28th Annual Meeting of the AAS Solar Physics Division
Bozeman, Montana, 27 June - 2 July 1997

Extended Gamma-Ray Emission of the Solar flares in June 1991

G. Rank, J.L ockwood, M. McConnell, J. Ryan
Univ. of New Hampshire, Durham, NH

V. Schönfelder
MPI for Extraterrestrial Physics, Garching, Germany

K. Bennett
Astrophysics Division, ESTEC, Noordwijk, The Netherlands

W. Hermsen
SRON-Utrecht, Utrecht, The Netherlands

Abstract

In June 1991, a series of six X-class solar flares took place in the active region 6659. For the flares on 11 and 15 June, extended γ-ray emission has been recorded by COMPTEL, EGRET and GAMMA-1 for hours. COMPTEL measures a two-fold exponential decay in the neutron capture line for both flares, with time constants of about 10 m for the fast and 200 m for the slow component. Within the statistical uncertainty both flares show the same long-term behaviour.

From the study of the neutron capture line, prompt nuclear lines and the γ-ray continuum above 50 MeV it was found that the measured decay times are independent of the energy of the accelerated protons. This favours the continuous acceleration of particles over long-term trapping as the explanation of the extended emission.

Here we present updated results for the flares on 11 and 15 June 1991. We also have analyzed COMPTEL telescope data from the flare on 9 June 1991 and present these new results. Our measurements clearly show an extended γ-ray signal also for this flare.

The long-term deveopment in γ-rays is very similar for all three flares. Our data seem to indicate that the large-scale magnetic structure of AR-6659 remains stable during this active period and supports the same kind of long-term acceleration for each flare.

COMPTEL Observations during the First Hour of the 11 June 1991 Flare

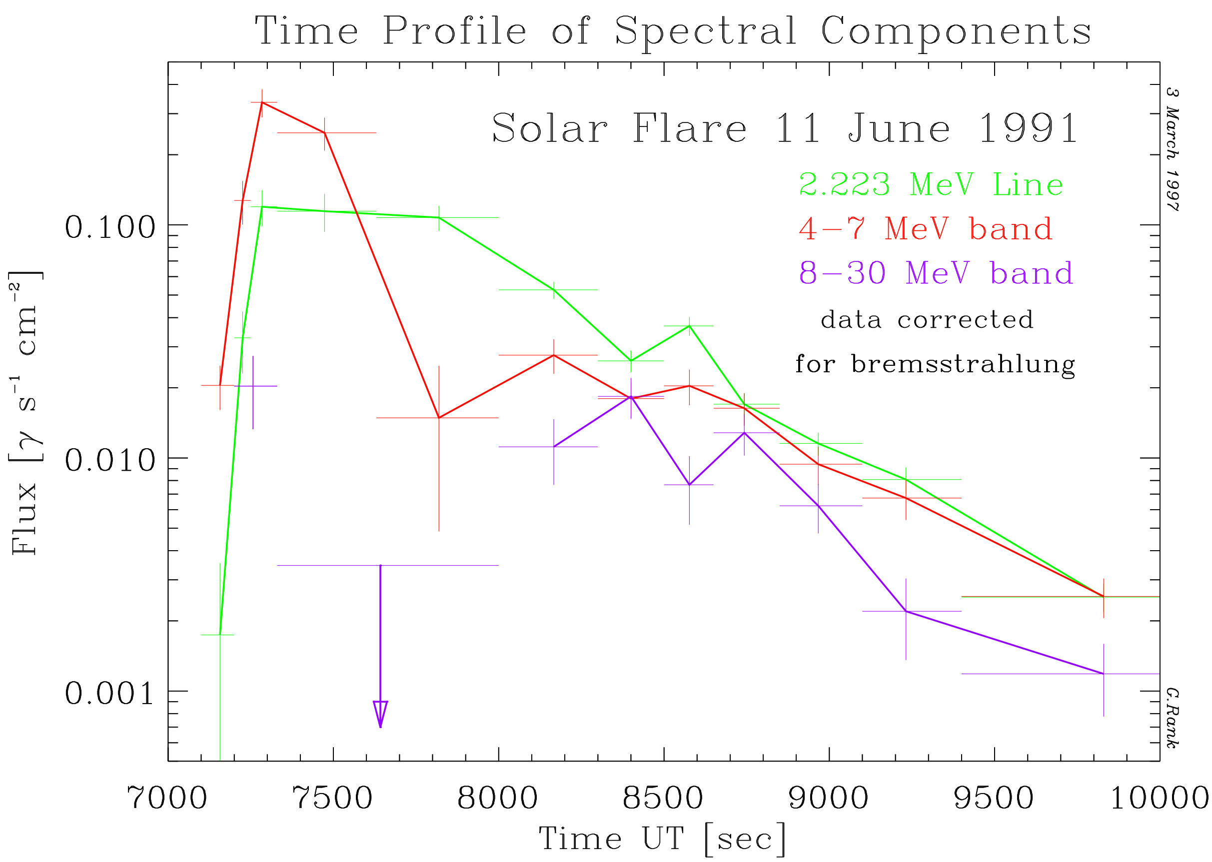
COMPTEL observations during the first hour of the 11 June 1991 flare reveal that the flare has a complex spectral and temporal behaviour and shows considerable evolution. From our observations this flare can be devided into three phases:

