL. The four main phases of the flare are marked.

Data Analyses

BATSE data analysis was done using *spex_proc* software written by Richard Schwartz. The Bremsstrahlung emission was modeled with a double power law where E_B is the break energy:

$$I(E) \propto \begin{cases} E^{-\gamma_1} \text{ for } E < E_B \\ E^{-\gamma_2} \text{ for } E > E_B \end{cases}$$

COMPTEL data analysis was done using the Maximum Entropy Method (MEM).In this method, a test photon spectrum is folded through an instrument response and compared to the measured count spectrum using a χ^2 test.

EGRET data analysis was done by David Bertsch (NASA/GSFC). The photon spectra were also generated by a MEM approach.

Spectra from CGRO

Figure 3 is a composite spectrum from the impulsive phase of the flare. The BATSE data are an extrapolated fit. The discrepancy between COMPTEL and EGRET spectra near 10 MeV and the emission near 60 MeV are most likely due to background subtraction issues with EGRET data.

Figure 4 shows detailed COMPTEL spectra during the impulsive and post impulsive phases. In both intervals, the 2.223 MeV line is prominent and several nuclear lines are evident between 4 - 7 MeV and near 1.6 MeV. The smooth black line denotes Bremsstrahlung emission.

During the post-impulsive phase (bottom) we see a clear energy shift of the ^{28}Si (1.78 MeV) and ^{20}Ne (1.63 MeV) lines. This shift is due to an inconsistency between the software and instrument energy calibration rather than an actual redshift of the lines.

