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G.S. Minasyants, T.M. Minasyants, V.D. Vdovichenko, A. G. Bibosinov

Fesenkov Astrophysical Institute, Almaty, Kazakhstan
gennadii_minasya@mail.ru, gennadii_minasya@mail.ru,
vdv1942@mail.ru, chingis.omarov@gmail.com

PROPERTIES OF ULTRAVIOLET EMISSION AT DEVELOPMENT OF SOLAR FLARES

Abstract. By means of processing photoheliograms in the λ1700Ǻ ultraviolet emission (temperature minimum, upper photosphere) obtained on the Solar Dynamics Observatory (SDO) spacecraft, the behavior of the relative intensity of bright plasma at the level of the photosphere during the development of impulsive phase of solar flares was studied. The interrelation of the course of change in flare ultraviolet emission with the profile of time derivative of the X-ray flux (1–8) Ǻ and with the value of enhancement in the density of electrons arising at development of flares has been revealed.

Keywords: Solar flares, photometry, emission of flares, gamma rays.

Introduction

With the help of modern space observations of the Sun with high temporal, spatial and spectral resolution, it is possible to study in detail the process of direct flare enhancement during the development of its impulsive phase. As a result of the effect of magnetic reconnection in the active regions of the corona, from areas of primary energy release, there are fluxes of rapidly moving plasma flows, heat waves and high-energy charged particles, some of which propagate downward through magnetic flux tubes. When interacting with a denser plasma at the footpoints of loops, X-rays, gamma rays are generated and the plasma is heated. The rapid and significant heating of plasma in the photosphere and the chromosphere leads to "evaporation" and raising it up and filling of all volume of the magnetic arches. During this period the greatest increase of soft X-ray radiation is observed. All this relates to the development of the impulsive phase. This is followed the main phase at which heated plasma in the system of arches radiates a long time in the soft X-ray range, gradually losing energy [1].

For powerful flares at a maximum of impulsive phase at photoheliograms λ1700 Ǻ there are bright thin vertical rays located in opposite directions from sites of hot plasma (bluming) that indicates to the excess brightness of radiation, overflowing of a charge in photomatrix pixels and its further redistribution.

At the same time, different flares have their own current sheet structure, as well as the underlying magnetic power tubes, which in each case leads to a unique direct flare energy enhancement, both in structural and in time dimension. Our purpose - to find regularities in properties of impulsive phase at development of various flares.

Processing of observational data

For each of the flares presented for consideration, the profiles of the change with time of the intensity of X-ray 1-8Ǻ (GOES), its derivative and the change in brightness of ultraviolet emission were compared. Temporal values of derivative X-ray (resolution 1 min) for flares events are taken in the SDO spacecraft database.

The VLAD program by means of which temporary changes of brightness of ultraviolet emission of flare concerning the center of a disk (figure 1) are received was developed for photometric processing of photoheliograms of SDO. The intensity of undisturbed photosphere was accepted for 1.00.

