

The single mechanism of solar and galactic cosmic rays acceleration arising during the flare process

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Abstract. Solar flares take place in the solar corona due to release of magnetic energy accumulated in the magnetic field of current sheet during instability of the current sheet. Solar cosmic rays are accelerated in the inductive electric field of the current sheet. The magnetic field of the solar wind forms the shape of an Archimedes spiral and affects the propagation of solar cosmic rays in interplanetary space. The modern detection of giant flares on the class G star dwarfs with the energy significantly exceeding the energy of the solar flares indicates the possibility of proton acceleration beyond the boundary of the solar system to energies significantly greater than the energy of solar cosmic rays. The recent experimental data shows that the energy of the stellar flares can exceed energy of 10^{36} erg. It is by 3-4 orders greater than the energy of a large solar flare, and, apparently, the energy of the protons accelerated in these stellar flares can significantly exceed the energy of the particles registered from flares on the Sun. Thus, the flare can be a universal astronomical process responsible for proton acceleration on the Sun and on the stars.

1. Introduction

Thanks to the rich information obtained from observations on the Sun, in particular the reconstruction of the magnetic field distribution and the measurements of intensities of X-ray and ultraviolet radiation on the solar disk, one can understand the physical mechanism of phenomena occurring in distant astronomical objects, studying similar phenomena on the Sun. Such phenomena include the origin of cosmic rays, that are mostly protons accelerated to high energies (solar cosmic rays up to ~ 20 GeV, galactic cosmic rays up to $\sim 10^{14}$ eV and higher). Fluxes of Solar cosmic rays appear during solar flares and are several orders of magnitude greater than the background fluxes of galactic cosmic rays. At least this applies to protons with energies of several tens of MeV, produced in such processes, are of interest for this study. Therefore, to study the origin of solar cosmic rays, it is necessary to understand the physical mechanism of a solar flare, and how particles can be accelerated to high energies during a solar flare.

2. Physical mechanism of solar flare

Solar flares occur above the active regions, where the value of magnetic field B can reach several thousand Gs (the background B on the surface is ~ 1 Gs). The linear size of active regions reaches several hundred thousand kilometers. One of the most interesting properties of a solar flare is its appearance in the solar atmosphere (in its upper part, so-called solar corona) at heights of 15 – 30 thousand km, which is $1/40$ – $1/20$ of the solar radius. This is evidenced by the absence of a change in the magnetic field of the active region on the photosphere during flares [1], observation on the limb of



thermal X-rays [2], observation of ultraviolet radiation in the lines of highly ionized iron ions that can appear only in the high-temperature plasma of the solar corona [3], as well as a number of other observational facts. Additional evidence of the appearance of a flare high in the corona is the formation of a current sheet in the corona obtained by numerical magnetohydrodynamic (MHD) simulation above a real active region, the position of which coincides with the observed source of flare thermal X-ray emission.

In the magnetic field of the current sheet the energy accumulates, which it is released during a flare. The formation of the current sheet occurs in the vicinity of an X-type singular line of magnetic field of the corona under the influence of disturbances propagating from the solar surface. Perturbations cause a current in the vicinity of a singular X-type line, so that the magnetic forces $\mathbf{j} \times \mathbf{B}/c$ have such a direction (from a singular line along one coordinate and to a singular line along another coordinate) that the plasma movement caused by them creates a current sheet. In the process of quasistationary evolution, the current sheet transforms into an unstable state, the instability of the sheet causes a flare release of the magnetic energy accumulated in the sheet. The flare mechanism, based on the accumulation of energy in the magnetic field of the current sheet, is currently the only one that can explain the slow accumulation of magnetic energy and then its rapid release when the system transforms into an unstable state.