— The impulsive phase is rich in prompt nuclear lines. Also emission in hard X-rays (from electron bremsstrahlung) is measured by PHEBUS (Trottet 1993) and reveals a similar time profile. Comparison of the 2.2 MeV line with the 4–7 MeV band reveals that the accelerated proton spectrum is quite soft. No substantial emission above 8 MeV is detected during this phase.

— The prompt emission fades away quickly after the impulsive phase. However, the 2.2 MeV line remains prominent and causes an uncommonly high 2.2 MeV/4-7 MeV ratio. COMPTEL detects no signature of pion production. The modeling of the 2.2 MeV line establishes a very long neutron capture time during this phase. This somewhat contradictory situation can be understood when many low-energy neutrons are produced during this phase from a soft proton spectrum.

— After $\sim$0213 UT strong emission is detected in both the nuclear lines and the 2.2 MeV line. Now also a strong signal $>$8 MeV is present and indicates that protons have been accelerated above the pion production threshold of a few 100 MeV. The spectrum in this extended phase is harder than during the impulsive phase. The emission falls off exponentially with a decay time of about 10 minutes until the end of the observation period (about 0300 UT). This emission extends further out and a signal in the 2.2 MeV line can still be detected in the following satellite orbits.

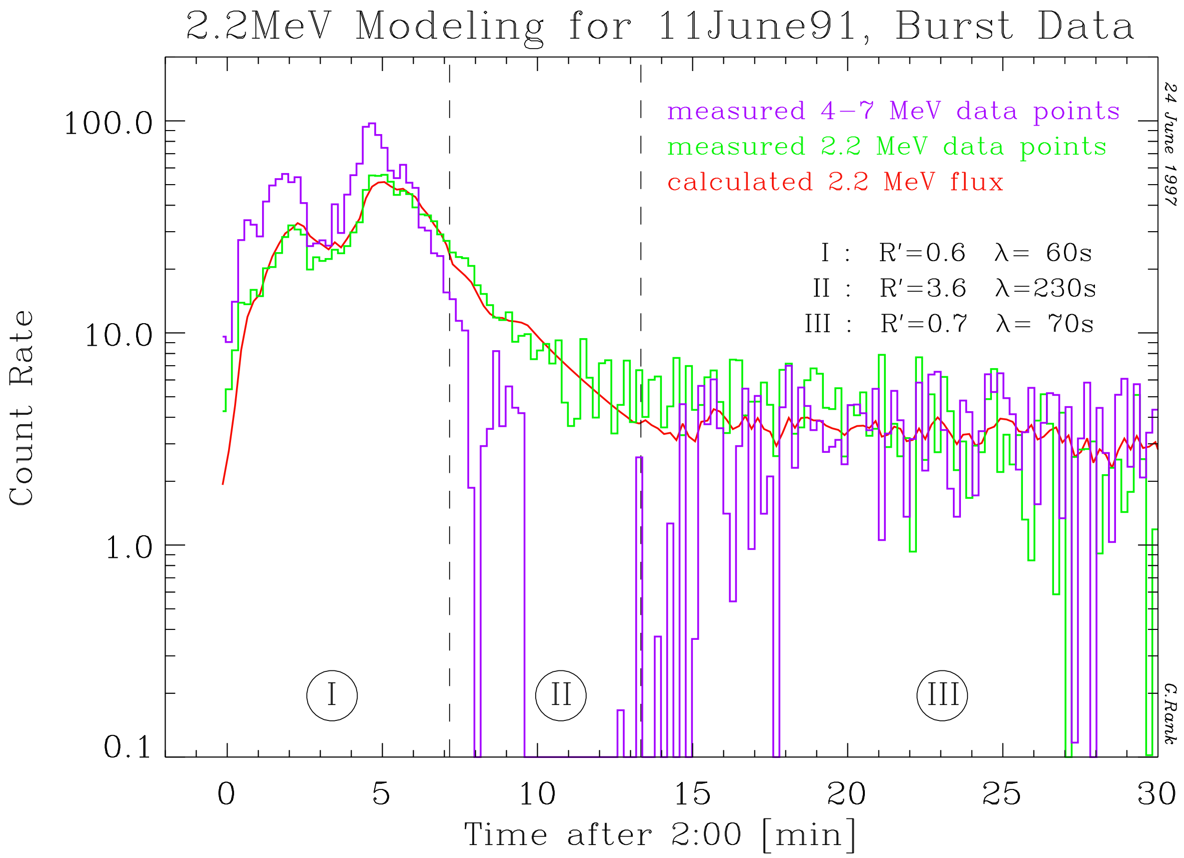
Time Profile of Gamma-Ray Components



Gamma-ray emission in different energy bands during the first hour of the 11 June 1991 flare:

— The 2.2 MeV line is generated by neutron capture onto hydrogen in the solar photosphere. The neutrons are produced in spallation reactions from protons in the energy range of about 50-100 MeV.
— The 4–7 MeV band is dominated by prompt nuclear de-excitation lines, which are caused by direct reactions of 10-20 MeV protons.
— Secondary electron bremsstrahlung (emitted by e^- that are produced in charged pion decay) can be detected in the 8–30 MeV band. Protons must be accelerated to about $>$400 MeV in order to produce pions.

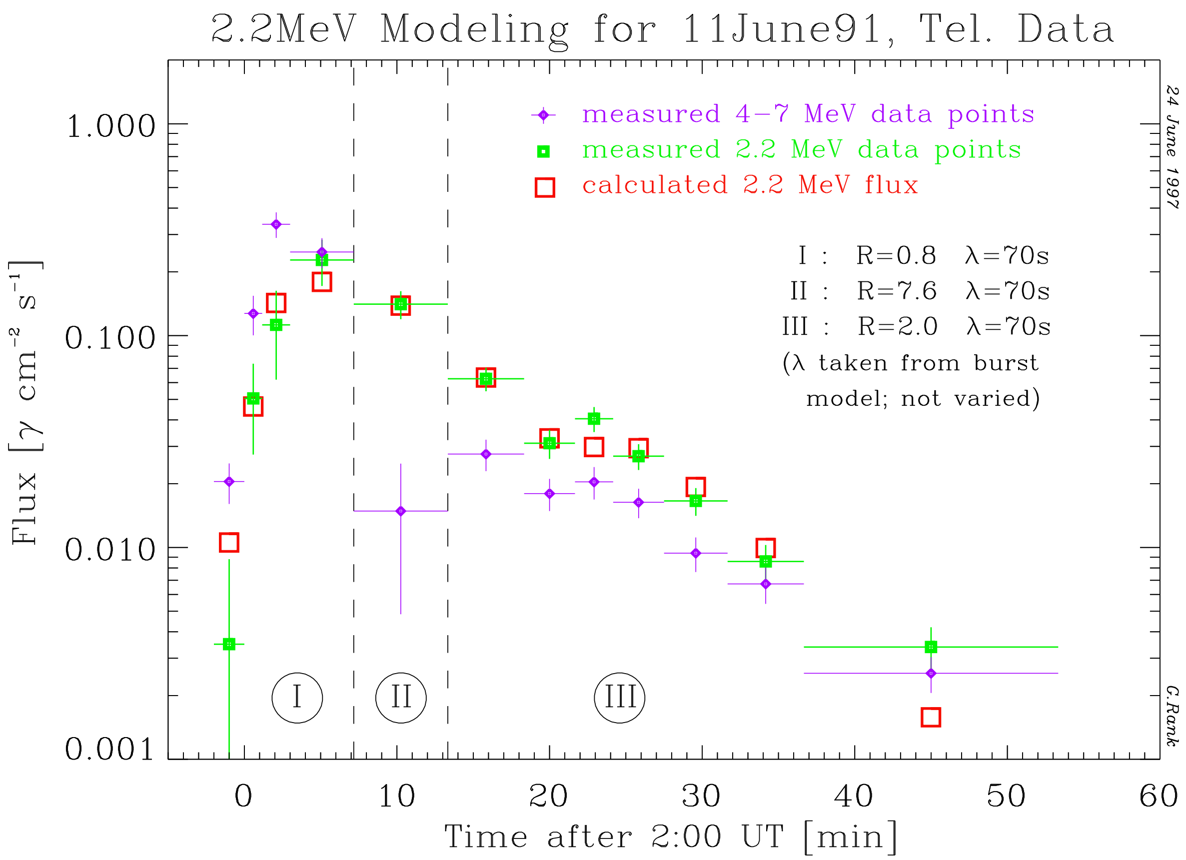
Modeling the 2.2 MeV Line (using COMPTEL Burst Data)