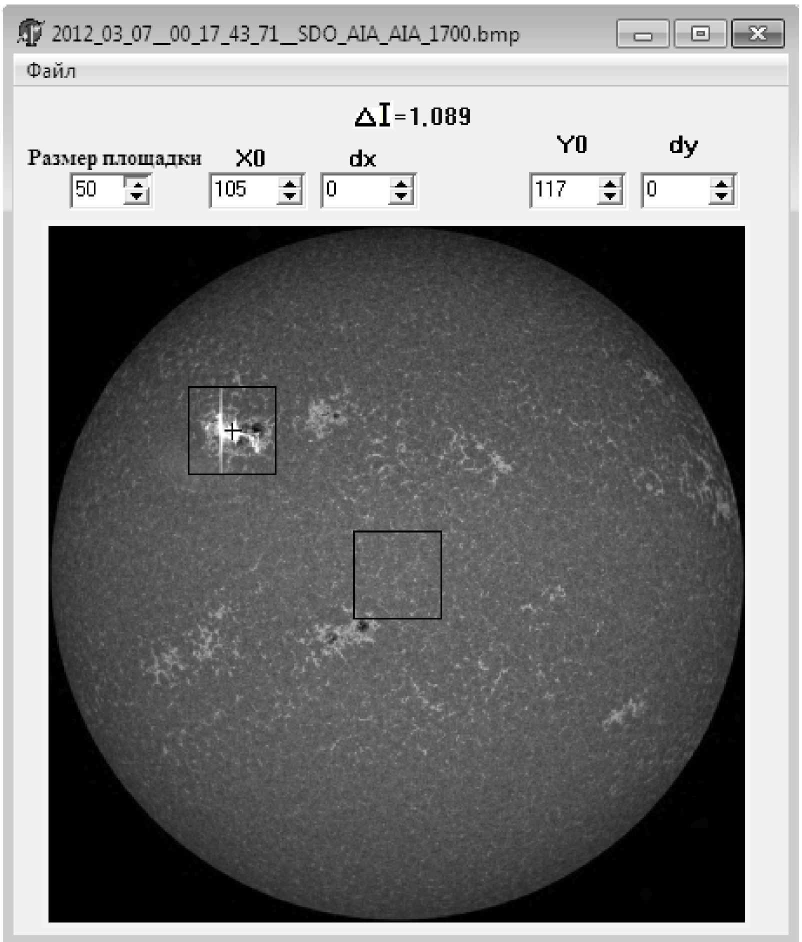

Figure 1 - A screenshot of process of photometric processing of photoheliogram λ1700 Å with the image of flare on March 7, 2012 at 00:17:43 UT

In total 12 flare events in the development of which were followed by bright areas of ultraviolet emission (table 1) are analyzed. Flares of various X-ray power from C2.5 to X6.9 and according to different classes are presented: impulsive and gradual.

Table I - Characteristics of the flares used in work, results of photometric processing and data on enhancement of density of electrons in flare plasma

№	Data and Onset Flares UT	Power X-ray Class of Flares	ΔImax λ1700Å	ΔN_{e^-} e^-/cm^3
1	07.03.2011 19:43	M3.7 Gradual	1.125	3.02
2	09.08.2011 07:48	X6.9 Gradual	1.236	3.00
3	06.09.2011 22:12	X2.1 Gradual	1.155	4.97
4	23.01.2012 03:38	M8.7 Gradual	1.099	2.50
5	07.03.2012 00:02	X5.4 Gradual	1.312	7.02
6	09.03.2012 03:22	M6.3 Gradual	1.141	2.98
7	06.07.2012 23:01	X1.1 Gradual	1.246	4.01
8	02.05.2013 04:58	M1.1 Impulsive	1.054	0.72
9	25.02.2014 00:39	X4.9 Gradual	1.253	4.03
10	16.05.2014 20:11	C2.5 Impulsive	1.020	0.51
11	20.10.2014 16:00	M4.5 Impulsive	1.051	1.03
12	24.10.2014 21:07	X3.1 Gradual	1.216	5.05

For three events in the figure 2 results of processing of observation data are presented. On geometrical arrangement and the sizes of bright areas of ultraviolet emission we can assume possible the structure of coronal loops in which flare radiation during the impulsive phase gets. Each of the flares shown in fig. 2, had a different number of flare nuclei at the level of the photosphere - from one to three. This was it corresponded in the number of peaks in the changes in the intensity of ultraviolet emission, in changes in the X-ray flux, as well as in the derivative of profile of this flux. Moreover, each peak is associated with changes in the brightness of an individual region, it indicates the discrete manifestation of sources of energy release during the development of flare in different parts of the corona.

Since the steady period of presence of negative values of a derivative on time of a flux of soft X-ray radiation, action of a source of flare enhancement – the end of impulsive phase actually comes to end. Further the main phase of development of flare begins. Between a maximum of impulsive phase and the beginning of the main phase there is a period of possible raising up of the heated plasma of photosphere and chromosphere (process of "evaporation" - an explosive stage) and fillings of all volume of coronal arches – an interval of maximum brightness of flare loops.

