The Northcott Theatre auditorium, main venue for the oral program (speaker: H. Cremades).

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Gamma-Ray Solar Flares and In Situ Particle Acceleration

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Abstract. At present two concurrent paradigms of solar energetic particle (SEP) origin exist: acceleration directly in the flare site or by the shock wave of coronal mass ejection (CME). Active discussions on a relative role of flares and coronal mass ejections for SEP acceleration and propagation are continuous until now. In my opinion only future observations of solar high energy γ–emission with better spectral, spatial and temporal resolution may clarify this issue. In my report I discuss possible signatures of the flare and shock acceleration processes. What is a picture provided by the current instruments? What can we expect to observe with a perfect instrument in high energy gamma rays in one or another case on a time scale of impulsive and long decay flare phases?

Keywords. Sun: activity, Sun: flares, Sun: x-rays and gamma-rays, Sun: particle emission

1. Introduction

A task to measure γ–radiation was set up just from the beginning of space era. A paper of Chupp (1964), possibly, was the first, where estimates for intensities of solar γ–rays and neutrons had been presented. Later Edward Chupp (1927-2017) became a principal investigator for the γ-ray spectrometer experiments on the OSO-7 and the Solar Maximum Mission satellites, which made pioneering observations of solar flare γ–rays and neutrons. Reading his reviews (Chupp, 1964; Chupp, 1971; Chupp, 1984; Chupp, 1996; Chupp & Ryan, 2009) one can follow the history of solar γ–ray observations from first proposals to the Fermi Gamma Ray Observatory (GRO).

Milestones of the solar γ–ray observations attributed to famous solar events and particular missions are: August 1972, OSO -7 - solar nuclear γ–lines (Chupp *et al.* 1973); June 3, 1982, SMM - pion decay solar γ–emission (Forrest *et al.* 1986), two phases of proton acceleration (Ramaty *et al.* 1987), first γ–flare statistics (Cliver *et al.* 1989); June 1991, Compton GRO (Kanbach *et al.* 1993, Rank *et al.* 2001, Murphy *et al.* 1997), GAMMA-1 (Akimov *et al.* 1996) – long duration solar γ–ray flares, GRANAT – coronal γ–ray source (Ramaty *et al.* 1997); July 23, 2002, RHESSI - precise γ–line spectroscopy (Lin *et al.* 2003) and γ–ray images (Hurford *et al.* 2003); Fermi GRO – images of pion decay emission(Ackermann *et al.* 2014), M class γ–flares (Ackermann *et al.* 2012), confirmation of long duration γ–flares (Ajello *et al.* 2014). The lastest reviews on the subject are Lin (2011), Vilmer *et al.* (2011) and Raymond *et al.* (2012).

High energy particles accelerated in flares interact in the solar atmosphere producing bremsstrahlung (electrons), γ–line ($>$ 30 MeV protons) and pion decay ($>$ 144 MeV protons) emission. Their fluxes should be rather high and they need to interact in a thick target in order to generate gamma emission observable at 1 AU. There are two possible sites of the thick target in the Sun, the photosphere (large density) and the corona (low density and, possibly, large time of trapping). A nice scheme of the flare gamma-ray diagnostics is presented in Chupp (1983). Studying spectral and temporal characteristics of this emission it is possible to separate cases of several acceleration episodes or trapping, to evaluate their characteristic time and to estimate a total energy of interacting particles. Spatial–temporal observations of γ–emission may allow to determine a position and size of the source, separate different sources, and to track the evolution of sources in time. In an ideal case the γ–ray observations may provide an injection function of solar protons into the interplanetary space.

What should the injection function of solar protons (> 30 MeV for γ–lines and > 144 MeV for pion production) look like based on their measurements near the Earth? Solar proton events (Kurt *et al.* 2004, Belov *et al.* 2005) at the Earth well correlate with M–X class solar flares with coordinates E10–W120 (the nominal Earth connecting field line is at W60). Generally a release time of solar protons we may not estimate better than ~ 10 min keeping in mind all possible uncertainties of a detector's background and a length of magnetic field line. To reproduce temporal profiles of proton intensity we need to consider several injection episodes with total duration from ~ 10 min up to several hours (Struminsky, 2003, 2013a). Prolonged injection of solar protons into the interplanetary space within ~ 60 degree is necessary, which may be provided by flare acceleration and coronal propagation or by CME–driven shock wave acceleration. Arguments between flare and shock acceleration protagonists are continuing, one of the last examples is a polemic between Grechnev *et al.* (2015), who are in favor of flare acceleration, and Cliver (2016), who is a strong supporter of shock acceleration. Recent reviews on the topic are Aschwanden (2012), Reames (2013), Desai & Giacalone (2016), Bazilevskaya (2017), Klein & Dalla (2017).

Below I discuss possible signatures of the flare and shock acceleration processes. What we might expect to observe by a perfect instrument in high energy γ–rays in one or another case on a time scale of minutes (impulsive phase) and hours (long decay phase)?