• MODEL: We use the prompt nuclear 4–7 MeV flux to model the delayed 2.2 MeV line flux. Parameters are the ratio $\mathrm{R} = \Phi_{2.2MeV}/\Phi_{4-7MeV}$ (depends on the hardness of the accelerated proton spectrum) and the neutron capture time λ in the photosphere. The 12 s time resolution of the COMPTEL burst data allows a direct measurement of λ. Since we use count rates, R gives only relative values.

• RESULTS: The 2.2 MeV emission cannot be understood with only one parameter set — the flare properties change with time! We derive 'normal' capture times of $\sim$70 s during intervals (I) and (III). For (II) we need a very long capture time of 230 s (1σ range: 140 s – 390 s).

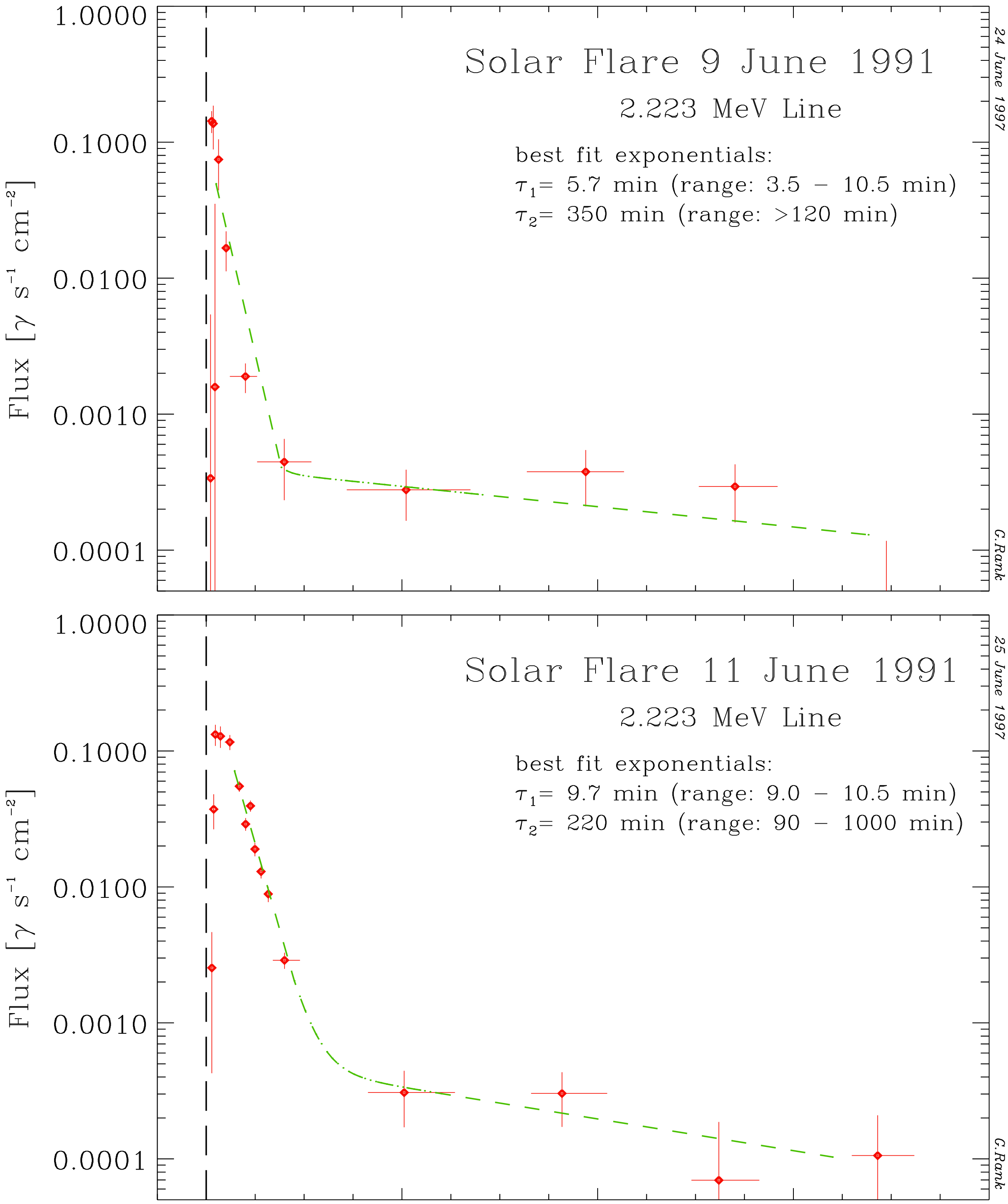
Modeling the 2.2 MeV Line (using COMPTEL Telescope Data)