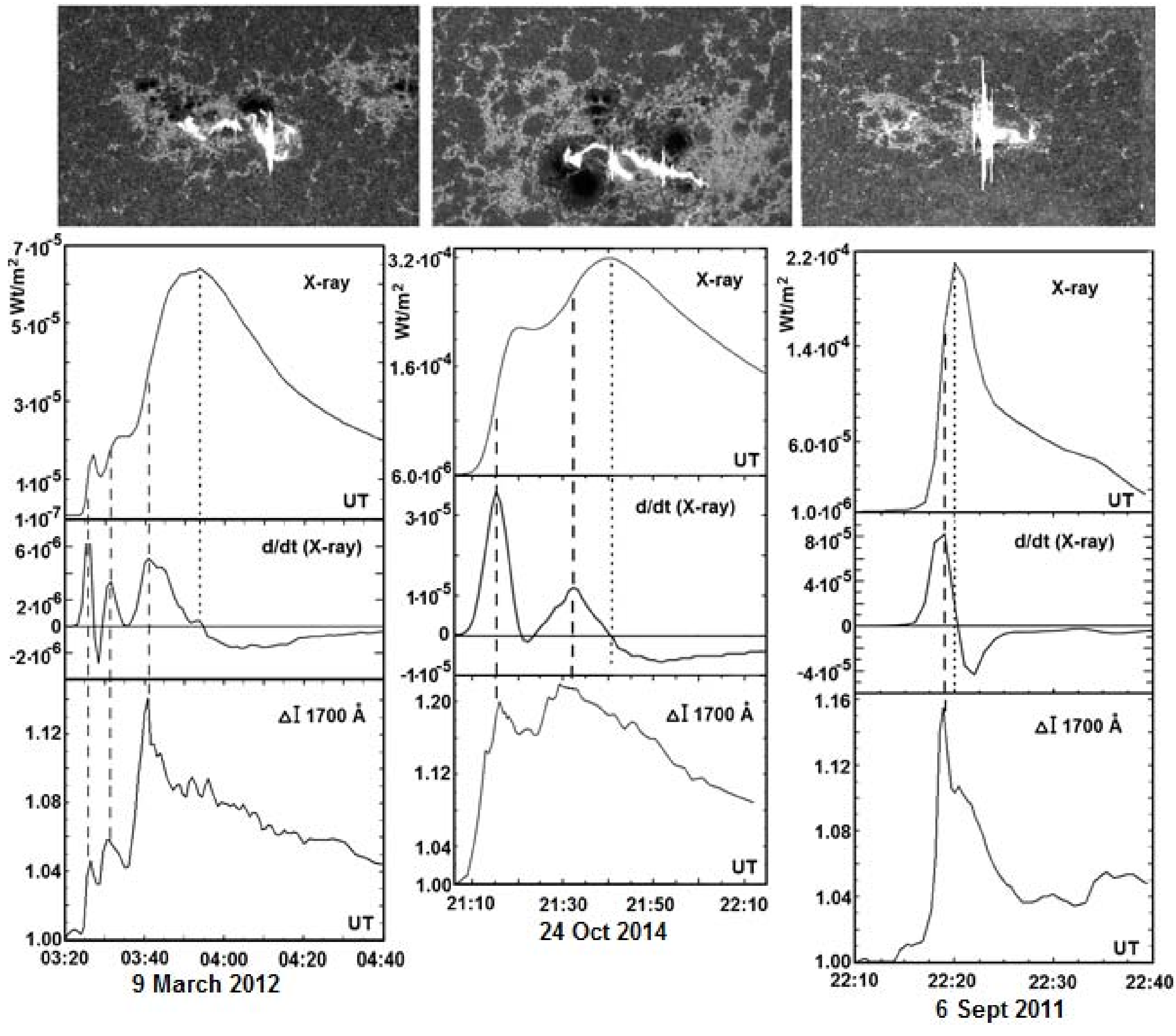

Figure 2 - Top panel: images of ultraviolet emission in a maximum of development of impulsive phase of flares: March 9, 2012 03:40:55 UT, M6.3; October 24, 2014 21:16:06 UT X3.1: September 6, 2011 22:18:55 UT, X2.1. Below - comparison of profiles of change fluxes X-ray intensity with its derivative on time and relative intensity of ultraviolet emission of flare plasma. Vertical dash lines are the moments of the greatest values of ultraviolet emission ΔI λ1700 Å; the dot line – maximum X-ray intensity

