Extended Emission of the Solar Flares on June 11 and 15, 1991

Extended Emission of γ–Rays in Flares

Before June 1991 flares: The longest emission in γ–rays observed was about $40 min$. The models favoured particle acceleration during a short period in the impulsive phase. Longer lasting emission could be explained by trapping of these particles in magnetic loops.
Now: We can show that this interpretation is no longer valid!

June 11, 1991

Extended emission of γ–rays $> 50 MeV$ was observed by EGRET for about 8 hours (Kanbach et al., 1993)
Extended emission of γ–rays in the $2.2 MeV$ line was observed by COMPTEL for about 4 hours (Ryan et al., 1993; Rank et al., 1993)

The $2.2 MeV$ emission after the impulsive phase shows a smooth decline and can be described by a 2-fold exponential decay. The time constants are:

Short decay: COMPTEL($2.2 MeV$):10.4 $\pm$ $2.0 min$, EGRET($> 50 MeV$): $25 min$
Long decay: COMPTEL($2.2 MeV$):208 $\pm$ $50 min$, EGRET($> 50 MeV$):$255 min$

June 15, 1991

Analysis of COMPTEL telescope data revealed extended emission in the $2.2 MeV$ line also for the June 15 flare. Although the flare happened during CGRO night, emission could be detected for several hours.

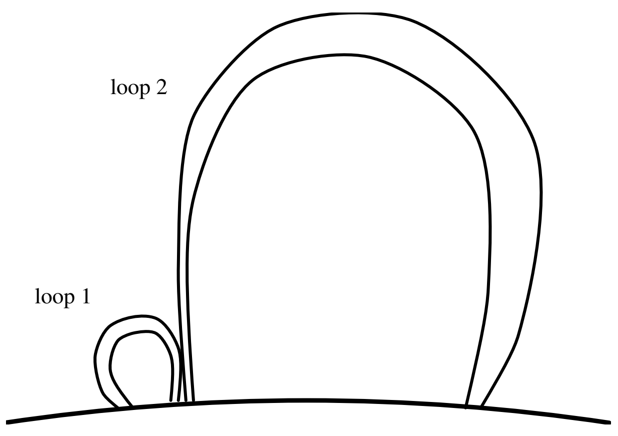
The emission looks very similar to the June 11 profile. We also fit it with a 2-fold exponential decay and get quite similar time constants.