Among the alternative models, the most common is the model according to which the flare energy accumulates in the field of a magnetic rope that appears in the solar corona. The magnetic rope is either set from the very beginning in an unstable or even in a non-equilibrium state, without explaining how it could appear as a result of a slow evolution of the magnetic field on the solar surface (photosphere), or it is formed as a result of unnatural plasma motion on the photosphere. Such a plasma motion can be either too fast or so complex that singular X-type magnetic field lines appear in the corona with current sheets creation. However, the formation of the current sheet alone is enough for a flare to appear, so in such a model a rope is not need to explain the flare.

An electrodynamic model of a solar flare was proposed [4], based on the fast release of the magnetic energy of the current sheet, using the results of MHD simulation in the corona above the real active region and the results of observations. The model explains all the main observational manifestations of the solar flare. According to this model, the Hall electric field along the current sheet, caused by the acceleration of plasma by the force of magnetic tension, leads to the appearance of a current circuit consisting of field-aligned currents along magnetic lines closed by Petersen current across the magnetic field in the lower dense layers of the solar atmosphere. The electrons accelerated in field-aligned currents, interacting with the lower dense layers of the solar atmosphere, cause beam hard X-ray emission at the places of intersection with the solar surface of the magnetic lines emerging from the current sheet. The electrodynamic model explains coronal plasma ejection (CME) as a result of plasma acceleration by magnetic tension force during the instability of the current sheet. The model explains also a number of other observational manifestations of a solar flare.

3. Magnetohydrodynamic simulation of flare situation

To find out the solar flare mechanism, numerical magnetohydrodynamic (MHD) simulation of the flare situation in the corona above the real active region was performed. When setting the problem, no assumptions about the flare mechanism were made. All conditions were taken from observations, the purpose of the simulation was to find out the flare mechanism. The distribution of the magnetic field measured on the solar surface was used to set the boundary conditions. To accelerate the computations, an upwind absolutely implicit finite-difference scheme conservative relative to the magnetic flux was developed specially for the numerical solution of MHD equations [5, 6]. The scheme is solved by the method of iterations. The numerical method is realized in the program PERESVET. The principle of limited simulation [7] is used. A simulation performed above the active region AO 10365 showed the formation of a current sheet at an altitude of 16 000 km, which coincides with the source of flare thermal soft X-ray emission (figure 1(f)) [8]. The location of lines in the

planes in figure 1(a)-(c) makes it possible to imagine the directions of the magnetic forces responsible for the process of creating the current sheet and the fast dissipation of the magnetic field in case of instability of the sheet. Figure 1(d), (e) present lines and surfaces of equal current density and gives an image of the shape of the current sheet.