All the boundaries of the existing phases in development of flares are determined by the moments of the maximum values the intensity of ultraviolet emission λ1700Å, the X-ray flux and its derivative. Including the position of the explosive stage, which is shown on figure 3.

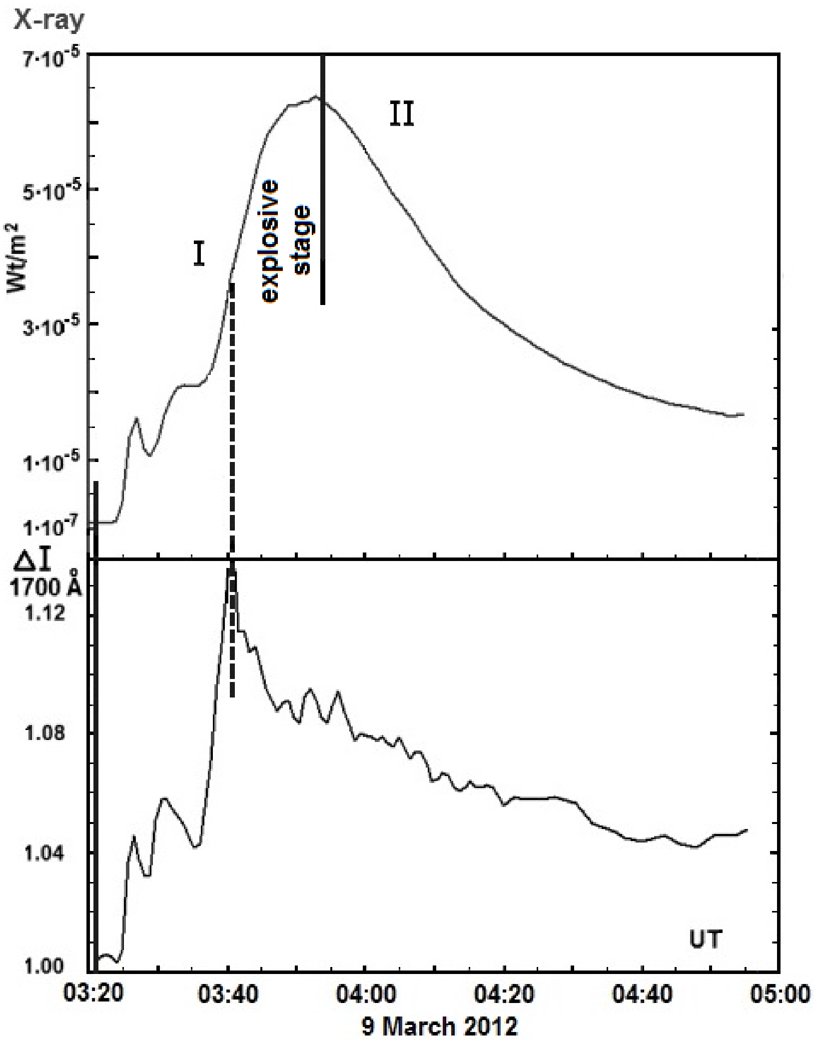

Figure 3 - Flare on March 9, 2012 M6.3 N15W03. Phases in flare development: I - impulsive phase (two vertical solid lines), II – the main phase. An interval between a maximum of impulsive phase and the beginning of the main phase – is explosive stage. The top curve - profile X-ray intensity and lower - relative intensity of ultraviolet emission of flare plasma