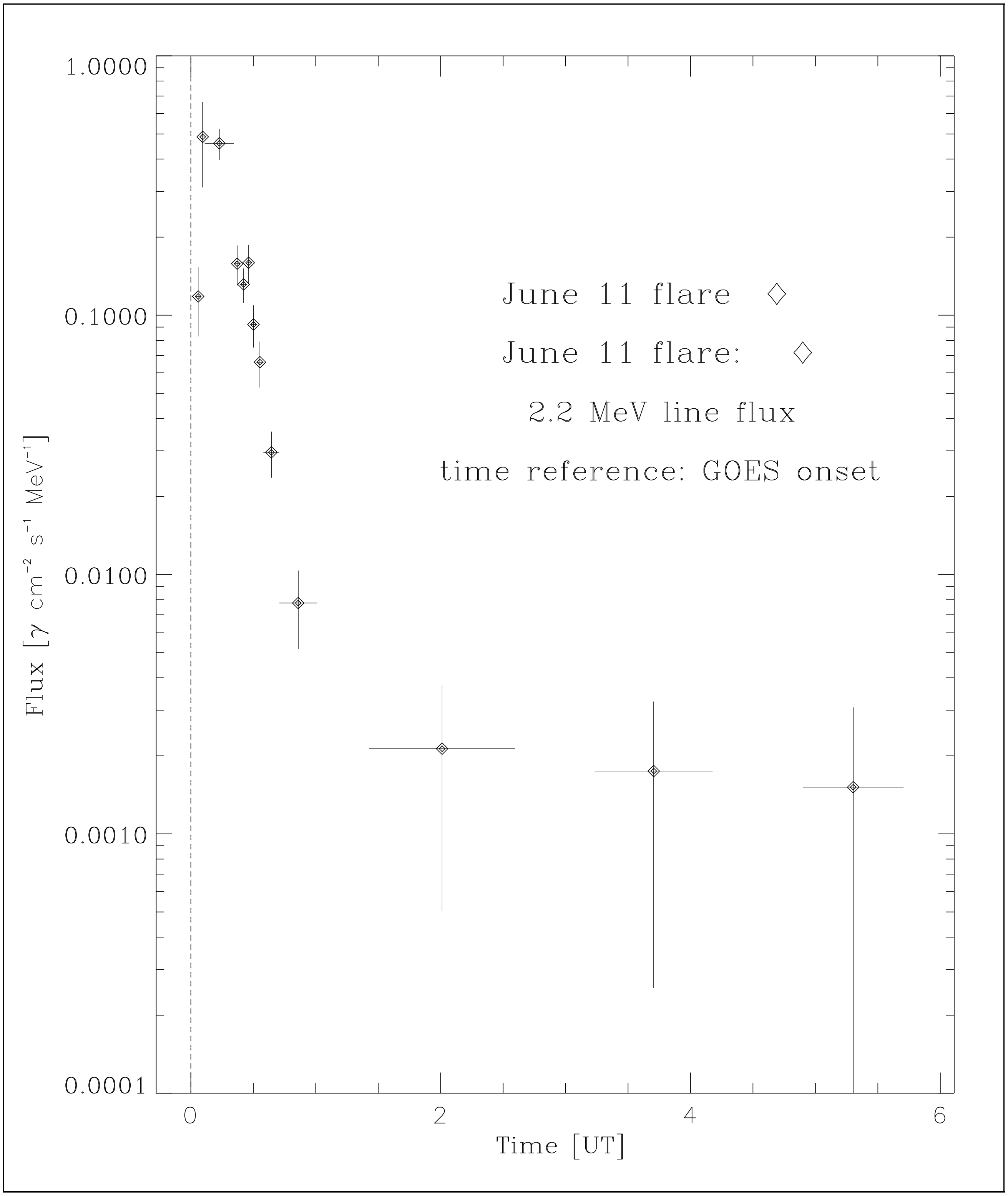
• The faster component of the EGRET time profile was so far explained by primary electron bremsstrahlung.
We can show, that this component is also nuclear in origin: The $2.2MeV$ line reveals a similar time profile than the pions and the spectrum is quite hard. Hence, also pions have to be produced simultaneously with the neutrons, powering this light curve.