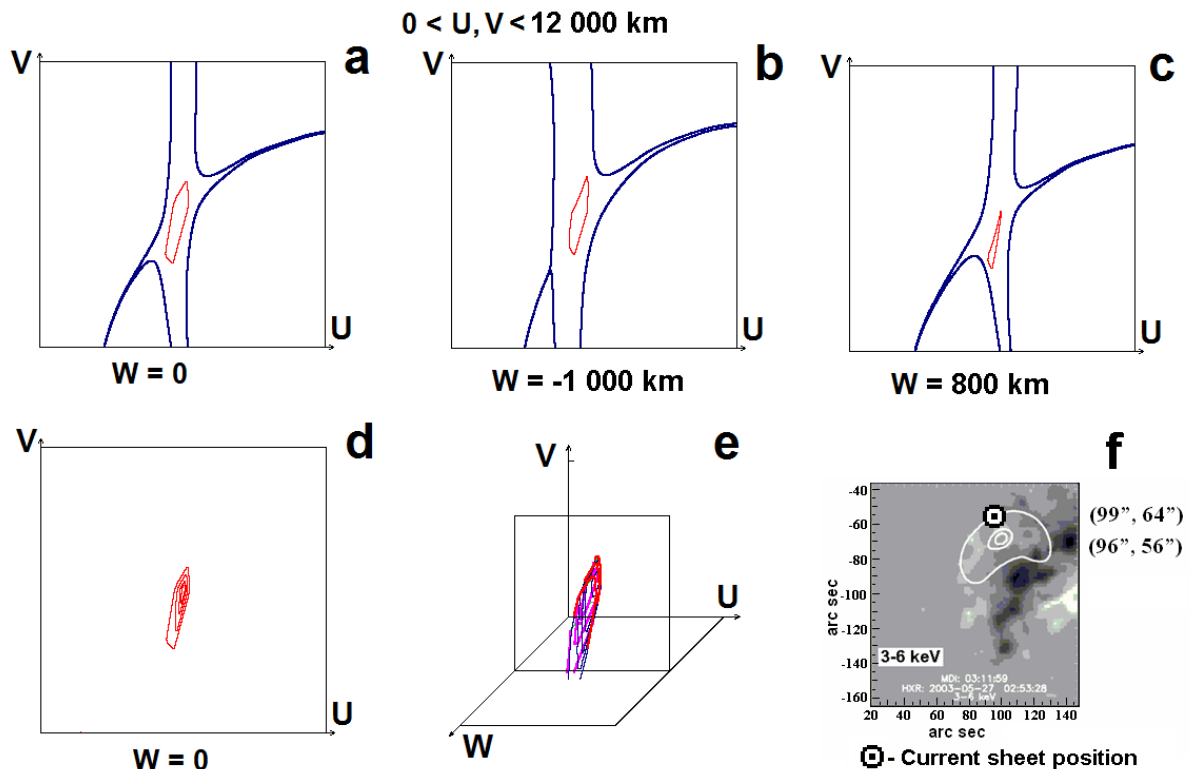


Figure 1.(a-c) – magnetic field configuration in the planes perpendicular to the current sheet, (d, e) – lines and surface of equal current density, (f) – the position of the current sheet on the map of the distribution of thermal X-ray radiation 3-6 keV.

4. Cosmic rays acceleration and propagation during solar flare

Moving in the current sheet, the protons are accelerated by an induction electric field directed along the current of the current sheet perpendicular to the plane of figures 1(a-c), resulting from a change in the magnetic field of the sheet equal to $\mathbf{V} \times \mathbf{B} / c$ near the sheet. Particles accelerated in the current sheet have an exponential spectrum, which is formed as a result of exiting the sheet of some accelerated protons under the influence of the magnetic field before they pass the entire length of the sheet. They come from western flares along magnetic lines having the shape of an Archimedes spiral, without changing their spectrum (prompt SCR component, [9]) and are recorded by a spacecraft or the worldwide neutron monitor network during the flare time. The exponential spectrum of accelerated particles is obtained by calculating their trajectories in electric and magnetic fields, taken from the results of MHD simulations for the Bastille flare of 07/14/2000. This spectrum coincides with the measured particle spectrum from this flare on the worldwide neutron monitor network for the inflow plasma velocity into the sheet (reconnection velocity) $V = 2 \times 10^7$ cm/s [9]. Earlier, approximately this velocity was obtained from simple estimates of the acceleration of a plasma flowing into a sheet by the magnetic pressure. Now, thanks to the study of the physics of solar cosmic rays, this velocity was found by analyzing observations using numerical simulation. The MHD simulation, as well as the previously made approximate estimates, shows the value of the magnetic field near the current sheet B

= 100 Gs, so that the electric field in the sheet $\mathbf{E}=\mathbf{V}\times\mathbf{B}/c$ is ~ 20 V/cm, and for the length of the sheet $L = 10^9$ the particle will gain the maximum energy of 2×10^{10} eV, having traveled the way on which the potential difference is EL . This energy corresponds to the maximal observed energy of solar cosmic rays.

