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PROTON ACCELERATION IN THE SOLAR FLARE

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Abstract. 100 years of research of high-energy particles coming from distant regions of space have not led to an understanding of the physics of acceleration of these particles. The most popular acceleration mechanisms are associated with shock waves. However, the possible acceleration mechanisms of cosmic rays in the shock waves are only hypotheses. Naturally, the discovery of sources of protons with energies up to 20 GeV, generated by the Sun, gives us hope for the opportunity to clarify the mechanism of the cosmic rays generation. The imported data about solar cosmic rays now obtained in PGI from the worldwide network of neutron monitors. The new information about the mechanism of proton acceleration in the Sun has been obtained by comparing the data of neutron monitors with the results of measurements on the *GOES* devices. Some analysis of *GOES* measurements have been reported by the authors in the Apatity seminar in 2015. The association of a proton event with a particular flare is beyond doubt. Measurements on *GOES* devices indicate propagation of high-energy protons from the flares on the western part of the solar disk without collisions. These protons move along helical magnetic field lines. Another part of the protons comes to the Earth's magnetosphere with the solar wind velocity. The protons from flares on the back side of the Sun can also come to the Earth's magnetosphere. The front of proton flux from eastern flares comes to Earth with a delay of several hours. The series of 2-3 weeks long proton events consisting of several large proton events are observed two - three times in the 11 year cycle of solar activity. Nature of the trigger for series of proton events is not clear.

Introduction. Explosive release of energy occurs in the solar corona above the active region at a solar flare. Just a few tens of minutes, the energy stored in the magnetic field of the current sheet [1-3] heats plasma with the density of ~ 10^{11} cm^{-3} up to the temperature 3-5 keV. The main manifestations of the flare: pulses of thermal and beam ($h\nu$>100 keV) X-ray, coronal mass ejections, causing a shock wave, visible, ultraviolet, and microwave radiation at different frequencies, pulses of relativistic protons (solar cosmic rays), etc. Some of these events are manifested in some flares, but the other phenomena may be absent. Here we consider the generation of pulses of cosmic rays with energies up to 20 GeV. Solar energetic proton measurements provide information which is not available in the study of cosmic rays coming from distant regions of space. The shock waves are the most popular mechanisms of cosmic ray acceleration. Proton acceleration in shock waves is also considered by many authors as a mechanism of the solar cosmic rays generation [4-7]. The shock wave is formed by a supersonic coronal mass ejection. However, any data on particle acceleration in a shock wave are based on some arbitrary assumptions. The acceleration of protons at reflection from magnetic inhomogeneities in the solar wind is also considered [8]. Measurements made on the world network of neutron monitors [9-11] showed that the front pulse of relativistic protons of the flares that have occurred in the western part of the solar disk (so-called "prompt" component) begins to register through time Δt ~15 min after the pulse of thermal X-ray emission of the flare onset. This delay is determined by the time of flight of the particles along the lines of the interplanetary magnetic field Archimedes spiral.

Not all of the protons accelerated during a flare enter the interplanetary space. Some of them hit the surface of the Sun, causing a nuclear reaction with gamma-radiation release. Since, as a rule, the duration of gamma-radiation caused by nuclear reactions in the Sun, is no more than ten minutes, it can be argued that the duration of generation of relativistic particles are also not more than ten minutes. However, neutron monitors on the Earth show the relativistic proton flow during the several days. Such delayed protons can not belong to the direct stream from the flare. They come to Earth from the flare as a result of transfer by the solar wind or diffusion. The main result considered in [9-11] is the fundamental difference spectrum of fast and delayed proton flux components. The fast component enters the Earth's orbit only from the flare occurring in the western part of the solar disk.

The prompt component consists of particles passing in small pitch angles along the lines of the interplanetary magnetic field without collision. It has the exponential spectrum ~exp ($-W/W_0$). Apparently, it is a spectrum of particles emitted from the source. After 15-20 minutes the velocity distribution recorded on the Earth's orbit becomes isotropic, and the spectrum becomes of a power type $W^{-\gamma}$. This delayed proton flux can last several days, and its distribution becomes a diffusive. The values of W_0 are not much different for the different events are observed in the range 0.5-1 GeV, γ is within 4-6. Numerical simulations have shown [20] that introduction of the magnetic turbulence leads to scattering of protons, and anisotropic velocity distribution at a later stage becomes isotropic.

