"Physics of Auroral Phenomena", Proc. XL Annual Seminar, Apatity, pp. 78-81, 2017

Polar Geophysical Institute

ON SOLAR COSMIC RAY PROPAGATION IN THE INTERPLANETARY SPACE AND HIGHLY IONIZED IONS EMISSION

I.M. Podgorny[1] and A.I. Podgorny[2]

[1]*Institute for Astronomy RAS, Moscow, Russia. podgorny@inasan.ru*
[2]*Lebedev Physical Institute RAS, Moscow, Russia*

Abstract. The cosmic rays discovery is the most revolutionary event of the modern physics. Rapid development of the nuclear physics takes plays. In dozens of books the possibility of particle acceleration in the space is considered. All these works are based on unproven assumptions, which have not been confirmed by long-term observations. The discovery of solar cosmic rays and information, received from the worldwide network of neutron monitors and from measurements on the GOES spacecrafts, allow to conclude that the source of solar cosmic rays (SCR) is a solar flare. The fundamentally important problem is arisen: can the mechanism of acceleration of solar flare protons explain particle acceleration of the galactic cosmic rays. The photos of the pre-flare state in the ultra violet (UV) spectral lines of the highly ionized irons FeXVIII, FeXXIII, and FeXXIV (SDO spacecraft) are observed during accumulation of the flare energy in the corona. The appearing of UV emission before the flare permits to predict flare appearing. The brightest pre-flare structure is demonstrated by emission of the FeXVIII line. The local corona temperature increases by order of magnitude during the flare. The explosive increasing of spectral lies emission of FeXXIII, and FeXXIV during a flare takes place in the corona. The temperature of a flare is reached 20 MK. These phenomena are well described by the electrodynamical solar flare model built on the basis of the observational data and numerical MHD simulations using the initial and boundary conditions, taken from observations of active regions before a flare. Unfortunately, the new observational data on solar flares are now missing due to anomalously low solar activity in the current solar cycle.

Introduction

According to the electrodynamical solar flare model [1, 2] the magnetic energy accumulation for a flare and flare energy release take place in the solar corona above an active region. The active region of the Sun is the place of concentration of magnetic field sources up to ~ 3000 G of the different polarity. A typical size of the active region is about 10^{10} cm. The active regions and individual sunspots appear on the solar disk with the eleven year periodicity. The numbers of sunspots on the visible solar disk is used as a measure of solar activity. During the solar activity minimum no active regions are observed on the visible solar disk, and about ~20 active regions can appear on the solar disk at the solar activity maximum. The solar activity is observed against the background of periodic changes of the global dipole magnetic field. The dipole magnetic field of about 1 Γ changes of its polarity at the each cycle. One of the most interesting features of the flare is solar cosmic rays generation. The century research of cosmic rays - protons and other nuclei, coming to the Earth from the depths of the universe, did not lead to understanding of the physics of acceleration detected particles. The most popular acceleration mechanisms are associated with shock waves. However, possible mechanisms of cosmic ray acceleration in the shock waves are only hypotheses. Numerous putative mechanisms of proton acceleration in the galaxy are based on these untested assumptions.
Registration of proton with neutron monitors [3, 4] with energy ~ 20 GeV, which generated by a solar flare, gives us the hope to obtain the new information about the mechanism of generation of galactic cosmic rays. It does not exclude the possibility of the same mechanism of acceleration of galactic and solar cosmic rays. A number of phenomena associated with the acceleration and transport to Earth of the particles accelerated in flares, become now available for observation. The paper [5] has analyzed measurements of protons with the energy of ~ 100 MeV using GOES devices. The connection of the proton events with specific flares and specific active regions are demonstrated.

The protons of solar cosmic rays are accelerated in the solar flare current sheet, and the characteristics of the pulses of high energy protons recorded on the Earth's orbit strongly depend on the interplanetary magnetic field [6, 7]. In this paper we analyze the pictures of the pre-flare state of the active region and flares obtained by the American SDO spacecraft in the emissions of the spectral lines of highly ionized iron ions that permit to reveal some information about the mechanisms of energy accumulation for flares and proton propagation to the Earth. The relationship between the spectral UV spectral lines of the high-ionized iron recorded by the SDO spacecraft and the electron temperature has been determined from *http://www.moveinfo.ru/data/sun/sunimage_sdo.*