The change in the intensity of bright plasma at the level of photosphere λ1700Å is a good index characterizing the direct flash strengthening, including the emission of flare gamma-ray fluxes. The materials of the telegram on the results of observations of the X6.9 flare on August 9, 2011 on FERMI spacecraft [2] reported that gamma radiation in the range energy >500 keV (the GBM tool, BGO device in period 08:02:05 - 08:03:43 UT) and LAT tool (20MeV – 1GeV, 08:01:40 - 08:05:00 UT) was recorded. It is remarkable that all these time intervals of enhancement fluxes of gamma radiation with emission peaks, coincide with a profile of maximum stage of development of ultraviolet emission flare plasma (fig. 4). At the same time the visibility period on photoheliograms of bright narrow rays with an excess brightness (08:01:43 - 08:03:43 UT), practically coincides with time of flare fluxes of high-energy gamma radiation. The flare on August 9, 2011 represents an exceptional case when at development of a gradual event the power prevalence of radiation in the period of impulsive phase, over main was observed.

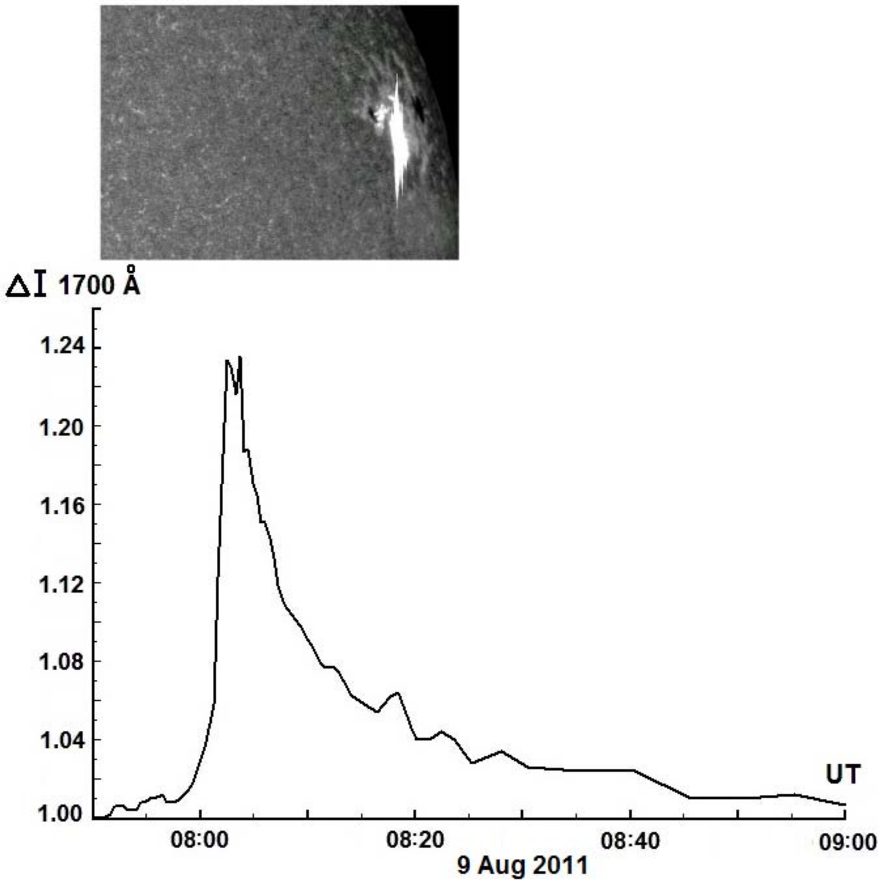

Figure 4 - Change of relative intensity of ultraviolet emission of flare plasma August 9, 2011 X6.9 N14 W69 and its look in the period of the maximum brightness - 08:03:43 UT (top picture)

Results of observations on the FERMI telescope for the period of impulsive phase were published also for flare on September 6, 2011 [3]. Significant increase in intensity of gamma radiation (~ 5 MeV) on the BGO device was observed from 22:18 till 22:23 UT, radiation peak at 22:19 UT. At the same time on images of the photosphere the increased flare brightness in the form of narrow rays is visible during the 22:18:07 – 22:23:19 UT, with a maximum at 22:18:55 UT (see fig.2). That is, there is a coincidence on time of the enhancement of gamma radiation with the maximum ultraviolet emission of flare.