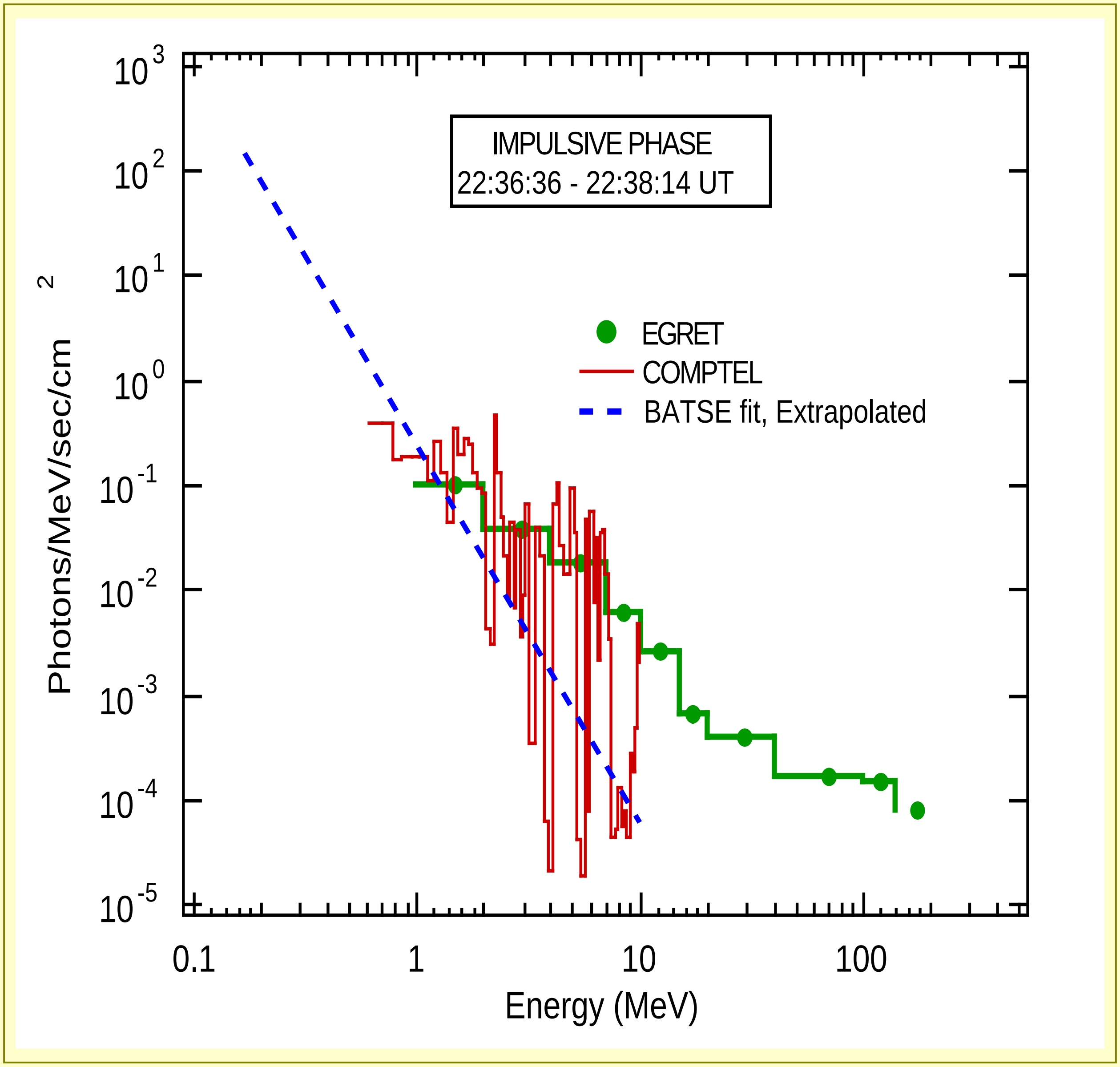
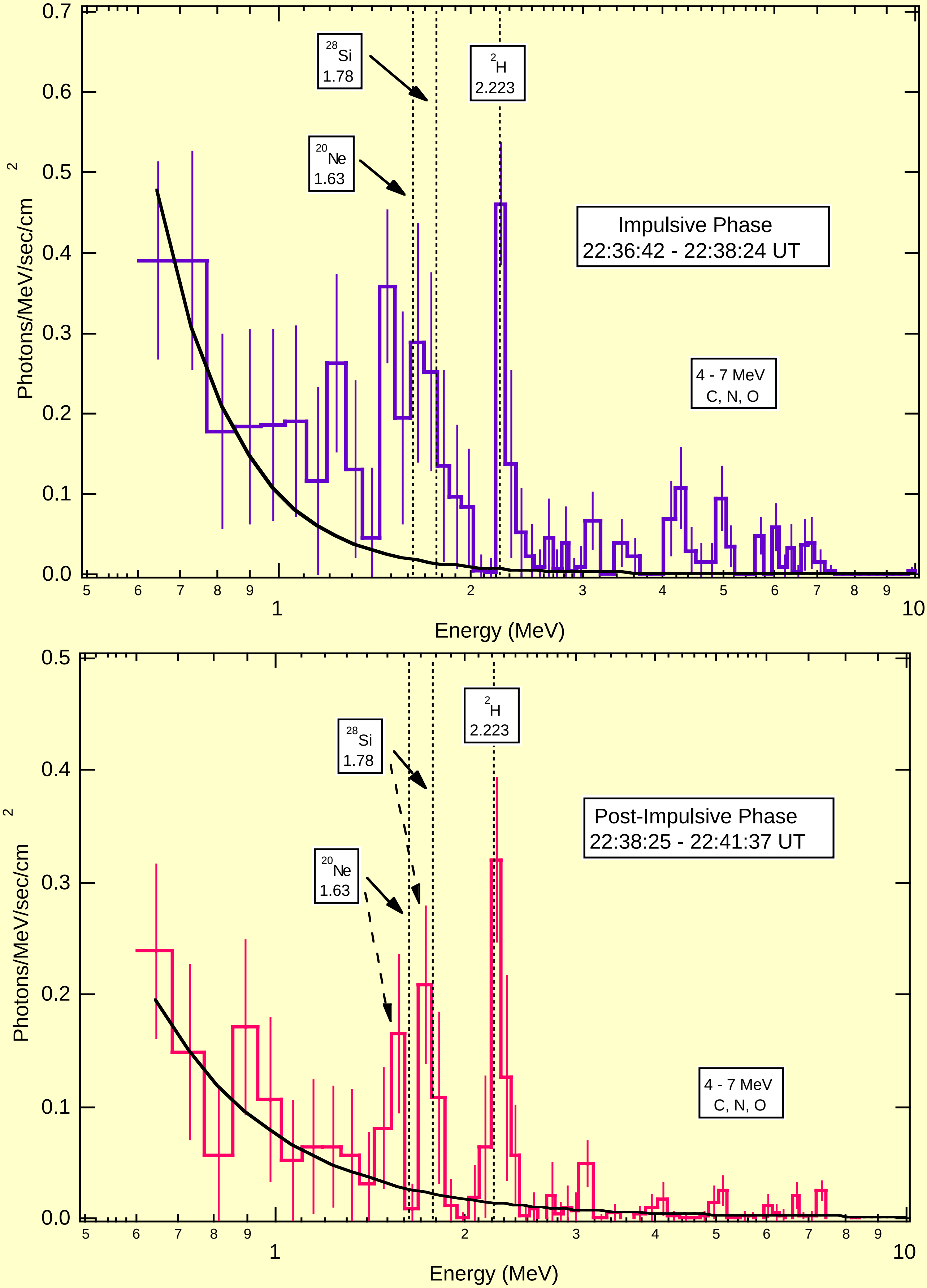