2. Spectral, temporal and spatial characteristics of solar γ–flares

Let us first consider statistical results of solar X–ray (SXR) and γ-ray observations in proton events. Solar proton events (Kurt *et al.* 2004, Belov *et al.* 2005) at the Earth well correlate with M-X class solar flares. Since plasma–emitting SXR is heated by electrons accelerated in solar flares (Neupert, 1968) it is reasonable to suggest that solar proton events should correlate well with hard X-ray (HXR) events. If electrons and ions are accelerated nearly simultaneously (Forrest & Chupp 1983, Ackermann *et al.* 2012) then fluences of HXR and γ–rays should correlate. However from the statistical analysis of the 2.223 MeV line fluence and the fluence > 50 keV it follows that such a correlation exists only when a threshold in the production of ions is reached (Shih *et al.* 2009). A similar relationship had been discussed at the time of SMM by Cliver *et al.* (1994). This ultimately suggests that while the acceleration of protons above 30 MeV is closely related to the acceleration of relativistic electrons, the acceleration of subrelativistic electrons is only proportional to the acceleration of relativistic electrons and ions when a given threshold of high energy particles is reached Vilmer *et al.* (2011). Possibly, there are two acceleration processes, one producing proportional quantities of relativistic electrons and ions, the other one producing mostly subrelativistic electrons (Frost & Dennis 1971).

The SMM data suggest that progressive hardening (soft-hard-harder, SHH, the Kiplinger effect) of HXR spectrum is a diagnostic of high-energy electron and proton acceleration (Kiplinger, 1995). This is not a manifestation of the big flare syndrome (Kahler, 1982). Grayson *et al.* (2009) checked the Kiplinger effect using RHESSI and demonstrated a statistically significant dependence of SHH and SEP observations. This a link that is unexplained in the standard scenario of SEP acceleration at the CME shock front and encourages further investigation of the mechanisms which could be responsible (Grayson *et al.* 2009). A critical view on the Kiplinger effect is presented by Kahler (2012).

A hardening of γ–spectrum is visible in individual events and it should be the characteristic of solar proton events. Ramaty *et al.* (1987) presented evidence of two stages of pion production on June 3, 1982. In the first stage pions were produced by particles with relatively soft spectrum and later in the second stage by particles with much harder spectrum. Kiener *et al.* (2006) analyzing INTEGRAL data on gamma-emission of the 2003 October 28 flare distinguished three phases: A – only continuum emission, B – nuclear gamma-lines, C – decay. According to Coronas–F observations (Kuznetsov *et al.* 2011) the pion production occurred in the B and C phases. Pion decay emission was observed by Coronas–F also in the flares of November 4, 2003 and January 20, 2005 (Kurt *et al.* 2010). If electrons and protons are accelerated by the same processes, then a temporal structure of γ–emission on time scale of several seconds should exist within each phase corresponding to a fine spatial structure of coronal loops (Zimovets *et al.* 2013). A zero time for the solar flare on December 6, 2006, which had showed clearly preflare, impulsive and decay phases, was defined by Struminsky & Zimovets (2010) as the beginning of 15.4 GHz microwave emission. Struminsky (2013b) deduced a zero time for the pion flares superimposing their temperature time profiles with that of the event on December 6, 2006. It appeared that a visible pion production in all events started 4-5 minutes after the zero time. These 4-5 minutes is a characteristic time for acceleration of relativistic protons (spectrum hardening). The acceleration mechanism responsible for this spectra hardening is still unknown.

Gamma line and pion decay emission are observed on a time scale of several hours during some solar flares. High energy solar protons, which produced this emission, might be accelerated during the impulsive phase and subsequently trapped, or they might be accelerated continuously during entire flare. Mandzhavidze & Ramaty (1992) showed that a model in which the particles were accelerated during the impulsive phase and subsequently trapped in coronal loops could explain the emission detected at the late phase of the flare on June 1, 1991. According to Kocharov *et al.* (1994) a continuous and simultaneous acceleration of protons and relativistic electrons at the gradual phase of the flare on June 15, 1991 gives a natural explanation of the data. Akimov *et al.* (1996) provided additional evidence that the gamma-ray and other emissions observed well after the impulsive phase of the flare on June 15, 1991 was initiated by the prolonged non–stationary particle acceleration rather than prolonged trapping. The observations of burst-on-tail (BOT) of the flare on October 23, 2003 presented by Zimovets & Struminsky (2012) showed distinctly that episodes of electron acceleration may occur well after CME lift–off. It is unknown whether protons have been accelerated during the BOT.

The brightest and longest solar high energy γ–flare to date was detected by the Fermi LAT on March 7, 2012. Ajello *et al.* (2014) showed that the fluxes and spectra of the high-energy γ–rays evolve differently during the impulsive phase and the sustained emission. Also they noticed correlations and some differences between the fluxes and spectral indexes of the protons required for the production of high-energy γ–rays and SEP protons seen at 1 AU. From these results Ajello *et al.* (2014) suggested that the high-energy γ–rays are most likely produced by protons (rather than electrons) accelerated in the corona (rather than in the associated CME shock) continuously during the entire flare.