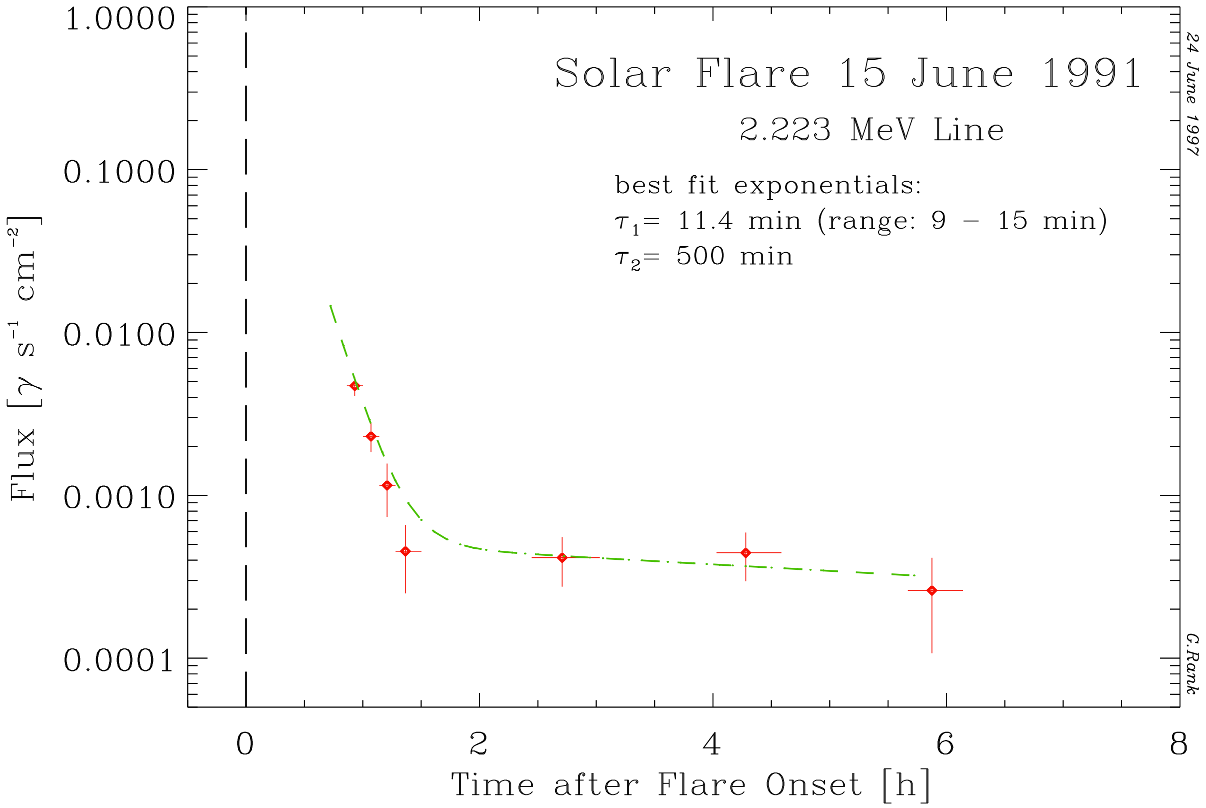
• MODEL: We use the same model as before, but now we work with deconvolved COMPTEL telescope data. Since the long integration times needed for deconvolution do not allow the determination of λ, we use the results from the burst data and keep λ fixed.