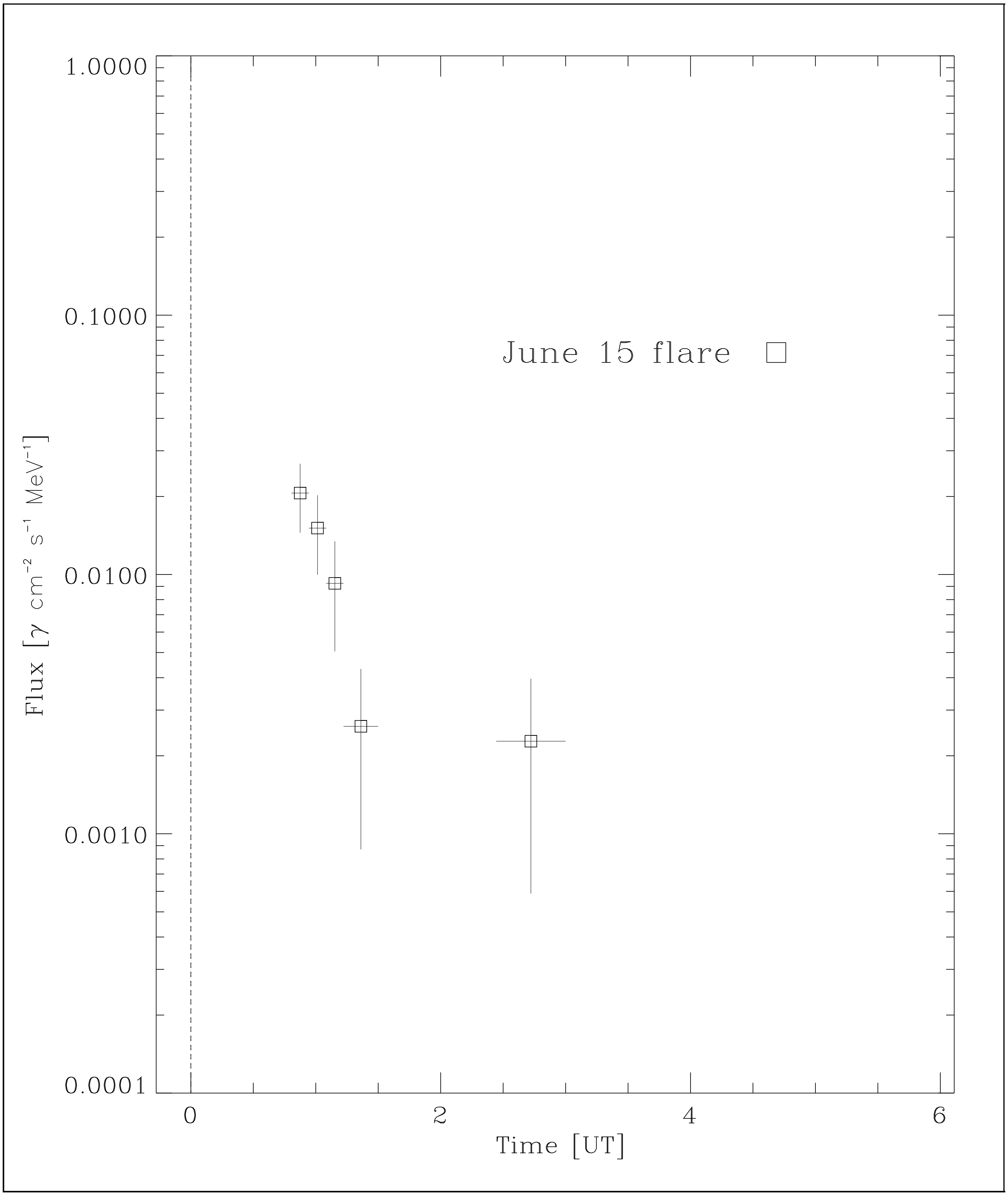
• To explain these very long extended emission by trapping of impulsively accelerated particles, pitch angle scattering has to be neglegible. This sets very restrict limits on the energy of plasma waves in the corona. After a flare event, however, the conditions of the coronal plasma are rather turbulent than quiet.

• A trapping model predicts different precipitation rates for particles with different energies.
While neutrons which create the $2.2MeV$ line are mainly produced by protons of $\sim 100MeV$, the pions originate from protons $> 400MeV$.
We measure comparable decline constants for the $2.2MeV$ line and the range $> 50MeV$. Therefore our observations are not in agreement with a trapping model. They give support to an explanation by continuous acceleration.

• The different decay times can be explained by particles that are in different magnetic structures: Particles in small loops would precipitate faster than others in large loops.
As both flares are very similar, the accelerated particles are probably populating identical magnetic structures.
As long as the diffusion constant is not variing within the loops, the declining times scale with the loop length as $\sqrt{10/210} \approx 1/5$.