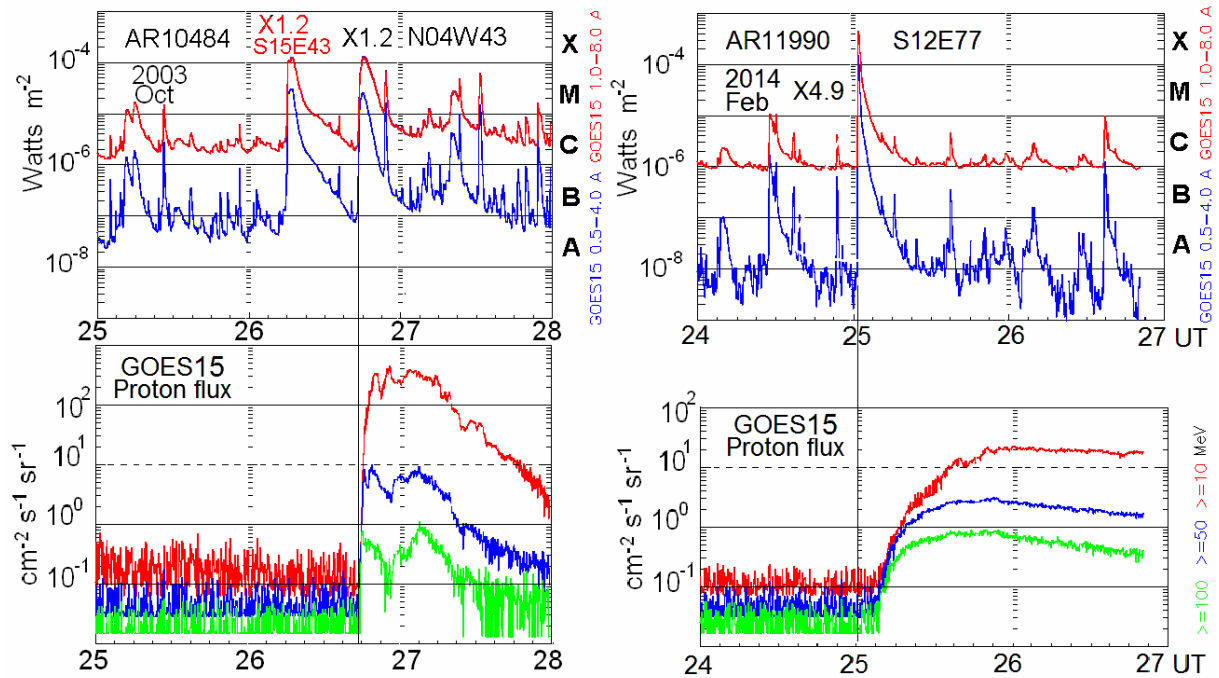


Figure 2. Thermal X-ray emission characterizing the flare, and solar cosmic ray fluxes from the western (left) and eastern (right) flares measured on the GOES spacecraft.

Measurements of the fluxes of cosmic rays and thermal X-rays, whose peaks indicate the time of occurrence of flares (data from the GOES spacecraft, figure 2), show that for flares near the western edge of the solar disk (figure 2(a)) accelerated protons arrive with a delay of 15–20 minutes. This time corresponds to the transit time from the western part of the disk along a magnetic line having the shape of an Archimedes spiral. The magnetic lines in the interplanetary medium are pulled out by the solar wind, acquiring the shape of the Archimedes spiral due to the rotation of the Sun. The rise time of the particle flux front from western flares is 15–30 minutes. The delay time for the arrival of accelerated particles from flares that occurred on the eastern part of the solar disk is 3–5 hours. This delay is explained by the absence of a magnetic line connecting the flare point to the spacecraft in Earth's orbit, due to which a direct flight of particles from the place of acceleration to the registration site is impossible. The rise time of the particle flux front from eastern flares is ~ 1 day. Particles from the eastern flares can reach the spacecraft, moving across the magnetic field along with the solar wind (drift in crossed magnetic and electric fields). However, in this case, the delay in the arrival of particles would be ~ 3 days (the time of motion between the Sun and the Earth with the solar wind velocity), which is significantly less than the observed delay in the arrival of particles. The observed delay can be explained by the diffusion of accelerated particles across the magnetic field due to their scattering on plasma inhomogeneities resulting from beam instability caused by the flow of accelerated particles along the magnetic line [10].