Figure 3: Composite Spectrum of the impulsive phase of the 15 November 1991 solar flare.



28Si 1.78
2H 2.223
20Ne 1.63
Impulsive Phase
22:36:42 - 22:38:24 UT
4 - 7 MeV
C, N, O
Photons/MeV/sec/cm2
Energy (MeV)
Post-Impulsive Phase
22:38:25 - 22:41:37 UT

Figure 4

Accelerated Protons

Using fluences derived from COMPTEL spectra we are able to deduce the shape of the accelerated proton spectrum. Our values with other published values are listed below. The proton spectrum above 0.6 MeV is best fit with a power law of s = –4.5.

Fluence Line Ratio	Value	αT(3)	s (2,3)
$\phi_{4.4}/\phi_{0.42}$	0.035 – 0.065[1]	--	--
$\phi_{4.4}/\phi_{2.223}$	**0.52 ± 0.14**	**--**	**4.5-5**
"	--	0.009±0.002[4]	--
$\phi_{4-7}/\phi_{2.223}$	**1.6 ± 0.34**	**0.008 -0.015**	**4-5**
"	--	0.010 ± 0.002[5]	--
$\phi_{4.4}/\phi_{6.13}$	**2.11 ± 0.47**	**--**	--
$\phi_{1.63}/\phi_{6.13}$	**4.95 ± 1.0**	--	**4.5-5.5**

Table 3: Fluence ratios and their respective αT and s values derived from various high-energy emission lines. [1]Kotov et al. 1996; [2]Ramaty et al. 1995a,b; [3]Ramaty et al. 1993; [4]Kawabata et al. 1994a,b; [5] Yoshimori et al. 1994.

The energy content of these ions is ~10^{27} ergs. **These particles do not have enough energy to produce the observed white light emission**, which has an energy content on the order of 10^{30} ergs (Hudson et al. 1992)

2.223 MeV Flux

Using emission between 3.956 and 7.055 MeV as a template for the neutron production rate S(t´), we compute the 2.223 MeV time constant τ using the expression

$$F_{2.223\,MeV}(t) \propto \int_{-\infty}^{t} S(t')e^{-(t-t')/\tau}dt'$$

We found the best fit to be 26 (+20, -15)s, which is consistent at the 2σ level with values of ~70 s found for other flares (**Figure 5**).