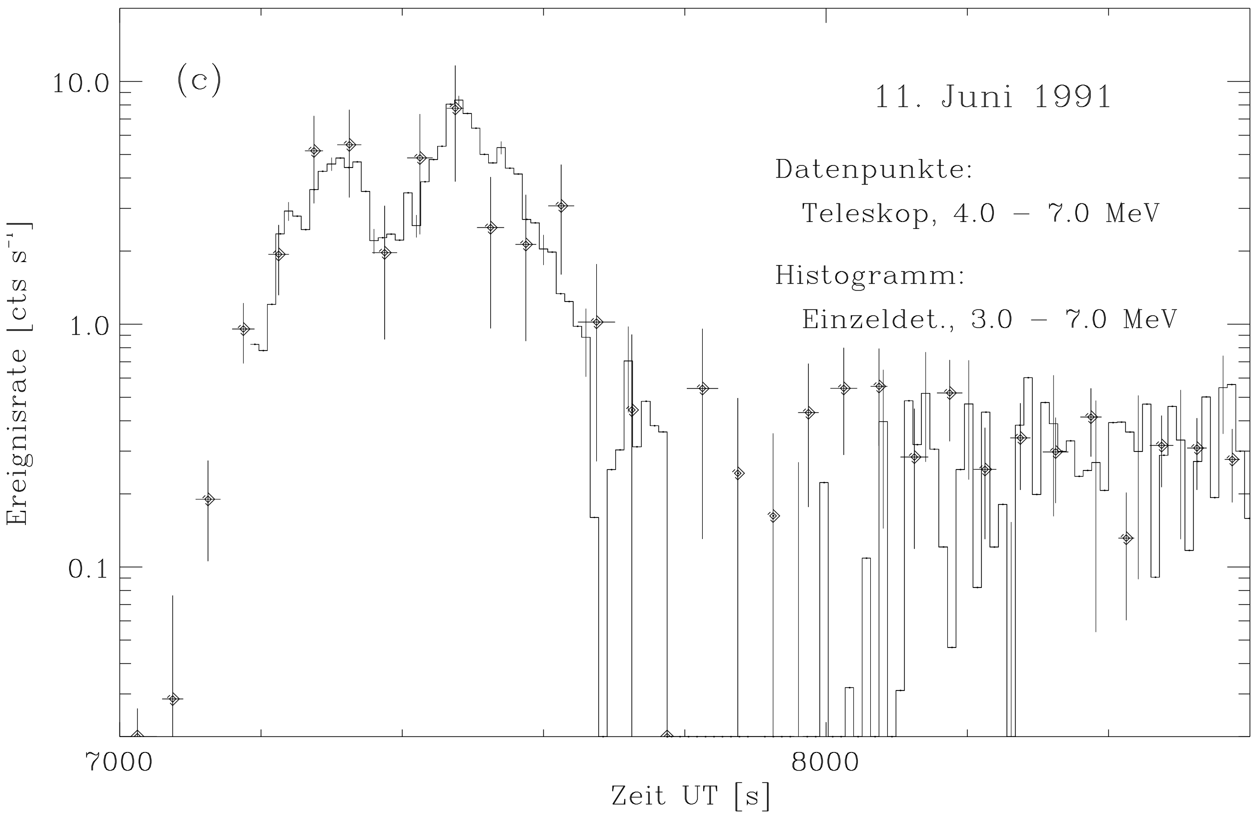

June 11 flare ◇
June 11 flare: ◇
2.2 MeV line flux
time reference: GOES onset
Flux [γ cm^{-2} s^{-1} MeV^{-1}]
Time [UT]
1.0000
0.1000
0.0100
0.0010
0.0001
0
2
4
6


1.0000
0.1000
0.0100
0.0010
0.0001
Flux [γ cm^{-2} s^{-1} MeV^{-1}]
0
2
4
6
Time [UT]
June 15 flare

Spectral Evolution of the 11 June 1991 Flare

Separation of Impulsive and Extended Phase:

Prompt emission (nuclear range $4 - 7MeV$) gives evidence for a distinct division between the 'impulsive phase' and the 'extended phase' of the June 11 flare.



Time profiles of the june 11 flare for the energy range $4 - 7MeV$. *For comparison also the Single Detector Mode data are included. They are scaled arbitrarily.*