As can be seen from figure 2, the time of existence of the solar cosmic-ray flux caused by a flare (usually ~ 3 days, sometimes up to 10 days) is more than two orders of magnitude longer than the time of the flare, which is estimated as the time of the thermal X-ray emission of the flare. Part of the protons, which do not travel the entire distance along the field line to the observer, diffusely propagate in the interplanetary space for several days, scattering on plasma inhomogeneities. During scattering, the spectrum of accelerated protons changes and this part of the protons, called the delayed

component, is recorded by a network of neutron monitors already with a power spectrum [9]. The delayed component of solar cosmic rays consists of particles propagating in a diffusion manner across the magnetic field; therefore, unlike the prompt component, it appears not only from western but also from eastern flares. Figure 3 illustrates the sequence of the appearance of fluxes of accelerated particles from the western and eastern flares without exact adherence to the time scale.

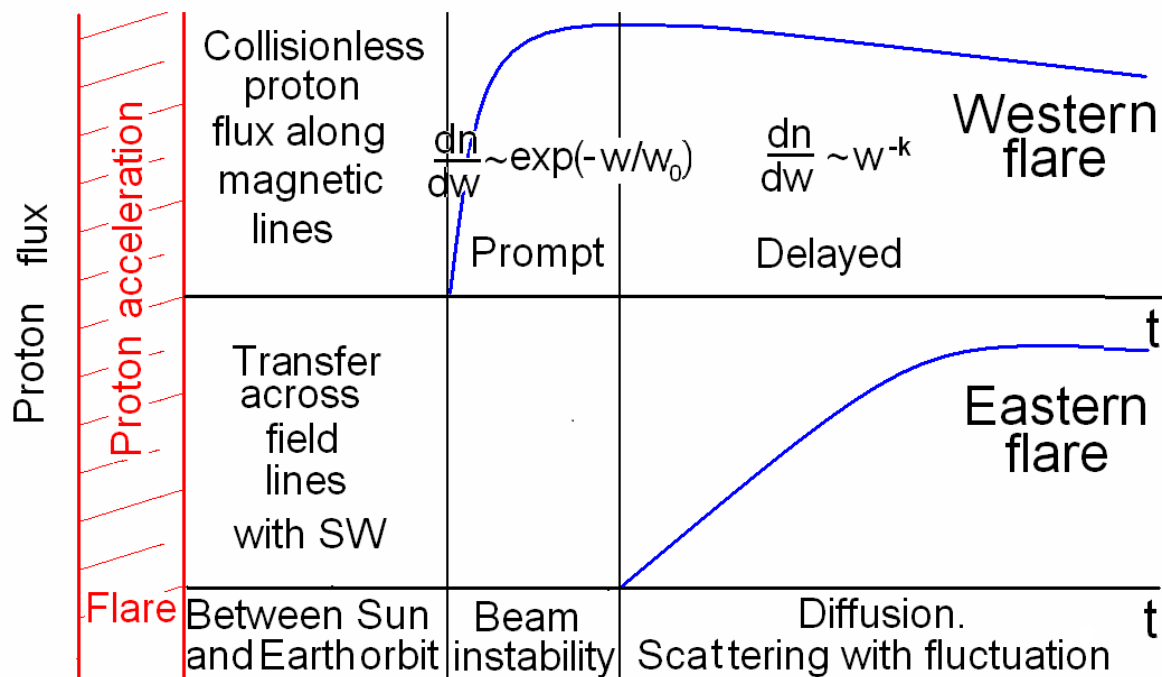


Figure 3. The flux of solar cosmic rays time development in the interplanetary space.