Energy accumulation in the corona and its explosive release during a flare

According to the electrodynamical flare model the magnetic energy accumulates in the corona over an active region at the temperature exceeding the corona temperature and then the accumulated energy quickly releases in the corona. The intense local heating of plasma over en active region takes place. Such scenario has been demonstrated by thermal

X-ray emissions in the corona during the X4.8 flare in 2002 year above the Eastern limb of the solar disk [8]. These processes should be investigated by UV spectral lines emission of the high ionized iron ions, which are characteristic for the temperature of the solar corona. But such data were not then available. Now the photos of flares and pre-flares state are obtained in the highly ionized iron spectral lines. This information is contained in the data of the SDO archive unit (*sdo.gsfc.nasa.gov*).

The most convenient for the analysis of flares are short UV spectral lines 94 Å, 131 Å, and 193 Å. The first of them belongs to ion FeXVIII, and the other to ions FeXXIII and FeXXIV. The maximum of 94A line brightness corresponds to the temperature of 6.3 MK. The emission of 131 Å corresponds to 16 MK, and the emission of the line 193 Å includes radiation of FeXXIV ions of very hot plasma (20 MK). The phenomena occurred in the chromosphere, where the temperature is low, could not produce hot plasma structures with ions FeXII, XVIII, XXIII, and FeXXIV at energy accumulation in the pre-flare state. Appearance of hot spectral lines demonstrates existence of the phenomena that occurred in the corona.

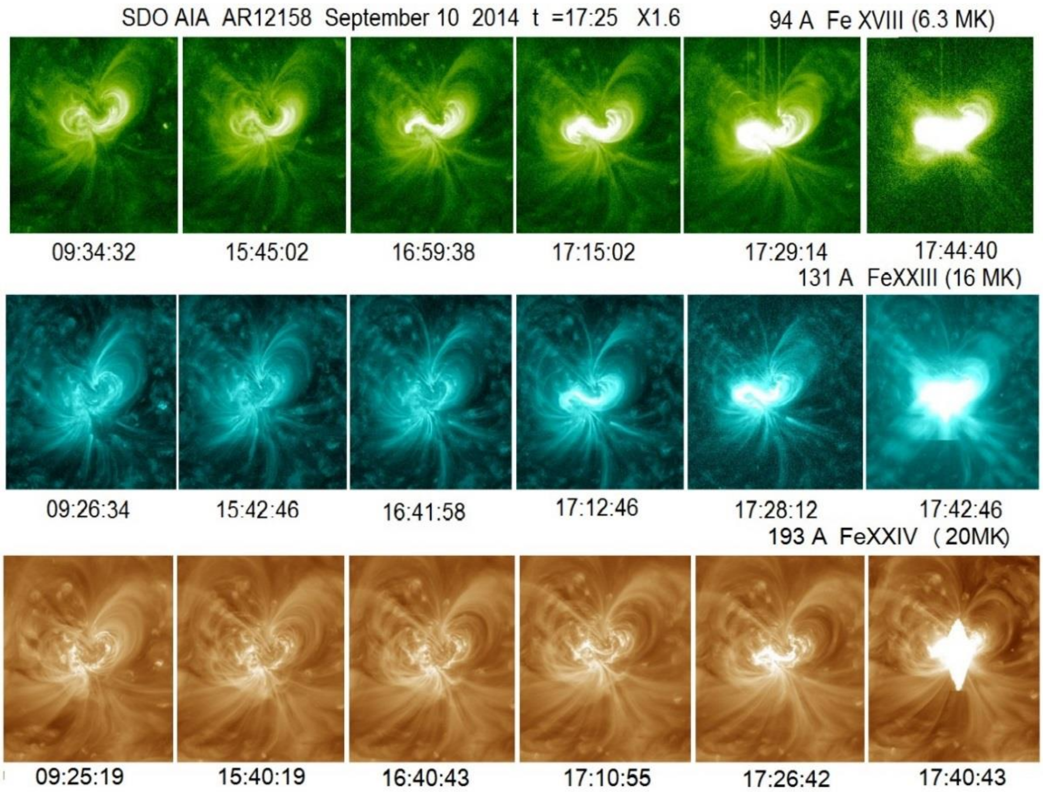

Figure 1. Photos of pre-flare and flare development taken with different spectral lines corresponding to different temperature. The flare is appeared in the solar flare disk (N11E05).

