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FIP EFFECT MANIFESTATION FEATURES IN CORONAL MASS EJECTIONS

Abstract. FIP effect manifestation features in coronal mass ejections are investigated. For the analysis observational data from SC ACE (SWICS device) spacecraft were used in an ion energy range (0.5-100) keV/e. In addition to the values of the relative content of Fe/O, an indicator was obtained that characterizes the degree of ionization of iron and oxygen ions Q(Fe), Q(O). To quantify the values of the parameters Q(Fe) and Fe/O, their mean values were calculated in the six-hour interval during the time period of these indexes. A comparison of the values of Q(Fe) and Fe/O showed that for Fe ions less than +13 there is practically no change in Fe/O with increasing Q(Fe). But with Q(Fe) ≥13, the manifestation of the FIP effect is sharply increased, due to the increase in the relative contents of Fe ions. Probably, due to the penetration of an energetic flare plasma into the body of the outbursts, when they develop together in the corona of the Sun, a significant increase in the degree of ionization of the Q(Fe) ions occurs. As a result, the Fe/O index can be used as an indicator of the possible presence of flare plasma in the coronal mass ejection charge structure.
Keywords: solar activity, coronal mass ejections, energy spectra, FIP effect, Fe/O ratio.

Introduction

Flares and coronal mass ejections (CME) are primary active processes on the Sun which influences on state of interplanetary environment and Earth's magnetosphere. According to a modern conceptions flare and CME may be consider as a unified process connected with an equilibrium violation of magnetic structure owing to free magnetic energy build-up in an active region. While energy releases of accumulated magnetic energy in flare dissipation regions (current sheets) it occurs a fast plasma heating and particle acceleration to a high energy [1-3]. Besides, a high-velocity CME (CME masses can reach up to 10^{15} - 10^{16} g and their velocities can exceed 2000 km/sec) are capable to generate a shock waves which can accelerate of particles effectively, when flare plasma flows move near the Sun and in interplanetary medium.

It is noted that in flare evolution a part of hot flare plasma can to penetrate into CME ejection body and then the observed spectrum of accelerated particles has a composite character. In this connection values of minor element ratio Fe/O play an important role which is consequence of FIP effect manifestations (FIP- first ionization potential) because this particle population accelerated by flare is a highly enriched Fe (Fe/O>1). On the contrary, particles accelerated by shock waves are depleted by Fe (Fe/O<1).

The composition of minor elements in the photosphere, fairly reliably determined by spectroscopic methods, is completely homogeneous over the entire visible solar surface; however, the abundance of admixtures in structural formations of the solar corona and solar wind appears to differently depend on FIP relative to their concentrations in photosphere. It has been established that the admixtures are fractionated according to FIP in the upper solar chromosphere. Elements with low FIP (<10 eV – Fe, Mg, Si, K, etc.) are easily ionized and carried away under driving the ponderomotive force of alfven waves to the upper solar atmosphere [4,5] where these ions are able to accumulate largely in the central parts of closed magnetic structures of active regions. Driving mechanism on minor ions by ponderomotive force of alfvenic waves was proposed by Laming [5] and in a present time it is considered as a most likely mechanism as far as it has ability to explain FIP effect manifestations not only in solar corona but in stars coronae too. Alfven waves are generated at footpoints of loop magnetic field structures under random plasma motions in photospheric layers and may be generated in magnetic reconnection regions also. Minor elements with a high FIP (>10 eV – C, N, O etc.) remain neutral in chromospheric layers and their abundances does not change because their ionization occurs in high-temperature coronal layers only. Consequently, the ratio value Fe/O in different coronal structures and in solar wind has a various values and it may be considering as an indicator of physical processes in solar plasma. In the first time the FIP effect manifestations in solar corona was established spectroscopically by Pottasch [6].

Recently, new results have been obtained on the evolution and distribution of impurity elements in the structures of solar active regions. Observations from the Hinode/EIS satellite have shown that impurity elements with low FIP potential can accumulate in the upper parts of the loop structures with strong fields in the central zones of active regions [7]. At the periphery of the active regions, the magnetic reconnection process with the emerging small-scale magnetic fields with a photospheric composition prevents the accumulation of elements with a low potential of FIP. As a result of the "exchange" magnetic reconnection, plasma with a reduced composition of elements with a low FIP goes beyond the active regions and can manifest itself in a slow solar wind [8].