Spatial observations of solar γ–ray are controversial. Comparisons of imaged and spatially integrated fluences (events on October 28, 29 and November 2, 2003) show that in all cases most, if not all, of the emission was confined to compact sources with size scales of tens of arcseconds or smaller that are located within the flare active region (Hurford *et al.* 2006). Thus, the ions producing γ–rays appear to be accelerated by the flare process and not by a widespread shock driven by a fast coronal mass ejection. The 28 October event yielded the first such image to show double–footpoint γ-ray line sources. These footpoint sources straddled the flaring loop arcade but were displaced from the corresponding 0.2–0.3 MeV electron-bremsstrahlung emission footpoints. As with the previously studied event on July 23, 2002 (Hurford *et al.* 2003), this implies spatial differences in acceleration and/or propagation between the flare-accelerated ions and electrons. An erupting flux rope can act as a trigger of energy release in two–ribbon flares. Its successive interaction with different loops of a parent active region can lead to apparent motion of HXR sources and to a series of HXR pulsations (Kuznetsov *et al.* 2016). Similar motion and pulsations can be observed for γ–ray sources in a case of flare acceleration.

Ackermann *et al.* (2014) and Ajello *et al.* (2014) showed that during most of the long-duration emission the high energy γ–rays appear to come from the same active regions responsible for the flare emission. Observations of γ-emission during flares behind the limb (occulted) show that a γ-source can be larger than an active region. Cliver *et al.* (1993) sugested that protons produced the γ–emission on the visible disk during the flare behind the limb on September 29, 1989 were accelerated by CME–driven shock wave. Ramaty *et al.* (1997) provided evidence for γ–ray production in the corona during the giant flare behind the east limb on June 1, 1991. Ackermann *et al.* (2017) presented Fermi GRO/LAT spatially resolved observations of four flares behind the limb. They believed that the HXR emission was due to electron bremsstrahlung from a coronal thin-target loop-top, but the > 100 MeV γ–rays to a pion production in the photoshere by the CME–accelerated protons precipitating downward.

3. Discussion and conclusions

Nuclear line and pion decay γ-rays are emitted on a time scale from several minutes up to several hours during some solar flares but their statistics are very poor. Accelerated protons (> 30 MeV, > 144 MeV) interact in the photosphere and the corona, and might be be injected into the interplanetary space, but spatial properties of the injection function is unclear from γ-ray observations. Consequently we still do not know what is accelerating mechanism of solar cosmic rays, what is a source of interplanetary (propagating) solar protons. In my opinion only future observations of solar high energy γ–emission with better spectral, spatial and temporal resolution will answer these questions. We need special telescopes for continuous observations of solar hard X-ray and γ–emissions with better sensitivity, energetic, temporal and spatial resolution aboard spacecraft in deep space, at the Lagrangian points, or in eccentric orbits with high apogees.

In a case of protons accelerated in flares we expect to observe γ–emission (lines, pion decay) multiple photospheric footpoint sources (target density $\sim 10^{17}$cm^3) and weak coronal sources (target density $\sim 10^9 - 10^{12}$ cm^3) with spatial scale up to active region size (L $\sim$ 10 degree=0.17R), its correlation with HXR and microwave emission, and fine temporal structure ($\sim$ 1 min, $\sim$ 10 sec). In a case of shok–accelerated protons that would be decreasing γ–emission from unstable photospheric footpoints (target density $\sim 10^{17}$cm^3), weak moving and extending coronal source (target density $< 10^9$ cm^3) $VT = 2500kms^{-1} \times 600s = L \sim 2.1R = 120°$), without fine temporal structure and not correlating with HXR and microwave emissions.

Lin *et al.* (2010) presented a concept of the Solar Eruptive Event (SEE) 2020 mission, which was unfortunately not supported. Comparing the spectral, spatial, and temporal behavior of ions and electrons requires X-ray and γ–ray imaging spectroscopy from < 10 keV to > 15MeV. For future progress we need high–resolution γ–ray imaging with a factor of > 10 increase in sensitivity and < 10 arcsec resolution compared to RHESSIs 35 arcsec resolution. A step in this direction is a development of the Gamma Ray Imager/Polarimeter for Solar flares (GRIPS). This instrument incorporates key technological improvements over the current state of the art at HXR/γ–ray energies. Dunkan *et al.* (2016) described GRIPS's first Antarctic long-duration fight in January 2016, and presented preliminary calibration and scientific results.

Last results in the high energy γ rays (> 100 MeV) were obtained by the Fermi GRO/LAT, but its sensitivity and spatial resolution are not enough to distinguish between interacting flare–accelerated ions that are localized to the flare loops and those ions accelerated by the CME shock that precipitate to form a larger diffuse source. Chupp *et al.* (1998) and Chupp *et al.* (2003) proposed two techniques which may locate the emission regions of high-energy neutral emissions to arcminute or better spatial accuracy and also determine their energy spectra. I do not know any development in this direction from that time.

Solar Probe Plus and Solar Orbiter may give a key for the problen of solar cosmic ray origin. Both spacecrafts are designed for measurements close to the Sun, where interplanetary scattering and transport effects are significantly reduced, allowing to discriminate between different acceleration sites and mechanisms and to isolate the contributions of numerous physical processes (Desai & Giacalone 2016).

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