As for development of gradual flares during the main phase, all of them were followed by joint influence of coronal mass ejections (CME). An additional source of proton acceleration associated with the development of high-velocity CME may be the occurrence of shock waves in the upper layers of the corona and in the interplanetary space. The flare protons accelerated on the shock front of emissions to energy E_k >500 MeV, became a source of gamma radiation of very high energy: (100 MeV-10 GeV) which was registered on the FERMI telescope. Only gradual events on August 9, 2011 and on October 24, 2014 showed the maximum values of energy of gamma radiation of smaller values.

The important parameter connected with relative intensity of flare emission at the level of photosphere the values of enhancement of density of electrons during flare development is represented. In figure 5 comparison of temporary change of relative intensity of flare brightness in the photosphere λ1700 Å and enhancement density of electrons of Ne^{-} in 1/cm^3 (SC WIND) is shown. Coincidence of the course of these profiles for two flares of an event on March 7, 2012 indicates relationship of the considered parameters.

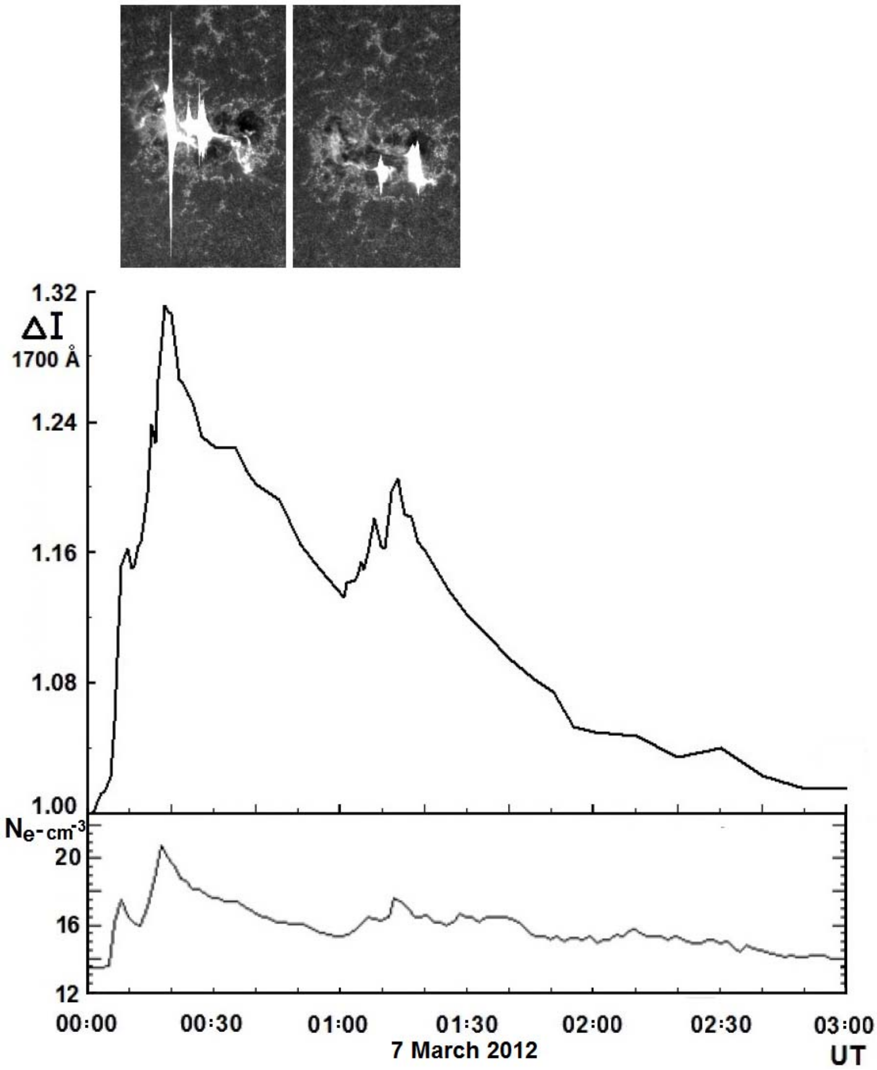

Figure 5 - Comparison of the relative intensity of the ultraviolet emission λ1700Å with the electron density of Ne^{-} during the development of flares on March 7, 2012. At the top: photoheliograms of flares March 7, 2012 00:17:43 UT X5.4 N18 E31 and March 7, 2012 01:13:43 UT X1.3 N15 E26 in the periods of maximum ultraviolet emission

The similar picture is observed for all events used in our work. Satellite observations show of enhancement of density of flare electrons practically simultaneous registration with gamma radiation of ultraviolet flare emission. To explain this fact, it is necessary to allow an exit of fluxes of high-energy flare electrons through open magnetic structures of active regions in interplanetary space and, in the minimum interaction with plasma of solar wind, before arrival to Earth orbit. So for flares on March 7, 2012 considerable raising of an integrated fluxes of electrons > 4 MeV from background value $1.7\cdot10^{1}$ to $2.9\cdot10^{3}$ $e^{-}/(cm^{2}$ s sr) was registered on the GOES spacecraft.