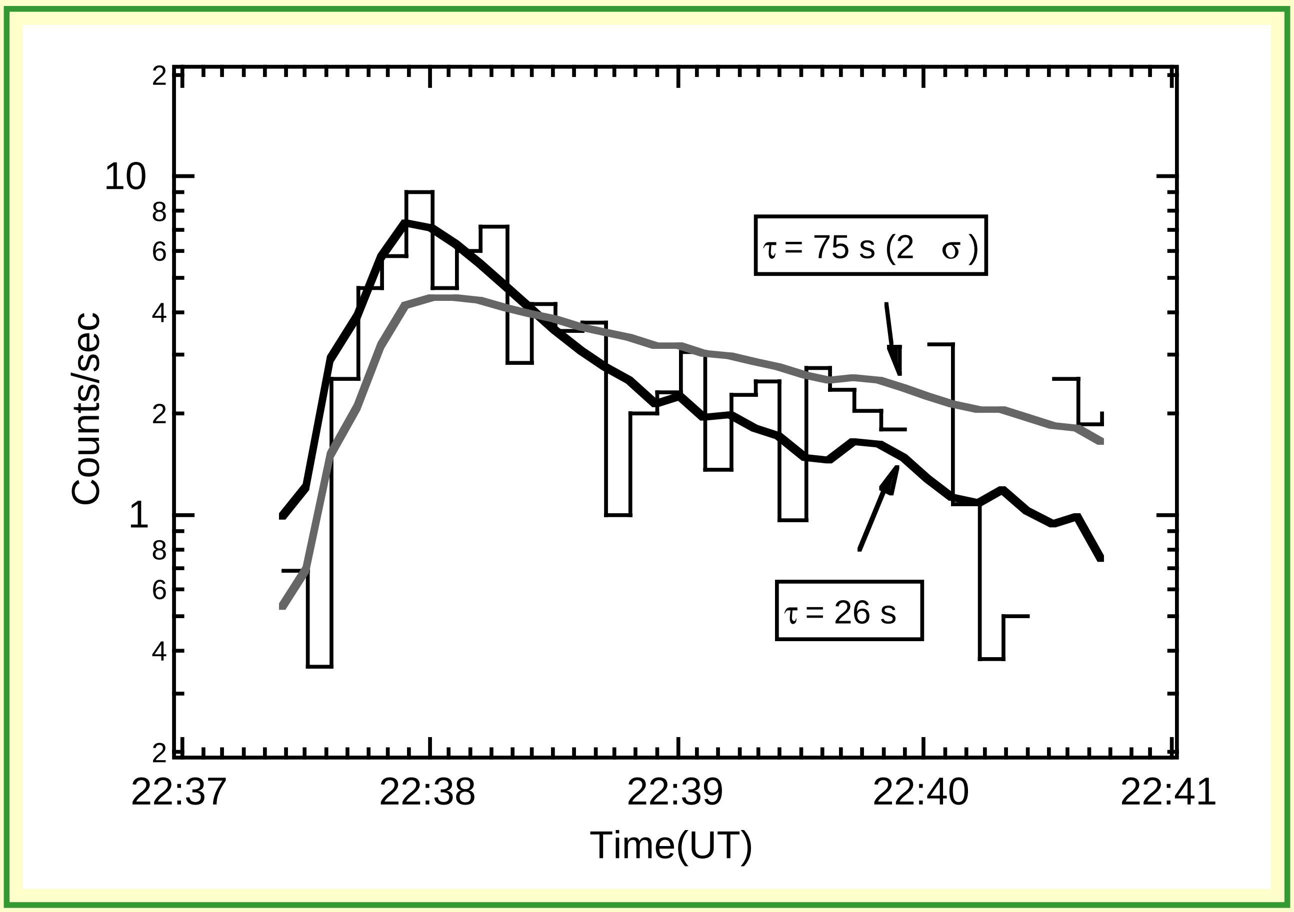


Figure 5

Possible Explanations for our “low” τ

A low value of τ suggests the presence of either an unusually high ^{3}He abundance or that neutron capture is occurring in a dense environment where neutrons thermalize and are quickly captured on ^{1}H.

Given our τ and a typical chromospheric density, we find a $^{3}He/H$ abundance ratio nearly an order of magnitude higher than values computed for other flares, but in agreement with recent results by Young (2001).

The white light emission from this flare suggests that very high energy protons are penetrating into the photosphere. The neutrons created in this dense layer would be captured quickly, resulting in a low τ.