The Fig. 1 shows the active region AO12158 photos taken with the SDO spacecraft (*sdo.gsfc.nasa.gov*) in spectral lines 94 Å, 131 Å, and 193 Å of highly ionized iron atoms. The photos show the pre-flare state in the corona above the active region and the flare X1.6 that emerged at 17:21 near the center of the solar disk. This flare is accompanied by the generation of solar cosmic rays. The local emission of the pre-flare UV structure is especially strong before the flare appearing in the line 94 Å associated with the temperature 6.3 MK. The shape of the pre-flare structure does not correspond to the shape of the magnetic field lines, which is clearly seen in the photographs. Some of these field aligned emission have an ark shape, but they do not connect with flare appearance.

The temperature of the local pre-flare structure is much higher than the chromosphere temperature. So, the pre-flare process is developed in the corona above an active region, but not in the chromosphere. The flare produces very strong and sharp increasing of the 193 Å spectral line that corresponding to the highest temperatures, but the most strong pre-flare image is demonstrated by the spectral line 94 Å. The maxima luminosity of the 94 Å line is achieved at the temperature 6.3 MK. In the place of the pre-flare structure, existed before the flare, the emissions of spectral lines 131 Å and 193 Å are manifested not strong flare emission, but they demonstrate explosive emission increasing after 17:21. The local strong plasma heating in the corona during the flare is manifested by the appearance of bright emission of spectral lines corresponding to the high temperature T ~ 20 MK. The brightest image during the flare shows the hottest line 193 Å.

The dynamics of pre-flare and flare emission in the spectral line 94 Å are shown in Fig. 2 in details in the larger time interval. From the panels placed in the right side of Fig. 2 it follows that arrival of the proton front from the flare, which occurred in the center of the disk and recorded on the Earth's orbit, is delayed almost 10 hours. That occurred for all flares that appeared in the center of the disk or its eastern part. The gentle front of proton flux order of a day is a typical for such a flare. These protons can propagate to GOES across the magnetic field lines due to diffusion.

The flare on the limb of the solar disk makes it possible to observe energy accumulation and energy release in the corona outside the disk, when the contribution of the luminescence of the solar disk is completely eliminated. The flare that very convenient for observation has been appeared in July 23, 2002 [8], when it is clearly shown that the source of the thermal X-ray emission from the X4.8 flare is a plasma cloud in the corona The number of particles is ~ 10^{37}. Despite this fundamental result of *Lin et al.*, several recent Russian papers have appeared [9], which state that the flare is a typical chromospheric phenomenon. Unfortunately, for the 2002 flares there are no photographs in various UV spectral lines that can demonstrate the pre-flare state in different plasma temperatures.

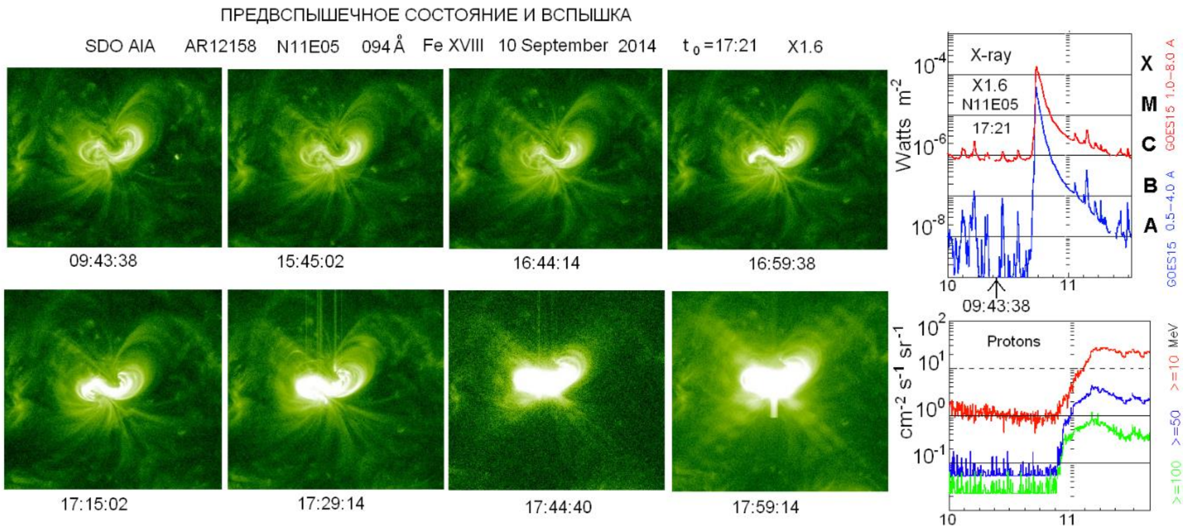

Figure 2. Pre-flare condition and flare X1.6 in the coronal line 94 Å according to SDO. The right panel shows the thermal X-ray radiation and solar cosmic rays according to GOES.