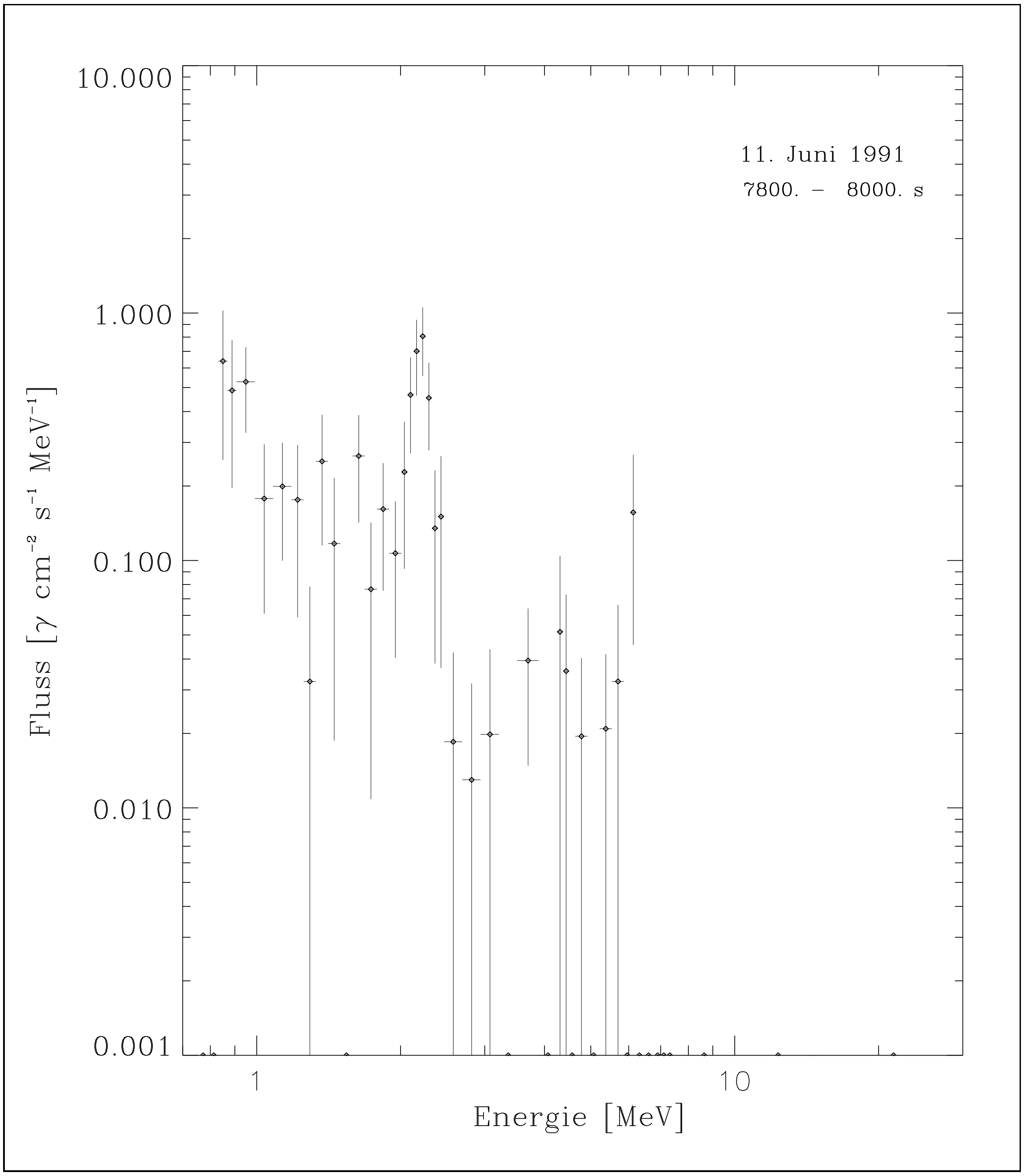
Spectral Hardness

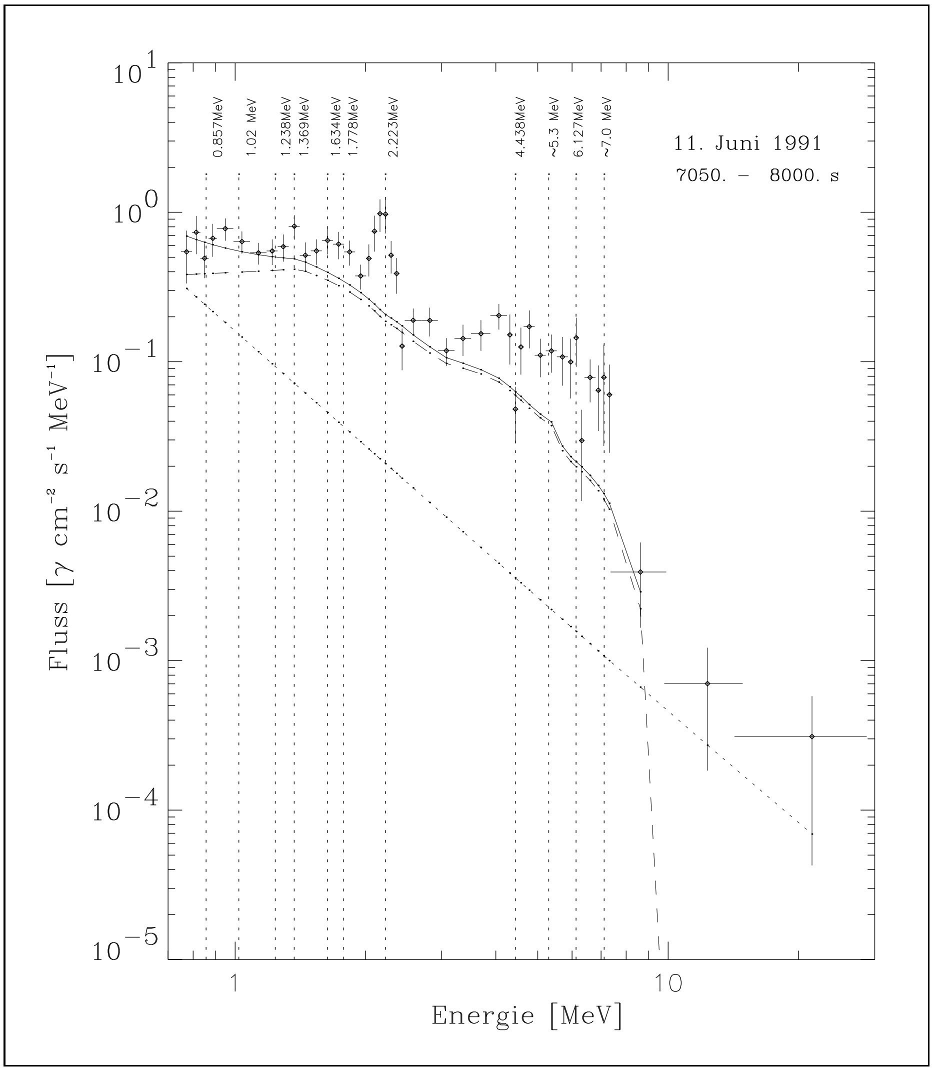
Comparison of these two time intervals shows, that the accelerated proton spectrum is significantly harder during the extended emission:
The fluence ratio between neutron capture line and nuclear emission

$$R = \frac{\Phi^E_{2.2}}{\Phi^E_{4-7}} = \frac{\int dt \phi^E_{2.2}(t)}{\int dt \phi^E_{4-7}(t)}. \tag{0.1}$$

