CORONAS-F satellite data on the delay between the proton acceleration on the Sun and their detection at 1 AU.

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Abstract: Instants of proton acceleration to sub-relativistic energies during solar flares of 28 October 2003 and 20 January 2005 were determined on the basis of the experimental data on solar flare gamma-rays obtained by the SONG instrument onboard the CORONAS-F satellite. The high-energy protons accelerated in the Sun are identified by detection of gamma-rays with the spectral shape having an excess near 70-100 MeV energies. A comparison of the time of proton acceleration and onset time of the proton enhancement near the Earth allowed us to conclude that these protons escaped from the solar corona immediately after their acceleration.

Introduction

Observations of gamma-ray emission with photon energies 0.03-3000 MeV are the most informative tool for particle acceleration study hence these observations provide information about primary energy release itself. This emission resulting from the interaction of high-energy particles with solar atmosphere matter, escapes from high-density regions with insignificant distortions, giving us information on parameters of processes in the acceleration region. High-energy electrons generate bremsstrahlung in a wide energy range up to the energy of electrons themselves. Electrons lose energy so rapidly that the bremsstrahlung emission behavior reflects temporal and energy parameters of the acceleration process. The shape of bremsstrahlung energy spectrum is directly related to the electron spectrum.

An indicator of proton acceleration to energies above 300 MeV is gamma–ray emission with a characteristic spectrum having a broad excess near 70-100 MeV generated as a result of neutral pion decay [1]. These neutral pions are produced in the interaction of energetic protons and ions in the dense solar atmosphere. Characteristic times of corresponding reactions are negligible therefore the gamma emission time profile coincides with the time profile of high-energy proton production. Simultaneously, the same protons produce high-energy neutrons which can escape the Sun and only small amount of these neutrons reaches the Earth orbit because the half-life time of the free neutrons is 10^3 s. Neutrons are the second source carrying out the information of the proton production in solar atmosphere.

Some part of high-energy protons may escape the Sun and being measured onboard Spacecraft or as GLE represents the third source of experimental data on proton acceleration up to high energies. However to make the conclusion that high-energy protons responsible for the GLE were accelerated in the flare volume we ought to make the comparisons of the onset time and time profiles of GLE with the temporal characteristics of the neutral pion decay emission [2-5] which reveals appearance of protons with energies > 300 MeV on the Sun. In this paper we bring forward an argument in favor that GLE particles have been accelerated during the impulsive phase of flare rather than by the shock wave connected with CME propagating through the solar corona.

Measurements of high-energy gamma rays and neutron fluxes by the CORONAS-F satellite

The SONG (SOlar Neutrons and Gamma rays) instrument [6] detected gamma rays with energy 0.04 - 200 MeV in several powerful solar flares during the operating time of CORONAS-F. Besides SONG detected neutron fluxes escaped from the Sun in three flares (25 August 2001, 28 October 2003 and 4 November 2003) [3] Thus, direct proofs of generation of energetic protons and electrons in solar corona were obtained during CORONAS mission.

We have studied in detail time behavior of the emission and evolution of the gamma ray spectrum with high time resolution (1-4 s) to define time of acceleration of those or other particles. It is possible to allocate three “episodes” of particles acceleration during development of the powerful flare: the first episode (duration ~1-2 min) coincides with the first impulsive energy release. It represents mainly electron bremsstrahlung in the energy range from 30 keV to 20-60 MeV. In the flare of 28 October 2003 the upper energies of accelerated electrons is estimated as ~ 60 MeV and in the flare of 20 January 2005 as 15-20 MeV. Acceleration of protons during this episode if it exists then their number is not great.

Then the second gamma-ray burst (acceleration episode having duration 2-3 min) is recorded, during that time a broad maximum caused by the decay of neutral pion decay arises in the emission spectrum. This spectrum shape with the maximum in the energy range of 60-100 MeV unambiguously suggests that 300-500 MeV protons appeared in the solar atmosphere. The third “episode” is a rather slow decrease of pion decay emission and bremsstrahlung emissions with a hint on some additional acceleration pulses.

