Proton acceleration in the solar flare

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Abstract. 100 years of cosmic ray investigations have not led to understanding the mechanism of particles acceleration. The most popular acceleration mechanisms of cosmic ray considered in the theory are associated with shock waves. The discovery of sources of protons with energies up to 20 GeV, generated by the Sun (solar cosmic ray), gives us hope for the opportunity to clarify the mechanism of cosmic rays generation. The important information about the mechanism of proton acceleration in the Sun has been obtained from results by GOES of measurements. The association of a proton event with a particular flare is beyond doubt. The GOES measurements indicate the high-energy protons propagation without collisions from the flares that appeared on the western part of the solar disk. These protons move in the interplanetary space along helical magnetic field lines. The protons from flares on the back side of the Sun can also arrive to the Earth's magnetosphere along magnetic lines. The protons from eastern flares come to the Earth's magnetosphere with the solar wind velocity or due to diffusion across the magnetic lines.

1. Introduction

The numerous theories of cosmic ray acceleration to the giant energy in remoted regions of the cosmos are based on untested assumptions. The hope for the understanding the physics of proton acceleration to the relativistic energies appears in connection with the discovery of solar cosmic rays accompanying some of solar flares.

The explosive release of the magnetic energy at a solar flare occurs in the solar corona above a strong ($\Phi > 10^{22} \text{ Mx}$) and complicated active region. The almost constant magnetic field distribution in the active region during a flare [1, 2] shows that magnetic energy dissipation takes part in the corona. The numerical MHD simulation demonstrates magnetic energy accumulation before the flare in a coronal current sheet [1, 2]. During the time order of ten minutes the flare energy stored in the magnetic field of a current sheet heats plasma with the density of $\sim 10^{11} \text{ cm}^{-3}$ up to the temperature 3 - 5 keV. Cosmic ray measurements are not provided information, which is available to study the mechanism of cosmic rays generation in the distant regions of space. Here we consider the generation of pulses of solar cosmic rays measured with GOES spacecrafts. The shock waves are the most popular theoretical mechanisms of cosmic ray acceleration. Shock waves are assumed by many authors but initial conditions are set arbitrarily to be convenient for numerical calculation. The discovery of fast particle generation on the Sun during the flares (solar cosmic ray) is supplied by new information about the possible mechanism of fast particle generation entered Earth environment.

The most valuable information about solar cosmic ray has been obtained by the world network of neutron monitors [3 - 5]. The monitor measurements are showed that pulses of relativistic proton generation (W $\sim$ 20 GeV) appear during a flare. 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
on the Earth orbit with the time delay Δt ~ 15 min after the onset of the emissions of the thermal flare
X-ray.

The prompt proton pulse from the western flare consists with of collisionless fast protons arriving
in small pitch angles along the lines of the interplanetary magnetic field. It has the exponential
spectrum \( \sim \exp(-W/W_0) \). Apparently, it is a spectrum of particles emitted from the proton 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 they
possess diffusive propagation. The values of \( W_0 \) are not much different for the different proton events.
They are observed in the range 0.5 - 1 GeV, \( \gamma \) is within 4 - 6. Anisotropic velocity distribution at a
later stage is changed in isotropic one, apparently, due to turbulence excitation by the beam instability.

The conditions for of solar cosmic rays acceleration are existed in the current sheet along the
singular magnetic field line. In a particular case it is a line of zero magnetic field [1, 2]. The electric
field \( V \times B/c \) along the current sheet singular X-line occurs at the plasma inflow in the current. The
reconnection of current sheet magnetic field lines takes place. 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. When a
particle is deviated from the X-line, it enters into the drift region and the acceleration is ceased. The
efficiency of particle acceleration by the electric field \( E = -V \times B/c \), directed along a singular line of
the magnetic field is known from results of laboratory experiments with a powerful pulsed discharge
[1, 2].