Detailed observations also showed that the composition of the elements in the hot plasma evaporating during large X-ray flares is close to the photospheric composition [9]. At the same time, the composition of ions in the plasma of CME emissions associated with such outbursts turns out to be a highly enriched element with a low potential of FIP and a high degree of ionization. Such emissions are called "compositionally hot" CME emissions [8]. It is noted that such CME emissions are injected from the central parts of active regions. In observations of the phenomena of pulsed heating in the solar transition region, a plasma composition close to the photospheric composition was also found. In contrast, the fan of the overlying coronal loops showed enrichment with elements of low FIP potential [10]. These authors concluded that the composition of the plasma can serve as an important sign of coronal heating. Naturally, the FIP effect is also manifested in the composition of energetic particles accelerated by flares and ejections, therefore some characteristics will be described here.

Based on the results of the analysis of 54 solar cosmic ray events (SCL) (November 1994-June 2012) in the energy range of 2-15 MeV/n, Reames [11] concluded that the main cause of variations in the abundances of heavy ions in the interplanetary medium, and, consequently, changes in the ratio of Fe / O is their scattering by Alfven waves, which depends on the magnetic stiffness of the particles. This process occurs during the propagation of particles from the region of acceleration due to shock waves caused by CMEs. Alfven waves in the solar wind are excited by vigorous protons and impurity ions themselves, which are accelerated both in flares and in shock waves from the CME [11]. Fe ions are scattered by Alfven waves less efficiently than oxygen ions, therefore, in the case of propagation in a turbulent medium, iron ions outstrip oxygen ions, which leads to registration of Fe / O> 1 ratios.

Thus, in this paper, some features of the manifestations of the FIP effect in the composition of CME will be described in terms of the characteristics of the ratio of Fe / O in the CME structures and the degree of ionization of Fe.

Processing of the observation data

For the research purposes, 17 CME (1998-2006) were selected, which had a pronounced front shock front with the highest confidence level - Shock4 (according to SOHO classification). All CME emissions belonged to the structural type "halo". In the course of propagation of CMEs in the corona and interplanetary medium, the magnetic structure of the ejection expands after the forward shock wave. The turbulent region of compressed plasma immediately behind the front of the shock wave is characterized by strong variations of the components of the interplanetary magnetic field B, increased values of the proton density N_p, their velocity V_p and temperature T_p [12]. Behind the area of turbulent compression (shell) is the actual "body" of the ejection. The data describing the time boundaries of each of the CME structures were taken in the "Wind ICME Catalog".

In the earlier work Minasyants et al. [13], Fe/O energy spectra were calculated in seven different energy intervals for the CME structures representing magnetic clouds with the help of the Fe and O energy spectra. The value of the Fe/O ratio in the region of turbulent plasma compression in the entire ion energy range remains less than unity, which indicates that the Alfven turbulence of the oxygen ions is weak, which have a high FIP value. In the magnetic cloud region in the energy range (0.2-0.6) MeV/n, the

Fe/O ratio is much higher and in some cases even exceeds unity. This may be due to the amplification of scattering by Alfven waves or to the effect of preferential accumulation of ions with a low ionization potential in a magnetic cloud before ejection.

To investigate the structure of the emissions, in addition to the values of the Fe/O index, an indicator was obtained that characterizes the degree of ionization of elements, including iron and oxygen ions. The hourly average values of these parameters, as well as the velocities of Fe ions (for the charge state Q= +10) and O (for the charge state Q= +6) were taken in the ACE spacecraft database (SWICS device)-all observations refer to the energy interval (0.5-100) keV/e.

To quantify the values of Q(Fe) and Fe/O, their mean values were calculated in the six-hour interval during the period of increase in the time profiles of these parameters (Table 1).

Discussion of results and conclusions

The following figure shows the changes in the O and Fe ion velocities with time, their degree of ionization Q(O), Q(Fe), and the relative Fe/O content for CMEs that resulted from the development of powerful events - solar cosmic ray bursts (GLE). Vertical dashed lines from left to right show: the arrival of the shock wave front (UV) CME, followed by the region of turbulent plasma compression (shell), between the second and third dashed lines - the "body" of ejection.