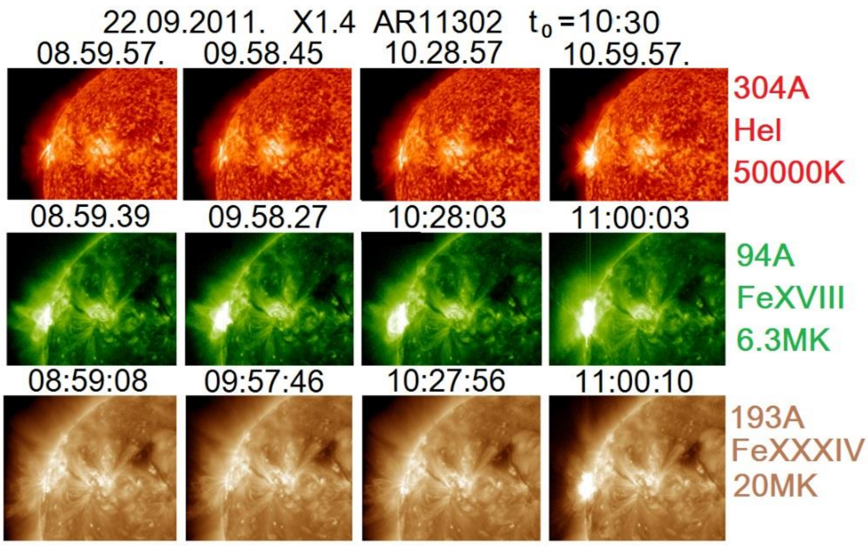

Figure 3. Pre-flare condition and flare on the East limb in the emissions from cold plasma of the chromosphere and the hot plasma of the solar corona.

Fig. 3 shows several frames taken from the archive of the SDO AIA spacecraft, which demonstrate the emission of various pre-flare spectral lines of the X1.4 flare observed on the eastern limb. Such rare phenomenon has been accompanied by the cosmic radiation with the delay of ~ 20 h, since the GOES devices could detect protons from such flares only after their drift across the magnetic field lines. The top photos of Fig. 3 demonstrate emission of the rather cold line of HeI on the eastern limb observed the half hour before the flare. May be, the HeI emission is appeared much earlier on the back side of the Sun, but it became clearly visible only after 09:00 as a result of Sun rotation. Before the flare a noticeable change in the structure of HeI emissions is not observed, and during the flare only a slight heating of the chromosphere is seen. The coronal line 94 emission slowly increases over the Sun surface in the phase of energy accumulation. It also increases during the flare. The other behaves demonstrate the emission of lines of highly ionized iron FeXXIII and FeXXIV of hot plasma with the temperature of 16 MK and 20 MK, much higher than the normal temperature of the corona. The image in the line 193 is barely visible before the flare, but during the flare a bright image in the corona over of the solar disk is appeared. The flare energy release is occurred in the corona above the active region. There remains no doubt in the coronal origin of the flare.

Fig. 4 shows M5 flare development of on the western limb in the line 193 Å. At frame 02:00:20 one can clearly see the appearance of the hot plasma cloud of the flare in the solar corona outside the solar disk boundary. The picture clearly indicates that the flare energy release takes part in the solar corona (black arrow). The pre-flare emission can be seen in all pictures, but the emission is very weak in the hot 193 Å line as usual. The flare is accompanied by the flow of solar cosmic rays with a sharp front, arrived with a delay relative to the flare front not more than 20 min. This means that the proton flow front arrive the GOES along the magnetic field lines of the Archimedes spiral without collision. The delay 15 - 20 min is typical for protons arriving from the western flares.