The conditions for the relativistic particles generation of solar cosmic rays are existed in the current sheet in the singular magnetic field line vicinity [2, 3]. In a particular case it is a line of zero magnetic field. The electric field - $\mathbf{V}\times\mathbf{B}$ / c in the current sheet occurs at the plasma inflow in the current sheet and reconnection of magnetic field lines. Here, **V** –is the velocity of plasma inflow into the sheet, that is the reconnection velocity, B is the magnetic field of the current sheet. The particles (ions and electrons) are accelerated along the singular X-type line. When the particle is deviated from X-line, it enters into the drift region and the acceleration is ceased. The efficiency of particle acceleration by the electric field E = -V×B/c, directed along a singular line of the magnetic field is known from results of laboratory experiments with a powerful pulsed discharge [12, 13], which were carried out in association with the problem of controlled thermonuclear fusion.

To determine the spectrum of particles accelerated in the flare current sheet, the method of test particles [10] is used. The current sheet magnetic fields configuration is calculated in the three-dimensional MHD numerical simulation for Bastille flare (14.07.2000) [14]. It is shown that accelerated protons do have an exponential spectrum which at the magnetic reconnection velocity 2×10^7 cm/c coincides with the spectrum measured by a network of neutron monitors at the front of the proton flux of the western flare. Thus, the prompt component of particles accelerated in the flare current sheet comes to the Earth orbit in the first 10-20 minutes. It travels during time of flight without collisions. They can propagate free only along the magnetic lines of the spiral of Archimedes. Such magnetic field lines must to connect flare with the proton registrar located on the Earth's orbit.

The time of protons arrival to the Earth increases, apparently, due to the beam instability [15]. The scattering by inhomogeneities leads to diffusion propagation along and across magnetic field lines. Independent and additional information about the flux of accelerated protons coming to the Earth can be obtained from measurements on the *GOES* spacecrafts located at geocentric orbit and recording streams protons in wide angle in three energy ranges (W≥ 10 MeV, W ≥ 50 MeV, and W ≥ 100 MeV) [16–19, 21].

Powerful complexes of proton events. The *GOES* measurements demonstrate powerful complexes of proton events caused by several proton flares, following each other at intervals of about a day. The powerful complex of proton events can be created by one active region or by several regions. During the 11 years of the solar activity period not more than two - three complexes of proton events are observed. Typical development of strong proton events that occurred over the active region AR10720 is shown in Fig. 1. Weak active region appeared at the eastern limb. Fluxes of protons were completely absent, and X-ray pulses were small. They are not exceeded the class B.

At Sun rotation the northern and southern magnetic fluxes are started to increase, the active region intensifies, and the magnetic field configuration becomes more complicated. The source of the magnetic field of the north direction is shown by white and the black shows the south direction. January 15 2005 the several X1 flares appear and one of them is followed by a proton event. Later, when the active region is passed on the western part of the solar disk, the large (X-type) flares arise. Some of them are accompanied by proton events. However, a large number of flares are produced by AR10720, and the superposition of several proton events does not allow comparing the proton events clearly with specific flares. For such comparison we used a single flare that occurred in the western of eastern parts of the solar disk.