The long duration of the pion decay emission testifies an existence of accelerated protons in the dense solar atmosphere. This fact was also observed previously [7-9]. Alternative hypotheses (i.e. prolonged proton acceleration by moving outward shock wave connected with CME) would be faced with difficulties to explain this observed effect.

On the other hand the observation of a broad 70-100 MeV line in the spectrum, associated with neutral pion allows us to define an exact time of energetic protons appearance in the solar atmosphere. This in turns makes it possible to compare proton acceleration time with the start time of the GLE recorded by neutron monitors network (NMs), and to calculate the time interval when GLEs particle escaped from the corona.

Let us to illustrate considered above results by the example of the flare of 20 January 2005. The gamma rays burst was measured from 06:43:44 UT at a very low background level during the satellite passage through the equator. Note that this time is very close to the time of the main energy release onset.

Figure 1 shows the temporal behavior of gamma rays recorded by two energy channels of the SONG instrument with 1 s time resolution (the background was subtracted) and presents the “episodes” described above. In the first episode, there is a small statistically significant flux of emission with energies 60-150 MeV. Then at 06:45:37 UT the intensity of high-energy emission begins to increase sharply and reaches its maximum at 06:47:00 UT. At 06:54:00 UT the SONG has started to detect high-energy protons. The CORONAS orbital location in this moment corresponds to vertical rigidity cutoff equal to 7-8 GV. Then a separation of gamma events from the total detector counting rate ceases to be unambiguous.

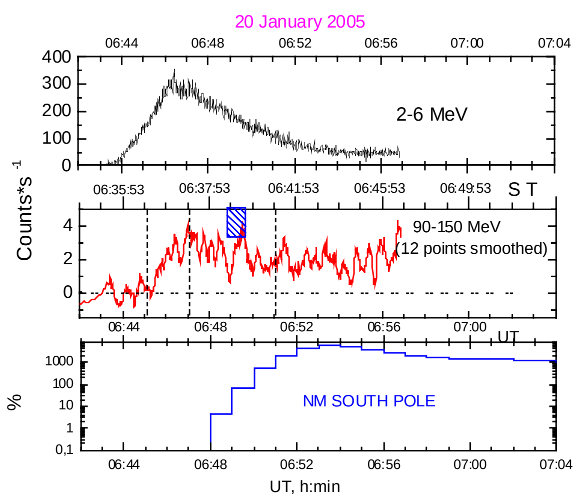

Figure1: Gamma emission time profiles observed by the SONG (upper panels) and GLE measured by South Pole NM (lower panel). The time scale between the first and second panels represents solar time of the event.

The gamma-emission spectra were restored from the count rate spectra using the SONG response function. The incident compounded spectrum consists of the bremsstrahlung with the slope γ=2.4 and of the pion decay spectrum created by protons with γ=3. The pion decay spectrum was calculated by R.Murphy (private communication). Figure 2 shows three spectra, each is accumulated in time interval equal 1 minute. The middle times of these intervals are specified by dashed lines in the middle panel of Figure 1. The statistically significant plateaus near 100 MeV are seen in all spectra however the photon fluxes in this energy range are noticeably smaller at the first spectrum than in the second and third one.

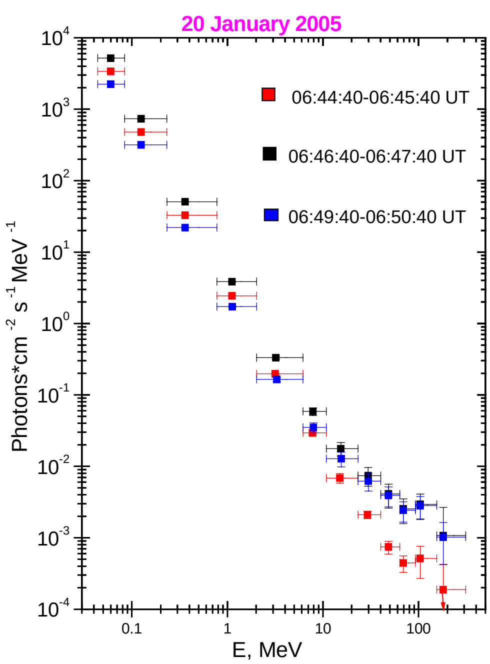

Figure2: The photon spectra measured by SONG.