• RESULTS: The value of R shows considerable changes: It is low during the impulsive phase (I) and high during the extended phase (III). Since the pion signal is weak during (I) but strong during (III) this can be understood as a hardening of the proton spectrum. During the transition phase (II) R is very high. However, the missing pion signal and the long capture time (which indicates the presence of low-energy neutrons) argue for a soft proton spectrum instead.

Extended Gamma-Ray Emission (plots for 9 and 11 June flare)



Extended Gamma-Ray Emission (plot for 15 June flare)



The three plots above show the time profile of the 2.2 MeV line measured in the COMPTEL telescope mode. For each of the time intervals shown, spectra were sampled, corrected for instrumental livetime and background and then deconvolved. Also the best fit (green curves) of a double exponential fitted to the data points is shown.

The flares on 9 and 11 June occured shortly after orbital sunrise and allowed the observation of the impulsive phase. The flare on 15 June occured during orbital night and the impulsive phase was unobservable. Nevertheless, COMPTEL measured extended emission also for this flare during the following orbits.

Extended Gamma-Ray Emission (description)

One of the most interesting findings from the June 1991 flare observations was prolonged γ-ray emission after the flares: For the flare on 11 June the EGRET instrument measured $>$50 MeV radiation for more than 8 hours (Kanbach et al. 1993) and COMPTEL detected emission in the 2.2 MeV neutron capture line for about 5 hours (Ryan et al. 1993; Rank et al. 1993).

Although the impulsive phase of the 15 June flare happened during orbital night for CGRO, COMPTEL measured gamma-ray emission for several hours (McConnell, 1992). The GAMMA-1 instrument observed $>$50 MeV gamma-radiation later and detected emission during the following orbit (Akimov et al. 1991; Kocharov et al. 1994).

For the flare on 9 June, a 20–200 MeV time profile measured by EGRET has been published for the flare orbit (Schneid et al. 1996). Here, we present results from the COMPTEL instrument.

The most significant feature of the flare spectrum in the COMPTEL energy range is the 2.2 MeV neutron capture line. As the figures to the left reveal, this line can be detected for several hours after flare onset in all three observed events. The similarities during the extended emission is remarkable: In each flare...
... the overall shape can be described as a two-fold exponential decay;
... the transition between the fast and the slow component occurs at roughly 1 to 1.5 hours after flare onset;
... the 2.2 MeV line flux value at which the transition occurs is on the order of 5 $10^{-3} \gamma cm^{-2} s^{-1}$;
... the decay times are on the order of 10 min for the fast and some 100 min for the slow component.

Extended Gamma-Ray Emission: Particle Trapping or Continued Acceleration?

The extended emission can be understood in two ways:
(1) Particles are accelerated during the impulsive phase and subsequently trapped in magnetic loops. They slowly leak out of the trap and cause the prolonged emission. The level of plasma turbulence in the loops must be extremely low to accomplish long trapping times.
(2) Particle acceleration takes place for a prolonged period after the impulsive phase. In order to accelerate particles efficiently enough to overcome losses, the level of plasma turbulence has to be sufficiently high in this model.