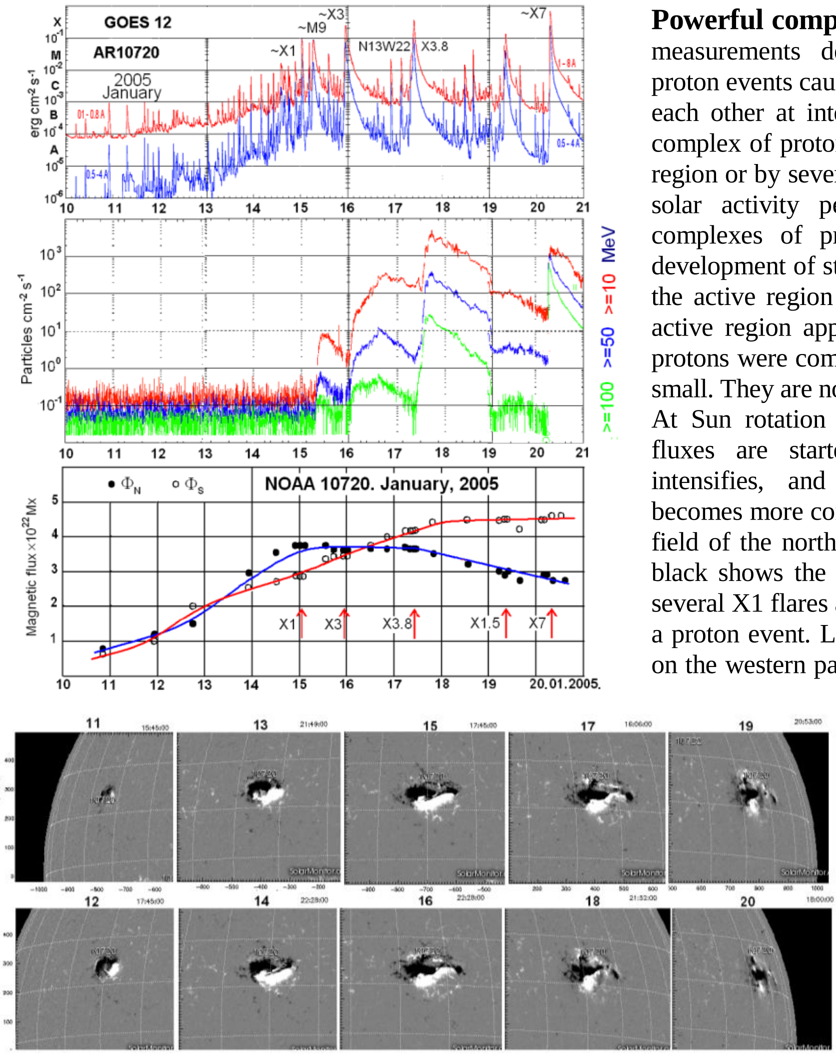

Figure 1. At the top - the solar flares caused by the region AR10720; lower - proton fluxes, registered by the *GOES* device; the north and south magnetic fluxes; magnetograms.

Proton events from western and eastern flares. Fig. 2 shows the typical single proton events accompanied by the flares appeared in the western (above) and eastern (below) part of solar disk. During the eleven-year cycle of solar activity 10-15 proton events can be observed. Each proton event is appeared after a flare (usually class X or class M). However, not all large flares produce pulses of solar cosmic rays. Only about 30% of large flares are followed by the registration of solar cosmic rays pulses. One of the main characteristics of solar cosmic rays is a significant difference in the duration of the proton fluxes ejection from the flare current sheet and duration of proton flux registration by the *GOES* devices on the Earth's orbit. The proton emission from the coronal source produces the gamma-ray radiation, caused by nuclear reactions in the Sun. The proton emission duration can be estimated from the duration of gamma-ray pulses. The gamma-ray radiation lasts about 10 minutes (Fig. 3) [22], which does not exceed the duration of the flare pulses determined from the thermal X-ray. At the same time the duration of the pulse of high energy protons detected on Earth orbit is in the ranges from one to several days [16–19, 21]. The typical pulse duration is about three days.