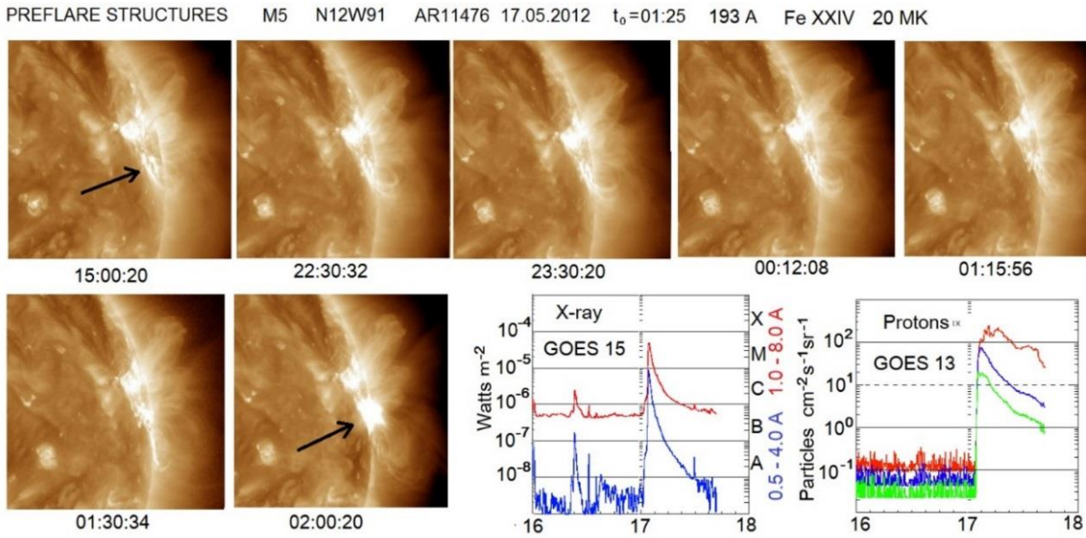

Figure 4. Pre-flare condition and the M5 flare on the western limb (black arrow) in 193Å spectral line from SDO data. The graphs show the flare thermal X-ray radiation and solar cosmic rays according to GOES data.

Conclusions

The appearance of local sources of UV emission in the corona above an active region before the flare and during the flare is investigated. The data of the SDO spacecraft are used. The pre-flare UV spectral line emission in the corona appears about 2 days. The flare appearance can be predicted by observation of a high-temperature plasma structure with the length ~10^{10} cm. The characteristic UV emission can be used for solar flare prognosis. The brightness of the UV emission sharply (~20 min) increases during the flare. The plasma structure above active regions reaches the temperature ~20 MK during the flare. At the solar flare a sharp (several minutes) increasing of the UV spectral lines emission of ions FeXXIV and FeXXIII, localized above the Sun surface, is observed. The strong local heating of the coronal plasma above an active region cannot be explained by the flare energy release on the surface of the Sun in the chromosphere. The flare energy release takes place in the corona. Flare development in the cromosphere is completely excluded. The temperature of the chromosphere at this time increases very weakly.

The rapid arrival of protons and the steep front of the proton flow from the western flare are created due to the particle propagation along the magnetic field lines of the Archimedes spiral without collisions. The delayed about 10 hours flow of protons from the eastern flare has a gently sloping front. Solar cosmic rays from the eastern flares can propagate diffusing across the magnetic field.

References

1. Podgorny A.I. and Podgorny I.M., Sol. Phys. **139**, 125–145 (1992).
2. Podgorny A.I., Podgorny, I.M.: Astronomy Reports. **50**, 842 (2006).
3. Balabin Yu.V., Vashenyuk E.V., Mingalev O.V., Podgorny A.I. Podgorny I.M. Astronomy Reports. **49**, 837 (2005).
4. Podgorny I.M., Balabin Yu.V., Podgorny A.I., Vashenyuk E.V. JASTP. **72**, 988 (2010).
5. Podgorny A.I., Podgorny I.M. Astronomy Reports. **59**, 888 (2015).
6. Podgorny A.I., Podgorny I.M. Astronomy Reports. **55**, 629 (2011).
7. Podgorny I.M., Podgorny A.I., Meshalkina N. S. Astronomy Reports. **59**, 795 (2015).
8. Lin R.P., Krucker S., Hurford, G.J. *et al.* Astrophys. J. **595**, L69 (2003).
9. Stepanov A.V., Zaitsev V.V., Melnikov V.F. *et al*. (In Russion). Solar solar-Earth physics-2011. Pulkovo. P. 197.