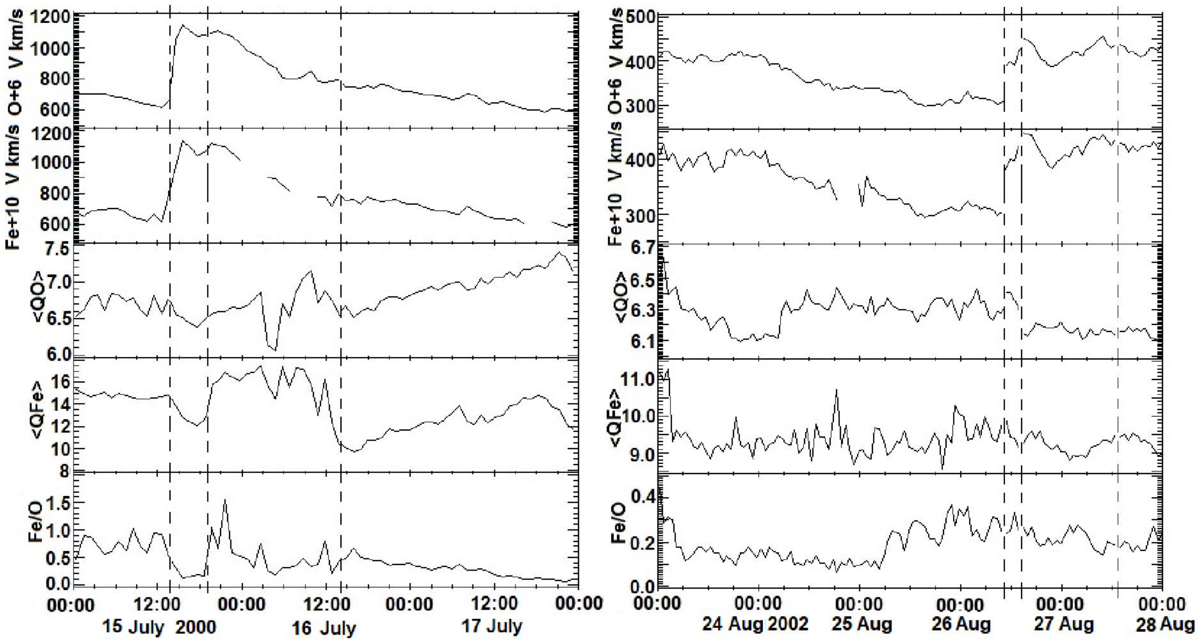

Figure 1 - Time changes with physical parameters in the structures of CMEs on July 15-16, 2000 and August 26-27, 2002

It is noted that the manifestation of the FIP effect associated with an increase in the relative content of Fe ions with respect to O ions is enhanced in those cases when ions with increased charge states Q(Fe) are present in the plasma of the CME emission (July 15-16, 2000). For the CME event, on the 26-27 August 2002, on the contrary, the values of the degree of ionization of the Q (Fe) ions, and, in fact, the lower, actually background values, and, accordingly, the Fe/O ratio does not show such amplification. It is likely that this testifies to the absence of more energetic flare plasma in the structure of the coronal ejection.

Consideration of temporal changes in parameters for all selected CMEs indicates their individual properties associated with the composition of the plasma in the ejection, which manifests itself in different values of the degree of ionization of Q(Fe), Q(O) ions, and their relative Fe/O content. In order to quantify the values of the parameters Q(Fe), Fe/O in each CME, their mean values were calculated over a six-hour interval during the period of increase in the time profiles of these indices.

One more feature in the CME emission structure was noticed. The region of turbulent compression, which is characterized by high values of the plasma parameters V, N_p, B, T, associated with the shock wave of the CME, as a rule, does not show the growth of the parameters Q(Fe), Q(O), Fe/O. This indicates a weak efficiency of scattering of ions by Alfven turbulence in this region (the turbulence of Alfven waves exist behind the shock wave).

Table 1 shows the time of passage of all structural elements for the CMEs considered: the front of the shock wave, the region of turbulent compression (shell), and the actual ejection body. For the plasma of the considered emissions, in separate columns of the table, the electric field strength is E^{-}, the charge states of the iron ions are Q(Fe) and the iron ion content with respect to oxygen is Fe/O with error averaging.