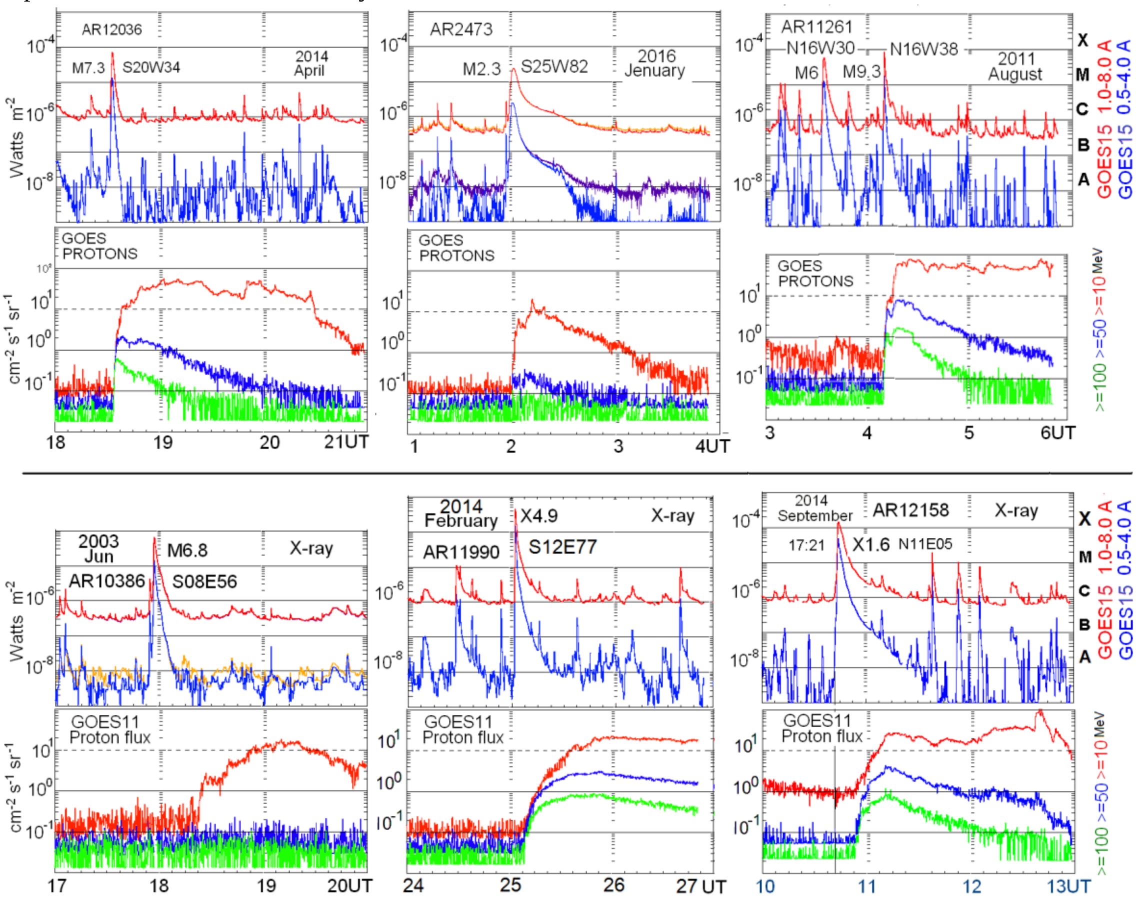

Figure 2. The flare X-ray and proton emission from *GOES* measurements. Proton flux is measured in three energy ranges (W> 10,> 50 and> 100 MeV) from the flares appeared in West side of the solar disk (above) and in the East side (below).

As it follows from Fig. 2, the proton pulse fronts from the western and eastern flares exhibit significantly different patterns. Proton flux from western flares has a steep front with duration not exceeding 20-30 min. The particle registration begins at 10-20 min after the start in the western solar flare. Low delay of western flare can be determined only by the flight of time without collisions to Earth at protons moving along magnetic field lines of the Archimedean spiral. For the whole energy range recorded by the *GOES*, the proton moving takes place with the small Larmor radius. Low plasma concentration in the solar wind provides collision-free flow of protons in the energy range that registered by the *GOES*. The Coulomb cross section is $\sigma \sim 5\times10^{-13}/W[eV]^2$. Collisionless proton flight does not distort the particle spectrum. The exponential spectrum registered by neutron monitors at the front of proton flux (fast component) from the western flare coincides with the spectrum calculated for proton acceleration along a singular magnetic field lines in the current sheet [9, 10].

Protons from the western flares, moving without collisions along the magnetic field lines, should to leave quickly the interplanetary space and go beyond Earth orbit, but they *GOES* apparatus registration lasts for several days. Collisionless propagation takes place only in the flux front during 20-30 minutes. Protons of the western flares move in the interplanetary plasma according to the laws of particle of motion in vacuum only at initial time (prompt component on the front of proton flux). However, after a short period of time, it seems to begin to play the role of plasma processes that develops beam instability [15], and scattering of protons in turbulent plasma causes the proton diffusion in the plasma.

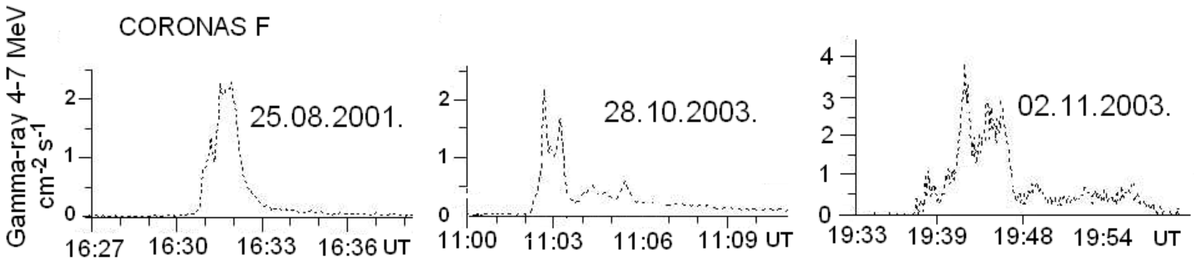

Figure 3. The flares gamma-ray according CORONAS F data.