To obtain the spectrum of protons accelerated in the flare current sheet, the method of test particles
[3, 4] is used. The calculation shows exponential spectrum of protons, which at the magnetic
reconnection velocity \( 2 \times 10^7 \) cm/c coincides with the spectrum measured by the network of neutron
monitors at the front of the proton flux of the western flare. Thus, the prompt component of particles is
accelerated in the flare current sheet comes to the Earth orbit in the first 10 - 20 minutes. It travels
along the field line during time of flight without collisions. These particles can propagate free only
along the magnetic lines of the spiral of Archimedes. Such magnetic field lines must to connect the
flare with the proton detector located on the Earth's orbit. After 20 - 30 min the proton flux becomes
isotropic. This isotropic delayed proton component can appear due to development of the beam
instability [6]. The scattering by the field inhomogeneities leads to diffusion proton flux propagation
along and across magnetic field lines. All this independent information about the flux of accelerated
protons coming to the Earth is obtained from analysis of the measurements on the GOES spacecrafts.

2. Proton generated in solar flare

During the eleven-years cycle of solar activity 10 - 15 strong proton events can be observed. Each
proton event is appeared after a flare. However, not all large flares produce pulses of solar cosmic
rays. Figure 1 shows the typical single proton events accompanied by the flares appeared in the
western (above in figure 1) and eastern (below) parts of the solar disk. The duration of proton emission
that measured by GOES can depend on acceleration mechanism in the current sheet and on the proton
propagation mechanism in space.

The duration of proton flux, accelerated in the current sheet, can be estimated from \( \gamma \)-ray pulses. Some protons of a proton event hit the Sun, and produce nuclear reaction on the Sun with \( \gamma \)-ray emission. The typical \( \gamma \)-ray radiation lasts about 10 minutes which does not exceed the duration of the
flare pulses determined from the thermal X-ray.

The proton pulses fronts from the western and eastern flares exhibit significantly different patterns.
The fluxes from western flares have a steep front with duration not exceeding 20 - 25 min. The
particle registration begins at 10 - 20 min after the start of a western solar flare. Low delay of proton
from western flare can be determined only by the flight of time of protons to the Earth without
collisions at moving from the flare along magnetic field lines of the Archimedean spiral. For the whole
energy range, measured by the GOES, the proton moving in the interplanetary space takes place with
the small Larmor radius. Collisionless proton flight does not distort the particle spectrum. The exponential spectrum registered by neutron monitors at the front of proton flux (prompt component) from the western flare front must coincide with the spectrum of protons accelerated along a singular magnetic field lines in the flare current sheet.

![Figure 1](image.png)

**Figure 1.** 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).

The protons from the western flares, moving without collisions along the magnetic field lines, should to leave quickly the space between the Sun and Earth and to escape beyond the Earth orbit, but they registration by GOES apparatus lasts for several days. The collisionless propagation takes place only in the proton flux front during 20 - 30 minutes. The protons from the western flares move in the interplanetary plasma according to the laws of particle of motion in vacuum only at initial time (the prompt component on the front of proton flux). However, after a short time the proton flux measured by neutron monitors becomes isotropic. It seems to be beginning to play a role a plasma process that develop the beam instability [6], and scattering of protons in the turbulent plasma takes place that causes the low velocity of the proton flux due to diffusion propagation in the plasma.

One of the main characteristics of solar cosmic rays is a significant difference in duration of the fast proton fluxes ejection from the flare current sheet and duration of proton flux that measured by the GOES devices on the Earth's orbit. The pulse duration of the of high energy protons detected on Earth orbit is in the ranges from one to several days [7, 8]. This long proton flux duration measured by
GOES can appear only due to particle interaction with interplanetary plasma. This time is comparable with time of solar wind propagation from Sun to the Earth.