At development of three considered impulsive flares (table 1): on May 2, 2013, ΔNe^{-}=0.7 (1/cm^3), on May 16, 2014, ΔNe^{-}=0.5 (1/cm^3) and on October 20, 2014 ΔNe^{-}=1.0 (1/cm^3), are registered only insignificant enhancement of density of electrons, in limits by ΔNe^{-}= 1.0 (1/cm^3). While the gradual flares led to more significant enhancement of density of electrons: ΔNe^{-}=2.5-7.0 (1/cm^3).

Thus, it is possible to claim about existence of relationship between the values of the maximum intensity ΔI λ1700 Å and enhancement of density of electrons ΔNe^{-} the arising from development of flares (fig. 6).

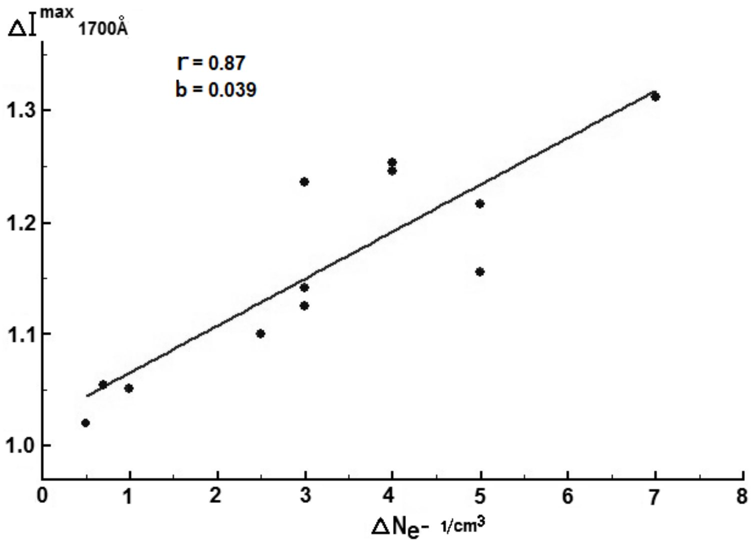

Figure 6 - Comparison of maximum relative intensity of ultraviolet emission λ1700 Å and values of enhancement of density of electrons ΔNe⁻ for the considered flare events. Averaging of dependence is shown on condition of minimum mean squared deviations of values from an average. A coefficient of correlation according to Pearson r=0.87 and a regression coefficient of b=0.039 are calculated

Discussion of the results and conclusion

12 flare events of different classes from C2.5 to X6.9 (March, 2011 – October, 2014) are analysed in which development bright ultraviolet emission (λ1700 Å), were observed. The program by means of which temporary changes of brightness of ultraviolet flare emission concerning the center of a disk are received is developed for photometric processing of photoheliograms (temporary resolution ~ 50 sec.). For each flares change profiles intensity X-ray (1-8 Å) were compared with its derivative on time and relative brightness of an ultraviolet emission. The maximum X-ray emission of flares, which coincides with the zero value of its derivative, corresponds to the end of the impulsive phase and the beginning of the main phase of the development of flares. The explosive stage of flares connected with "evaporation" of the chromosphere and fast raising of hot plasma up occurs in a period between a maximum of impulsive phase and the beginning of the main phase.