The proton flux from the flare that occurred on the eastern part of solar disk (Fig. 2 below), can not reach the *GOES* spacecraft, moving along the magnetic field lines. At the propagation without collisions, the protons in the interplanetary medium must drift across the magnetic field with the solar wind velocity. Consequently, the particle drift lead to delay the arrival of the protons front to Earth AU/Vsw 3-4 days. In reality (Fig. 2) the delay of protons front from the eastern flares relative to the solar flare is about 3-5 hours. This rapid transfer of protons across the magnetic field may be associated with turbulent diffusion across the magnetic field. Proton flux from the eastern flares, unlike the flux of western flares arises slowly as it should be because of diffusion. Its typical front duration is about a day.

The particle flux directed along the magnetic field line and across the lines is recorded for several days after the end of the flare. That is the flux with the velocity directed along the magnetic field, which decreases by several orders of magnitude, but the diffusion flux velocity of the protons across the magnetic field increases. This behavior is characteristic for protons including the relativistic proton. The measurements on neutron monitors have shown [9-11] that the so-called prompt component of relativistic protons has a strong anisotropy (magnetic field proton velocity vector is parallel to the lines of the spiral of Archimedes), but the delayed component with an isotropic velocity distribution begins to register in 20-30 minutes. Such a scenario should take place, if the front of the beam of accelerated protons caused the development of plasma turbulence, and then the following particles are scattered in this turbulence. The proton flux becomes isotropic, and its propagation velocity along the field lines decreases.

Currently we do not have sufficient information about the development of turbulent processes in the solar wind. Our working hypothesis can be stated as follows. Streams of protons from the flare that occurred on the eastern limb (Fig, 2 below), can not reach the device located at the *GOES* Earth, moving along the magnetic field lines. At the propagation without collisions, the protons in the interplanetary medium, where the Larmor radius is much smaller then AU, must drift across the magnetic field with the solar wind velocity. The narrow beam of proton front of a western flare moves to the Earth with the particle velocity. The beam caused the development of turbulence, and particle scattering with magnetic fluctuations dramatically increased. The transfer of particles along the field becomes diffusion and its velocity decreases, but the diffusion across the field increases. The velocity of propagation across the field on the long flux front of the eastern flares also rises. As a result, the front of proton fluxes from the eastern flares can move across the magnetic field lines faster then the solar wind. Formulated scheme is in good agreement with measured data, but the detailed investigation of the dynamics of solar cosmic rays requires careful observation and theoretical analysis.

The difference of forms of the proton pulses that arrived from the western limb and from the disc center flares can be clearly seen in Fig. 4. This is a rare case when the two proton events occurred with an interval of two days in different active regions of the Sun. At right side of the figure the fronts of arrival of protons and X-ray pulses are presented in an extended time-scale. The event 06/01/2014 7:30 is appeared just after a start of very weak X-ray flare pulse C2.1. Such weak flares occurring on the visible disc of the Sun never generate large streams of protons. The C2.1 06/01/2014 flare according to the RHESSI data belongs to the active region AO11936. It is located on the limb (S15W89). Apparently, X-rays are generated mainly on the back side of the sun. The recorded X-rays might arrive along the Sun surface. Most of X-ray could be screened by the chromosphere. Apparently, the flare C2.1 intensity is greatly underestimated. Protons from this western flare have begun to register in ~ 20 min after the start of the flare. The proton flux of the C2.1 flare demonstrates a steep front, typical for the large proton pulses of western flares. Fast collision-free flux of protons from C2.1 flare could come to Earth from the back side of the Sun along the magnetic lines of the Archimedes spiral.

The flare X1.2 is produced by S12W08 active region near the Sun center little bit shifted to the West. The accelerated protons from this flare appear with 1.5 hours delay and possesses front about 10 hours. The front is not as long as for the proton fluxes generated by flares that appeared in the far West.