The EGRET measurements of the 11 June flare could be explained in a trapping scenario by Ramaty & Mandzhavidze (1993). The model predicts energy-dependent losses in the loops and therefore different decay times for different spectral regimes.
By combining the measurements of COMPTEL (nuclear lines and neutron capture line) with EGRET and GAMMA-1 (>50 MeV pion decay emission) it could be shown for the flares on 11 and 15 June 1991 (Rank et al. 1995), that the measured γ-ray time profiles are energy-independent and thus incompatible with a trapping scenario. Using COMPTEL data alone, the same argument is true for the first hour of the 11 June flare and shows that trapping cannot be important during this period.
A model using continuous particle acceleration was presented by Ryan & Lee (1991) and Ryan et al. (1994). A proton spectrum from an earlier (impulsive) acceleration is injected into a large coronal loop with high plasma turbulence. It was shown that the flux rises to a maximum and then decays exponentially, independent of the hardness of the injection spectrum.

Conclusions

We have presented Gamma-Ray measurements of the June 1991 flare done by the COMPTEL instrument. Our main conclusions are:

• The flare of 11 June 1991 allows a detailed study of the first hour of emission. We can devide the flare into three major phases:

— inpulsive phase ($\sim$7 min): strong nuclear line emission; no substantial pion signal; quite soft proton spectrum; distinctive temporal modulation.

— transition phase ($\sim$6 min): very weak nuclear lines; no pion signal; strong 2.2 MeV line emission; can be best explained by a soft proton spectrum, producing many low-energy neutrons.

— extended phase (for several hours): strong prompt and 2.2 MeV line emission; clear pion signal (now protons get accelerated to several 100 MeV); quite hard proton spectrum.

• COMPTEL measures extended emission in the 2.2 MeV line for several hours. When comparing data of different energy regimes, we find that the temporal evolution is independent of the proton energies. This excludes particle trapping as the major reason for extended emission, but is in agreement with continuous accelration.

• The overall properties of the extended signal are remarkably similar for all three flares. It appears as if the particles find the same properties in the acceleration site in all three events. Either the expanding post-flare loop systems develop in a very similar way and go through reproducible stages of acceleration after each event, or the loops responsible for the prolonged acceleration are stable during the whole period.

Conclusions/ References

It is interesting to note that the development of AR-6659 could be followed for a total period of six solar rotations in magnetometer measurements (Bumba 1993). Even though the small scale structure in the sunspot group rearranged after each flare, the large scale structure might be stable.

REFERENCES:

— Akimov V. V. et al., in *Proc. 22nd Internat. Cosmic Ray Conf., Dublin*, **3**, 73 (1991)

— Bumba V. et al., *Astron. Astroph.*, **276**, 193 (1993)

— Kanbach G. et al., *Astroph. J. Suppl.*, **97**, 349 (1993)

— Kocharov G. E. et al., in *High-Energy Solar Phenomena — A New Era of Spacecraft Measurements, Waterville Valley, NH*, Ed. J. M. Ryan & W. T. Vestrand, AIP Proc., **294**, 45 (1994)

— McConnell M. et al., *BAAS*, **180**, 45.01 (1992)

— Ramaty R. & Mandzhavidze N., in *High-Energy Solar Phenomena — A New Era of Spacecraft Measurements, Waterville Valley, NH*, Ed. J. M. Ryan & W. T. Vestrand, AIP Proc., **294**, 26 (1994)

— Rank G. et al., in *The 1st Compton Symposium, Washington Univ., St. Louis, MO*, Ed. M. Friedlander, N. Gehrels & D. J. Macomb, AIP Proc., **280**, 661 (1993)

— Rank G. et al., in *High-Energy Solar Physics, Greenbelt, MD*, Ed. R. Ramaty, N. Mandzhavidze & X.-M. Hua, AIP Proc., **374**, 219 (1995)

— Ryan J. M. & Lee M. A., *Astroph. J.*, **368**, 316 (1991)

— Ryan J. M. et al., in *Advances in Solar Physics, Catalina, Italy, 1993*, Ed. G. Belvedere, M. Rodonò & G. M. Simnett, Springer, *Lecture Notes in Physics***432**, 273 (1994)

— Schneid E. J. et al., *Astron. Astroph. Suppl.*, **120**, 299 (1996)

— Trottet G. et al., *Astron. Astroph. Suppl.*, **97**, 337 (1993)