Table1 - The passage time of the structural elements of the CME and the values of the electric field parameters, the degree of ionization of iron ions and the ratio of Fe/O in the release plasma

№	Arrival of CME Shock	Shell End/Frontal part of CME body	CME End	E, mV/m	Q(Fe)	Fe/O
1	04:20.08.11.1998	08:00.08.11.	23:31.08.11.	7.09±0.16	13.18±0.18	0.37±0.05
2	14:17.15.07.2000	19:10.15.07.	14:30.16.07.	21.61±6.89	16.80±0.18	0.81±0.17
3	18:19.11.08.2000	06.05.12.08.	05:05.13.08.	14.55±1.19	14.92±0.17	0.63±0.04
4	00:14.31.03.2001	12:00.31.03.	02:00.02.04.	15.47±2.14	15.58±0.19	0.79±0.13
5	23:57.17.04.2001	06:20.18.04.	07:20.19.04.	4.28±1.53	10.35±0.06	0.23±0.02
6	04:28.28.04.2001	17:59.28.04.	04:48.02.05.	-	15.99±0.11	0.88±0.10
7	02:33.28.10.2001	11:00.28.10.	03:17.30.10.	5.92±0.43	14.36±0.89	0.40±0.05
8	05:51.24.11.2001	15:47.24.11.	13:17.25.11.	5.38±3.45	13.26±0.32	0.53±0.06
9	04:08.23.04.2002	07:11.24.04.	23:59.24.04	0.44±0.07	11.37±0.07	0.18±0.01
10	10:20.26.08.2002	14:23,26.08.	13:40.27.08.	2.46±0.41	9.41±0.07	0.27±0.01
11	05:51.29.10.2003	11:16.29.10.	10:00.30.10.	-	16.31±0.25	0.79±0.15
12	16:00.30.10.2003	04:30.31.10.	23:00.02.11.	-	16.77±0.20	1.20±0.23
13	05:53.04.11.2003	14:00.04.11.	12:00.06.11.	0.87±0.05	9.74±0.07	0.16±0.01
14	18:24.09.11.2004	20:38.09.11.	16:47.10.11.	15.80±0.85	13.87±0.18	0.64±0.08
15	16:48.21.01.2005	23:45.21.01.	19:12.22.01.	1.75±0.60	12.23±0.28	0.21±0.07
16	02:19.15.05.2005	04:17.15.05.	22:47.16.05.	22.51±7.16	16.34±0.19	0.89±0.09
17	13:57.14.12.2006	22:36.14.12.	13:40.15.12.	12.43±0.50	16.31±0.10	0.51±0.10

A comparison of the values of the degree of ionization of Q (Fe) ions and the relative content of iron ions to Fe/O oxygen in the CME plasma is shown in Fig. 2. At Fe ions less than 13, practically no Fe/O changes with Q (Fe) increase are observed. But for Q (Fe) ≥ 13, the manifestation of the FIP effect is sharply increased, due to an increase in the relative content of Fe ions. This is probably due to the presence of flare plasma in the body of emissions.

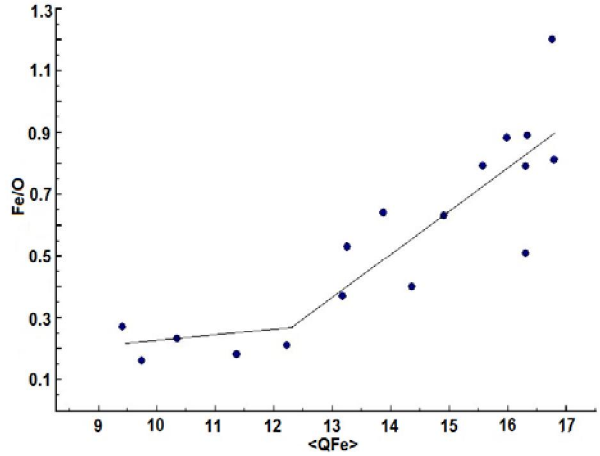

Figure 2 - Degree of Fe ionization versus Fe/O values for considered CME events.

The obtained result agrees well with the conclusions of Zurbuchen et al. [8], devoted to the study of the relative contents of various elements in the structures of a number of CMEs, where a tendency was established to enhance the effect of the FIP effect upon the growth of the charge state of Fe ions.