The same character of diffuse flux of delayed protons from the western and eastern flares in the interplanetary space and the different forms of the proton flux fronts of western and eastern flares are particularly well illustrated by the single flares accompaniment by very long proton fluxes (Fig. 5). No distinctions are observed in the decaying parts of proton pulses that generated by the western and eastern flares. There is no reason to suppose that the mechanism of propagation of protons in the interplanetary medium of the decaying part of the proton pulses is different for the western and eastern flares. The decay of over several days of the proton flux corresponds to the propagation time longer then of the time of solar wind moving from the Sun to the Earth. This means that diffusion along and across the magnetic field lines plays the main role in decaying parts of the proton flux.

Turbulent diffusion should promote protons moving across the magnetic field lines. However, the proton flux from the eastern flares does not always achieve *GOES* apparatus. It is not always occurs quite effective the strong turbulence development. The flux of protons from the eastern flares is recorded much less frequently than from the western flares.

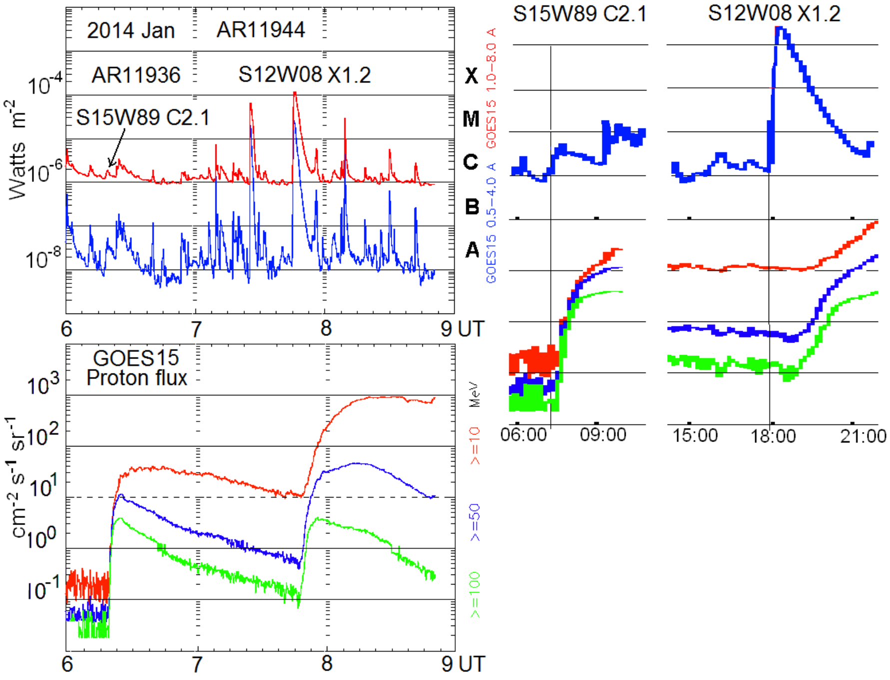

Figure 4. Proton pulses with very steep front arrived from western limb flare and from the flare appeared near Sun center flare. The proton flux from the central AR S12W08 flare increases not so fast.

Conclusion

The scheme of the main sequence of effects of proton events is shown in Fig. 6.

1. The typical duration of accelerated protons gene-ration (ten minutes) determined from the gamma ray pulses does not exceed the flare duration.
2. The time of arrival of the front of proton flux from the western flare (about fifteen minutes) is determined by the velocity of the accelerated particles and the magnetic field lines length, connecting the flare and the registrar in the Earth orbit.
3. Collisionless flux of protons along the helical magnetic field lines carries information about the spectrum of flare protons, which, according to neutron monitors is exponential one.
4. Collisionless flux should cause a beam instability, the flux becomes diffuse due to scattering by the fluctuations. The propagation speed of the protons along the magnetic field lines is reduced.
5. The typical duration of the accelerated proton flux on the Earth's orbit is equal to the propagation time of the solar wind from the solar corona $t_{SW} = 1AU/V_{SW} \sim 3$ days. Most retarded protons are captured by the magnetic field of the solar wind. They drift across the Earth magnetic field with the solar wind velocity.
6. The front of the proton flux from the eastern flares is never steep. The arrival of a gentle (one day long) front of associated protons flow from the eastern flare to the Earth's orbit through 3 - 5 hours is faster then the solar wind. This can be related to the diffusion of protons across the field lines due to the scattering by the fluctuations. The fluctuations can be generated due to beam instability.