A quite satisfactory relationship was found between the values of the maximum intensity of bright regions of ultraviolet emission at λ1700Å and the magnitude of the enhancement of the electron density, ΔNe^{-}, arising during the development of flares.

The course of the relative intensity of bright flare plasma at the level of the photosphere coincides with the profile of the derivative of the X-ray flux, and its values are a good index of direct flare enhancement, including the emission of gamma-ray fluxes in the impulsive phase of flare development.

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Г. Минасянц, Т. Минасянц, В. Вдовиченко, А.Ж. Бибосинов

В.Г. Фесенков атындағы Астрофизикалық институт, Обсерватория-23, Алматы, Қазақстан

КҮН ЖАРҚЫЛЫНЫҢ ДАМУ КЕЗІНДЕГІ УЛЬТРАКҮЛГІН ЭМИССИЯНЫҢ ҚАСИЕТТЕРІ

Аннотация. Solar Dynamics Observatory (SDO) ғарыш аппаратынан алынған, ультракүлгін эмиссиялы λ1700Å, фотогелиограмм көмегімен (температура минимумын, жоғарғы фотосфера) өңдеу, күн жарқылының импульсті фазаның дамуында фотосфера деңгейіндегі жарық плазманың салыстырмалы интенсивтілігінің ерекшелігі зерттелді. Уақыт бойынша туынды профильді рентген сәулеленуінің (1-8) Ǻ ағынын, ультракүлгінді эмиссиялы жарқылмен өзара байланыстыратын және жарқылдың даму кезіндегі пайда болатын, электрондар тығыздығының күшею шамасының өзгеру жолдары анықталды.

Түйін сөздер: күн жарқылы, фотометрия, эммисиялық жарқыл, гамма сәулелену.

УДК 523.62

Г.С. Минасянц, Т. М. Минасянц, В.Д. Вдовиченко, А.Ж. Бибосинов

Астрофизический институт им. В.Г. Фесенкова, Обсерватория-23, Алматы, Казахстан

СВОЙСТВА УЛЬТРАФИОЛЕТОВОЙ ЭМИССИИ ПРИ РАЗВИТИИ СОЛНЕЧНЫХ ВСПЫШЕК

Аннотация. С помощью обработки фотогелиограмм с ультрафиолетовой эмиссией λ1700Ǻ (температурный минимум, верхняя фотосфера), полученных на космическом аппарате Solar Dynamics Observatory (SDO), проведено изучение поведения относительной интенсивности яркой плазмы на уровне фотосферы при развитии импульсной фазы солнечных вспышек. Выявлена взаимосвязь хода изменения вспышечной ультрафиолетовой эмиссии с профилем производной по времени потока рентгеновского излучения (1-8) Ǻ и с величиной усиления плотности электронов, возникающих при развитии вспышек.

Ключевые слова: солнечные вспышки, фотометрия, эмиссия вспышек, гамма излучение.

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Information about authors:

1. Minasyants Gennady Sergeevich, Fesenkov Astrophysical Institute, Leading Researcher, gennadii_minasya@mail.ru;
2. Minasyants Tamara Mihailovna, Fesenkov Astrophysical Institute, Senior Researcher, gennadii_minasya@mail.ru;
3. Vdovichenko Vladimir Dementjevich, Fesenkov Astrophysical Institute, Leading Researcher, vdv1942@mail.ru;
4. Omarov Chingis Tukenovich, JSC «National Centre for Space Research and Technology» (JSC «NCSRT»), president, chingis.omarov@gmail.com.

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