Gamma-Ray Burst and Ground Level Enhancement

The earliest onset and the largest effect of the 20 January 2005 GLE were recorded with the South Pole NM (Figure 1). The first protons came to the Earth at 06:48:30 UT±30 s, unusually rapidly contrast to most of GLEs. To understand an origin of high-energy protons responsible for the GLE, we compare the onset time at the South Pole with temporal characteristics of the neutral pion decay emission which revealed us the appearance of 300÷500 MeV protons on the Sun.

We start with the assumption, that protons have been accelerated or on the Sun during the flare itself or near to the Sun, instead of in interplanetary space. To estimate the *latest possible escape time* from/near the Sun, firstly we consider proton straight-line (radial) propagation between the Sun and the Earth neglecting any delays caused both by the curvatures of their trajectory and by scattering. On 20 January the Sun-Earth distance was R_{SE} =0.984 AU, which defines the Sun-Earth light propagation time Δt=489 s and hence defines the solar time scale as ST =UT-489 s.

Plainaki et al. [10] defined that the effective energy of protons at the GLE onset was about 7 GeV, that corresponds to their velocity of v = 0.993c and their straight-line propagation time of 492 s. Hence, the protons responsible for the GLE onset *had to escaped Sun not later than at 06:40:18 ST±30 s.* If the energy of first particles recorded by the South Pole NM was much less, for example ~1 GeV (v = 875c, propagation time 559 s), then they had to escape the Sun not later than 06:39:11±30 s ST. Thus, with all uncertainties, *the latest escape time* of the first GLE particles lies in the range between 06:39:11±30 s ST for 1 GeV and 06:40:18±30 s ST for 7 GeV (a blue line-filled box in the middle panel of Figure 1). This time interval is the physical limit of the escape time of the first GLE particles into interplanetary space. Real length of charged particle path with necessity should be more than the Sun-Earth distance due to curvature of magnetic field lines, drift motions, non-zero particle pitch angles relative to the guiding magnetic field line.

Therefore, to arrive at Earth at 06:48:30 UT±30 s, the first protons had to leave the Sun still earlier than we estimated. If the first 7 GeV GLE protons were accelerated and promptly escaped during the first neutral pion decay emission sub-burst (06:35:31 ST) even though they have escaped at the same time that the main burst occurred (06:37:21 ST), then their real Sun-Earth path has to be equal to 1.65-1.30 R_{SE} .

Both our time rule and the reasonable value of proton total path are in favor of common nature of protons responsible for the high-energy flare gamma-rays and GLE. In addition note that the time profiles of the neutral pion decay emission and the GLE at the South Pole show that propagation effects broadened the GLE, but did not significantly change its shape with respect to the gamma-ray burst. This result reliably demonstrates that energetic protons detected at the Earth escaped the Sun immediately after their acceleration in the lower solar corona. Moreover, this result suggests that protons responsible for the very anisotropic part of GLE, recorded by South Pole NM had no time for prolonged acceleration delayed with respect to acceleration near the Sun. A comprehensive analysis of the 20 January data in the different wavelength combined with the imaginary of the flare is presented in [11].

The time of GLE detection by the NM network in event 28 October 2003 also confirms the absence of the delay between acceleration of protons and their escaping the Sun. Having lead comparison just as it has been made for 20 January 2005 event, we found that energetic protons appeared at the Sun at 10:55:45 ST with an intensity maximum at 10:57:15 ST exactly near the time of neutral pion-decay emission detection by SONG [5].

The neutron detection technique used in the SONG instrument does not allow unambiguous determination of the detected neutron energy. Based on the difference between the time of energetic proton appearance in the corona determined by observing gamma rays with pion decay spectra, and the time of detection of such neutrons themselves by the CORONAS-F satellite, we estimated the velocities, hence, energies of measured neutrons as 100-400 MeV [3].

Conclusions

Above estimations for 20 January 2005 and all other combined measurements provided by SONG, namely high-energy gamma-ray emission, neutrons, high-energy protons and their comparison with GLEs, demonstrate that high-energy particles responsible both for the gamma-rays/neutrons and for the GLE onset belonged to the same population created by an acceleration process in the fare region.

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