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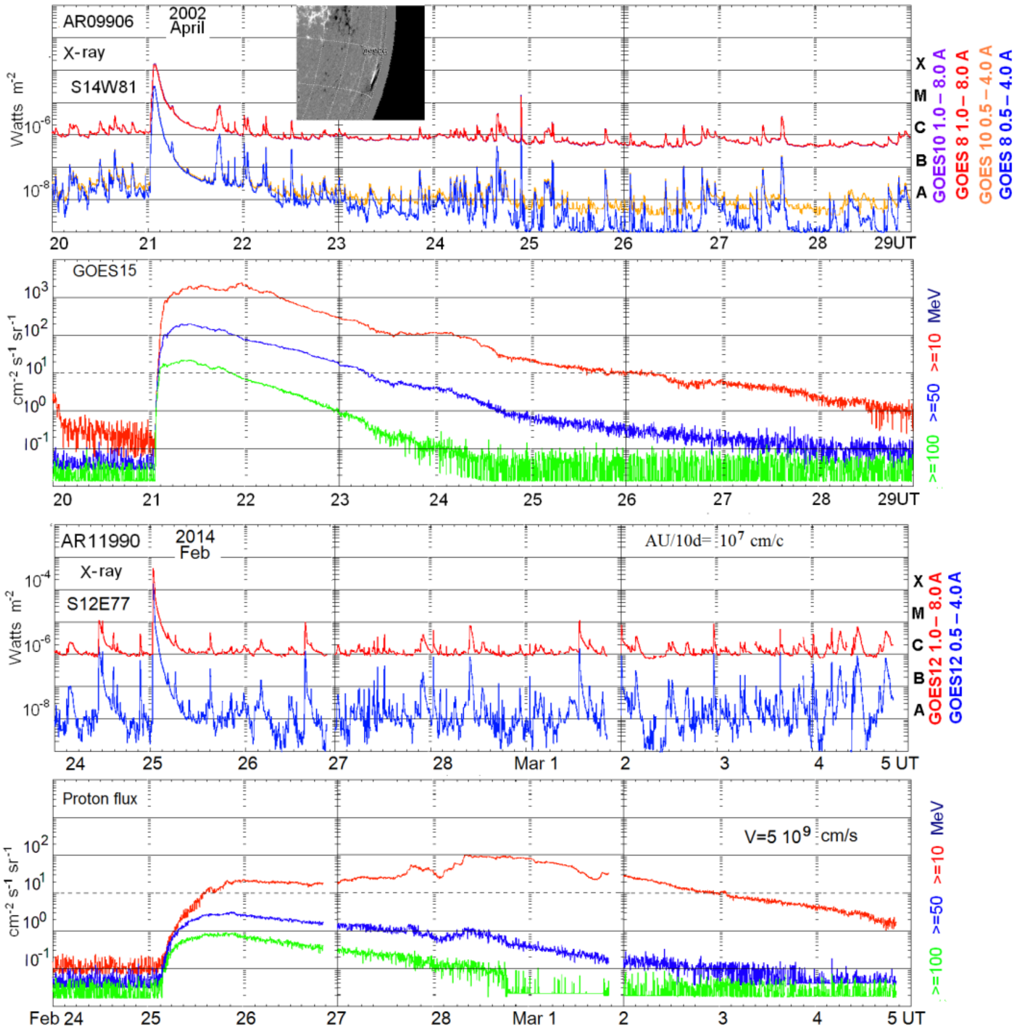

Figure 5. The long time proton events generated by western and eastern flares.

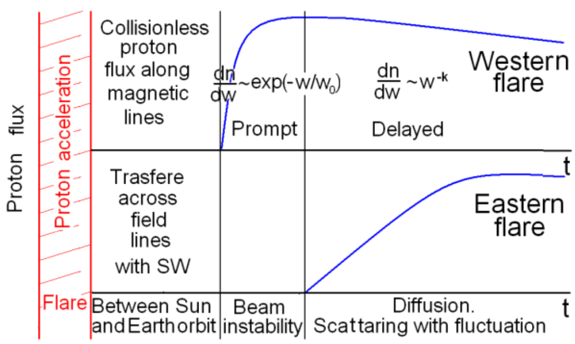

Figure 6. The proton flux development.