Accelerated Electrons

The spectral indices of accelerated electrons derived from spex_proc are summarized below. The data do not all agree within error bars, however the discrepancies may be explained by the different viewing angles of each instrument. We use the indices derived from BATSE data in our work.

Satellite (Viewing Angle)	Impulsive Phase Temporal Features	γ_1	E_B (KeV)	γ_2
BATSE (~20°)	P 1-3, V 1-2	2.66 ± 0.27	168 ± 51	3.61 ± 0.23
OSSE (~20°)	"	3.0 ± 0.7	100	--
Yohkoh (~20°)	"	2 – 4.5[3] 3.7 ± 0.3[4]	93	--
PVO (~52°)	P1	--	150	3.37 ± 0.05[1]
Ulysses (~80°)	"	--	"	2.72 ± 0.07[1]
"	V2, P3	3.08[2]	166	--
Yohkoh (HXS)	"	3.20[2]	87	3.82[2] 3.70 ± 0.03[1]
Yohkoh (HXT)	"	3.39[2]	93	--

Table 2: Summary of spectral indices from various instruments. Included are satellite viewing angles, temporal features included in observations, power law spectral indices and break energies. If error bars are not included, they were not present in the literature. [1] McTiernan et al. 1994; [2] Kane et al. 1998; [3] Sakao 1994; [4] Yoshimori 2000.

The energy content (lower limit) from electrons above 170 keV is ~10^{23} ergs.

Modeling

We modeled the impulsive X-ray emission with a 1-D spatial diffusion equation (Ryan and Lee, 1991):

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[\kappa(E)\frac{\partial f}{\partial x}\right] - \frac{\partial}{\partial E}\left[\dot{E}(E)f\right] + Q$$

where **f** is the omnidirectional particle distribution function, κ**(E)** is the spatial diffusion coefficient, $\dot{E}$ is the energy loss rate due to collisions, and **Q** is the injection function.

We assumed a constant magnetic field and that both turbulence and collisions affect the transport of particles.

Model constraints were based on the following observations:

- One footpoint was consistently brighter
- The footpoints were simultaneous within 0.1 s
- The footpoints were separated by ~13″, leading to a loop length of 15.3×10^3 km.
- A single X-ray source (loop) lay between the footpoints.
- The rise and decay times within the impulsive phase range between 1 - 11 s.
- Radio emission peaked during the impulsive phase.
- The proton spectrum is $\propto E^{-4.5}$ above 0.6 MeV.
- The electron spectrum is $\propto E^{-4.6}$ above 170 keV

For relativistic electrons we found that X-ray observations during the impulsive phase can be explained if turbulence is present such that the mean free path between interactions is 0.1% of the total loop length. Collisions can be included but are not necessary. We also found that the injection source of accelerated particles is most likely located near the apex of the coronal loop.

Conclusions

Our goals with this work were to add to the extant body of knowledge of the 15 November 1991 solar flare by introducing new high-energy data from the CGRO.

These data allowed us to confirm previous results and to compute the 2.223 MeV time constant, which is consistent (but only at the 2 σ level) with the *lowest* values computed for other flares. We computed the accelerated particle spectra and subsequent energy content of these particles. We also found that the accelerated protons do not have enough energy to produce the observed white light emission.

In addition, the Ryan and Lee (1991) 1-D diffusion model was able to explain many of the observations made during the impulsive phase of the flare.

Future Work

Once we have had the opportunity to analyze EGRET data in more depth we will further improve our understanding of the high-energy particle dynamics within this flare. If EGRET does observe extended pion emission we have further evidence that high-energy protons are reaching deep into the chromosphere or photosphere. This extended pion emission would also allow us to reclassify this event as a long duration gamma-ray flare.

The Ryan and Lee model has the potential to help us further explore the physical conditions within the flare. Future plans are to include magnetic field convergence and modeling non-relativistic electrons and protons.

The 15 November 1991 solar flare was unique because it was observed in a broad energy range with detailed X-ray images. We look forward to HESSI providing us with similarly well observed events.

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