Not all solar flares cause the appearance of solar cosmic rays. Only about 30% of Class X flares (very powerful flares with a thermal X-ray flux in the range of 1 to 8 Å in the Earth's orbit exceeding 10^{-4} W/m²) cause cosmic ray fluxes. This is explained by the fact that in many cases the configuration of the field above the active region holds the particles accelerated in the current sheet, preventing them from escape into the interplanetary space. At present, the Fermi mechanism of acceleration of both galactic and solar cosmic rays on shock waves is widespread. According to this mechanism, a particle crosses the shock wave front several times, reflecting off plasma inhomogeneities, and gains energy due to the difference in the average speed of the inhomogeneities on both sides of the shock front (the average speed of the inhomogeneities is assumed to be equal to the plasma velocity in the place of these inhomogeneities). For solar cosmic rays, such a mechanism is considered on the front of a shock wave propagating before the plasma ejection. A plasma ejection (CME) occurs during an explosive process of a flare. According to the electrodynamic model, the plasma is accelerated in the current sheet by the force of magnetic tension. For powerful flares, the plasma ejection velocity (10^8 cm/s and more) exceeds the solar wind speed, the sonic and Alfvén velocity, therefore a shock wave appears at the ejection front. The front of the shock wave is in the solar wind at a distance of many radii of the Sun from the solar surface. Therefore, the magnetic field in the solar corona above the active region, which has a noticeable effect at heights of no more than one tenth of solar radius, cannot prevent particles from entering the interplanetary space and their registration by a spacecraft in Earth orbit, unlike the case when protons accelerated in the current sheet in corona. The appearance of flares, accompanied by rapid emissions with powerful shock waves that did not cause solar cosmic rays (Figure 4), proves that solar cosmic rays are accelerated in the current sheet, and not on shock waves. This is due to the lack of a sufficient number of inhomogeneities near the shock wave, from which the

particles would be able to be reflected a sufficient number of times for their effective acceleration to occur. Indeed, the Larmor radius of a proton with an energy of ~ 2 GeV in the magnetic field of the solar wind of $\sim 5 \times 10^{-4}$ Gs is $\sim 10^{10}$ cm, which corresponds to the size of the plasma inhomogeneity from which the particle could be reflected in the acceleration process. The accumulation of such huge inhomogeneities in the solar wind has never been observed. Estimates show that the effective Fermi acceleration can be carried out for particles with energies of less than 10 MeV, but we are primarily interested in the possibility of acceleration to much higher energies.