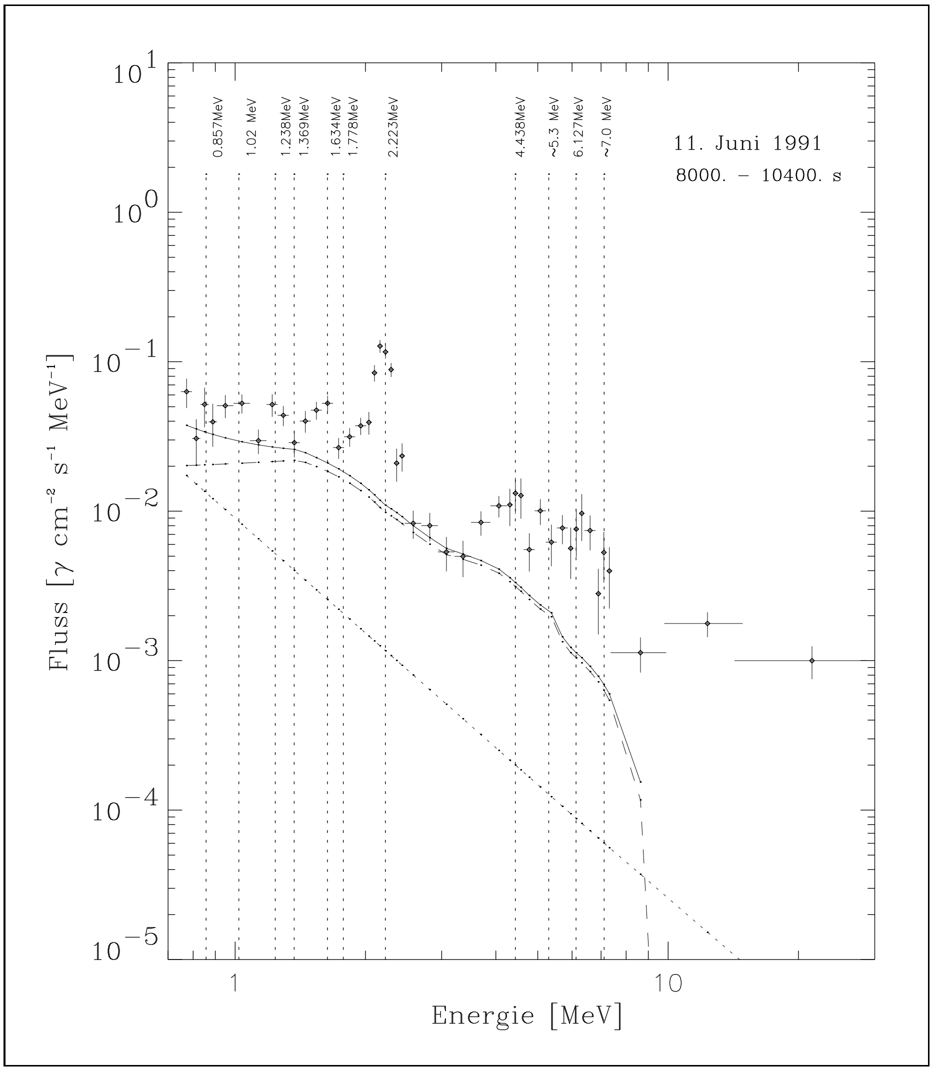
can provide the spectral hardness of the proton spectrum:

interval:	1:58 - 2:53 UT	1:58 - 2:12 UT	2:12 - 2:53 UT
$\Phi^E_{2.2}$	313.1 ± 27.7	238.4 ± 27.3	74.7 ± 4.5
Φ^E_{4-7}	359.5 ± 30.2	299.2 ± 29.8	60.3 ± 4.6
$R = \Phi^E_{2.2}/\Phi^E_{4-7}$	0.92 ± 0.11	0.80 ± 0.12	1.24 ± 0.12
horizontal fan beam	$\alpha T = 0.022 \pm 0.002$ $s = 3.5 \pm 0.1$	$\alpha T = 0.020 \pm 0.002$ $s = 3.6 \pm 0.1$	$\alpha T = 0.026 \pm 0.002$ $s = 3.3 \pm 0.1$
isotrop	$\alpha T = 0.015 \pm 0.0015$ $s = 3.9 \pm 0.1$	$\alpha T = 0.014 \pm 0.0015$ $s = 4.0 \pm 0.1$	$\alpha T = 0.018 \pm 0.0015$ $s = 3.6 \pm 0.1$


11. Juni 1991
7800. – 8000. s
Fluss [γ cm⁻² s⁻¹ MeV⁻¹]
10.000
1.000
0.100
0.010
0.001
1
10
Energie [MeV]



11. Juni 1991
7050. – 8000. s
0.857MeV
1.02 MeV
1.238MeV
1.369MeV
1.634MeV
1.778MeV
2.223MeV
4.438MeV
~5.3 MeV
6.127MeV
~7.0 MeV
Fluss [γ cm⁻² s⁻¹ MeV⁻¹]
Energie [MeV]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
1
10



0.857MeV
1.02 MeV
1.238MeV
1.369MeV
1.634MeV
1.778MeV
2.223MeV
4.438MeV
~5.3 MeV
6.127MeV
~7.0 MeV
11. Juni 1991
8000. - 10400. s
Fluss [γ cm⁻² s⁻¹ MeV⁻¹]
Energie [MeV]

Pion Related Emission

The signature of pion emission in the $> 8MeV$ range shows a peak during the impulsive phase. Pretending pions emission, however, sets in at late times of the flare.
As the creation of pions requires energies above $\sim 400MeV$, we conclude, that protons are accelerated to these high energies predominantly during the extended phase.