The proton flux from the flare that occurred on the eastern part of the solar disk (figure 1 below), cannot reach the GOES spacecraft, moving along the magnetic field lines. At the propagation without collisions, the protons must drift in the interplanetary medium across the magnetic field with the solar wind velocity. Consequently, the particle drifting from East side of the solar disk must produce the protons front delay of the arrival of to Earth up to \( AU/V_{sw} = 3 - 4 \) days. In reality (figure 2) the delay of the proton front from the eastern flares is only about 3 - 5 hours. The rather rapid transfer of protons across the magnetic field may be associated with the turbulent diffusion across the magnetic field. The proton flux from the eastern flares, unlike the flux of western flares, arises slowly as it should be because of diffusion. The typical front duration of the proton flux from eastern flares is about a day.

The particle of fluxes that arrived along the magnetic field line from western flares and the particles that arrived across the magnetic lines from eastern flares are recorded for several days after the end of the flare. The proton flux velocity directed along the magnetic field decreases due to diffusion by several orders of magnitude, but the diffusion flux velocity of the protons across the magnetic field increases. The measurements on neutron monitors [7, 8] have also shown that the so-called prompt component of relativistic protons has a strong anisotropy (the proton velocity vector is parallel to the lines of the of Archimedes spiral), but the delayed proton component with an isotropic velocity distribution begins to register after 20 - 30 minutes. Such a scenario should take place, if the front of beam of accelerated protons initiates 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. Numerical simulations have shown [9] that introduction of the magnetic turbulence leads to scattering of protons, and the distribution of the vector velocity at a later stage becomes isotropic.

![Figure 2](image-url)

**Figure 2.** Proton pulses with very steep front arrived from the western limb flare and protons from the flare appeared near the Sun center flare. The proton flux from the central AR S12W08 flare increases not so fast.

Currently we have not sufficient information about the development of turbulent processes in the solar wind. Our working hypothesis can be stated as follows. Fluxes of protons from the flare that occurred on the eastern limb (figure 1 below) cannot reach the device located at the GOES, moving along the magnetic field lines. At the propagation without collisions, the protons in the interplanetary medium, where the Larmor radius is much smaller than AU, must drift across the magnetic field with the solar wind velocity. The narrow beam of the proton front of a western flare moves to the Earth with the particle velocity. The beam instability causes the turbulence development, and particles scattering with magnetic fluctuations dramatically increased. The velocity of particle propagation across the field in the long flux front of the eastern flares rises due to collisions. As a result, the front of proton fluxes from the eastern flares can move across the magnetic field lines faster than the solar wind.
wind. The formulated scheme is in a good agreement with measured data, but the detailed investigation of the solar cosmic rays dynamics 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 figure 2. This is a rare case when the two proton events occurred with an interval of two days in different active regions of the Sun. The proton event 06.01.2014 7:30 is appeared just after the very weak X-ray flare pulse C2.1. According to the RHESSI data the C2.1 06.01.2014 flare 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, but most of X-ray radiation could be screened by the chromosphere. Apparently, the C2.1 real flare 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. The fast collision-free flux of protons from C2.1 flare could arrive to the Earth from the back side of the Sun along the magnetic lines of the Archimedes spiral.

The flare X1.2 is produced by the S12W08 active region near the Sun center. It little bit shifted to the West. The accelerated protons from this flare cannot arrive to the Earth orbit along magnetic lines. They appear with 1.5 hours delay and possess the front about 10 hours. This front is longer than the front of protons from western flares, but not as long as for the proton fluxes generated by flares that appeared in the far East.

3. Conclusion
The time of arrival of the front of solar cosmic ray 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 detector of protons on the Earth orbit.

Collisionless flux should cause the beam instability. The flux proton becomes diffuse due to scattering by the fluctuations. The propagation velocity of the protons along the magnetic field lines is reduced.

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.

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 than the solar wind. This can be related to the diffusion of protons across the field lines due to the scattering by the fluctuations. These fluctuations can be generated due to plasma beam instability.

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