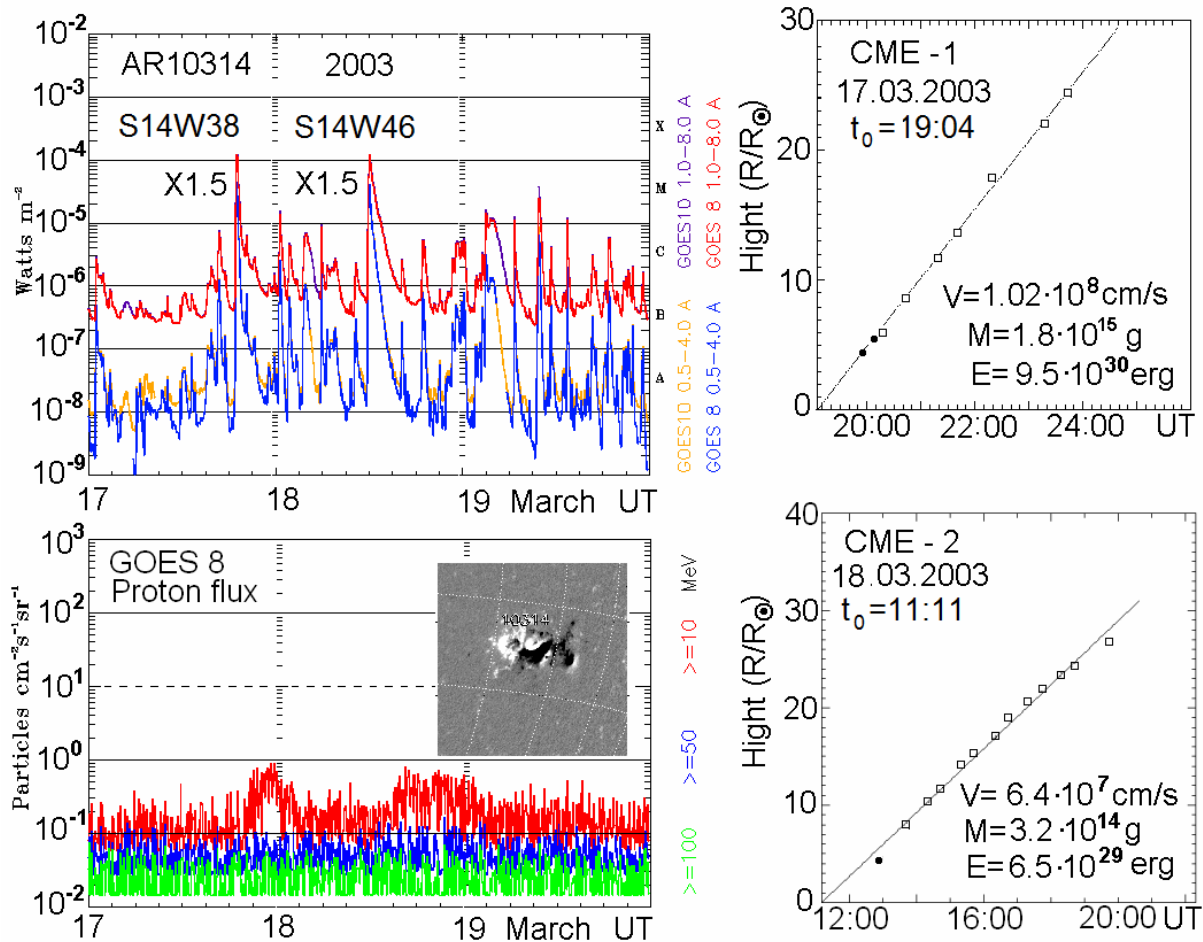


Figure 4. Power solar flares in March 2003, which produced strong coronal mass ejections and interplanetary shock waves, does not produce solar cosmic rays.

5. The necessity for fast calculations to study and predict solar cosmic rays

Despite the use of mathematical methods developed specially to accelerate computations, numerical MHD simulation in the corona above the real active region is rather slow, so it was possible to carry out it on a personal computer during the foreseeable time (~ 3 months) only in a very strongly reduced time scale (in 10^4 times). An unnaturally fast change in the magnitudes at the photospheric boundary over time leads to instability near this boundary, since there is a large magnetic field gradient in the direction perpendicular to the boundary. Specially developed numerical methods made it possible to limit the growth of instability near the photospheric boundary and prevent its spread into the region. Therefore, in spite of the development of numerical instability near the photospheric boundary, the position of the current sheet, found from the simulation results, quite well coincides with the position

of the observed source of thermal X-ray emission. It is quite possible that the resulting configuration of the magnetic field near the current sheet and the shape of the current sheet is quite consistent with the actual formation in the solar corona. It is possible that, due to the emergence of numerical instability near the photospheric boundary, the magnetic field configuration obtained as a result of MHD simulation turned out to be such that the magnetic lines emerging from the current sheet did not cross the photospheric boundary of the region at the locations of the beam X-ray sources, as it should follow from the electrodynamic model of the current sheet. It is possible that, due to the numerical instability near the photospheric boundary, the magnetic field configuration obtained as a result of MHD simulation turned out to be such that the magnetic lines emerging from the current sheet did not cross the photospheric boundary of the region at the locations of the beam X-ray sources. Such position of beam hard X-ray sources should follow from the electrodynamic model of the current sheet. The behavior of magnetic lines gives only some indications of the possibility of such a crossing of the photospheric boundary. It is planned to significantly increase the speed of calculations, to perform numerical simulation of the flare situation in the corona in real time scale. For this purpose, it is necessary to parallelize the calculations, to carry out the calculation on a supercomputer. When simulating in real time, the magnetic field at the photospheric boundary changes much slower, therefore, as calculations have shown for the active region AR 10365 during the first 7 minutes of its evolution, there is no instability at the photospheric boundary. Simulation in real time scale will make it possible to clarify the position of the current sheet to compare it with the observed position of the flare source of thermal soft X-ray emission, the configuration of the magnetic field near the current sheet and the shape of the current sheet. It permit more accurately calculate the energy for the flare accumulated in the magnetic field of the current sheet. It will be possible to carry out a more accurate simulation of the acceleration of particles in the current sheet by calculating their trajectories in the electric and magnet fields obtained by numerical MHD simulation. It will be possible to obtain the configuration of the magnetic field in a large region containing the current sheet, including the field near the photospheric boundary. A sufficiently accurate calculation of the magnetic field in a large region containing the current sheet will make it possible to compare the observed positions of hard X-ray emission with the places of intersection with the photospheric boundary of the magnetic lines emerging from the current sheet. Also, knowing this field, it will be possible to find out in which cases the particles will be able to exit from the magnetic field above the active region by calculating the trajectories of the particles in this field after they are accelerated in the current sheet. Perhaps in this way it will be possible to find out why a sufficiently large number of flares do not produce cosmic rays. When using the fastest modern supercomputers, the planned modeling is supposed to be used to predict flares and solar cosmic ray flux.

Since there is no information about plasma inhomogeneities, and, consequently, the diffusion coefficient in the equation of propagation of accelerated particles is unknown, the prediction of the appearance of cosmic rays in interplanetary space that can cause cosmonauts to be irradiated will be based on the proposed here analysis of observational data.

6. Galactic cosmic rays

The pulses of relativistic protons accompanying flares are recorded against the background of a continuous flux of galactic cosmic rays with the energy of more than 10^{15} eV. Their acceleration occurs outside the solar system. For more than 100 years the galactic cosmic ray acceleration has been studied, but the physical mechanisms of acceleration remain unclear. The most popular, but unproven hypothesis, is the galactic proton acceleration in interstellar shock waves. It is impossible to exclude that galactic cosmic rays are accelerated by the same mechanism as the solar cosmic rays. However, the energy of galactic cosmic ray particles is several orders of magnitude higher than the maximum energy of protons accelerated on the Sun. For a long time, this fact did not allow us unequivocally state that the acceleration of galactic and solar cosmic rays can occur by the same mechanism. The modern observation of giant flares on the star dwarfs of the class G [11, 12] with the energy significantly exceeding the energy of the solar flares indicates the possibility of proton acceleration

beyond the boundary of the solar system to energies significantly greater than the energy of solar cosmic rays. The generation of superflares with the energy much greater than the energy of big solar flares on variety of class G stars was reported, some of which are rapidly rotating and some of which are of an ordinary solar type [11]. 365 superflares were observed on the stars, including some superflares that are generated on the slowly rotating solar-type stars. About 83,000 stars have been investigated over 120 days using Kepler spacecraft data.

The previously considered significant difference in the energy maximums of galactic and solar cosmic rays did not contribute to the idea of the same cosmic ray acceleration mechanisms on the Sun and on stars. The recent data [12] are showed that the energy of the stellar flare can exceed 10^{36} erg. It is by 3-4 orders greater than the energy of a large solar flare, and, apparently, the energy of the protons accelerated in these stellar flares can significantly exceed the energy of the particles registered from flares on the Sun. The flare and dynamics of the pre-flare state of the active region that caused the flare are available for direct investigation only on the Sun. Such possibility is not existed for stars.

7. Conclusion

The acceleration of particles of solar cosmic rays occurs in a flare current sheet above the active region. The spectrum of the front of particles coming to Earth and recorded by the worldwide neutron monitor network coincides with the spectrum of accelerated particles in the current sheet, which is calculated in a numerical MHD experiment for the initial and boundary conditions specified for the dynamics of the preflare state of the active region. According to recent data obtained on the spacecraft Kepler, which show that the energy of the stellar flare can be by 3-4 orders greater than the energy of a large solar flare, the flare can be a universal astronomical process responsible for acceleration of both solar and galactic cosmic rays.

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