A special study was devoted to the identification in the CME structure of a correlation relationship between changes in the values of individual physical parameters V, B, N_p, E^-, T° K and Fe/O, Q(Fe) values. Of all the parameters considered, the best correlation with changes in Q(Fe) and Fe/O in the plasma of coronal discharges is shown by the values of the electric field strength E, which have a natural relationship with the electron density (Fig. 3).

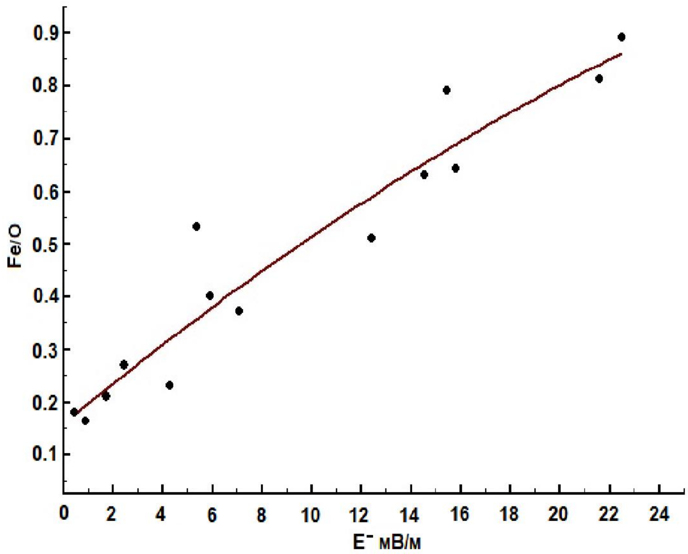

Figure 3 - The dependence of the electric field strength E^- mV/m on the relative content of iron and oxygen ions Fe/O from observations in the plasma of coronal mass ejections

Thus, the most probable reason for the enhancement of the values of Q(Fe) and, respectively, of Fe/O, is the penetration into the body of the ejection of an energetic flare plasma significantly enriched by electrons in the initial phase of their joint development. Based on the observational data described in the Introduction, it can be concluded unambiguously that "composite hot" CME emissions are injected from the central parts of the active regions. It is there, at the tops of the loops, the accumulation of elements with a low potential of FIP. In the process of ejection and associated outbreaks, strong electric fields appear in this region, and hot and dense plasma is produced, with accelerated electrons. Naturally, multiply charged ions are strongly affected by electric fields, so the observed increase in the Fe/O ratio can be explained. As a result, the Fe/O ratio can be used as an indicator of the possible presence of flare plasma in the coronal ejection structure.

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МАССАНЫҢ КОРОНАЛДЫ ШЫҒАРЫЛУЛАРЫНДА FIP-ӘСЕРДІҢ КӨРІНУІНІҢ ЕРЕКШЕЛІКТЕРІ

Аннотация. Массаның короналды шығаруларында FIP-әсердің көрінуінің ерекшеліктері зерттелді. Өңдеулер үшін иондар (0.5-100) кэВ/е энергиясы диапазонында ACE (SWICS аспабы) ғарыш аппараты бақылауларының мәліметтері пайдаланылды. Fe/O салыстырмалы құрамы мәнінен басқа темір және оттегінің Q(Fe), Q(O) иондарының иондану дәрежесін сипаттайтын көрсеткіш тартылды. Q(Fe) және Fe/O параметрлерінің мәнінің сандық бағалауы үшін бұл индекстердің уақытша бағыттарының артуы кезеңінде алты сағаттық интервалда олардың орташа мәні есептелді. Fe иондары зарядтары кезінде Q(Fe) және Fe/O мәндерін салыстыру Q(Fe) өсуімен Fe/O шамасының өзгеруі +13 –ден азырағы бақыланбайды. Бірақ Q(Fe) ≥13 кезінде Fe иондар құрамы салыстырмалы артуымен байланысты FIP-әсердің көрінуі кенет күшейеді. Күн тәжінде олардың бірлескен дамуы кезінде мүмкін шығарулар денесіне энергиялық жарқыл плазманың енуі нәтижесінде, Q(Fe) иондарының иондану дәрежесінің айтарлықтай артуы болады. Нәтижесінде индекс Fe/O индексін короналды шығарулары құрылымында жарқыл плазманың болу мүмкіндігімен индикатор ретінде пайдалануға болады.

Түйін сөздер: күн белсенділігі, массаның короналды шығарылуы, энергия спектрлері, FIP – әсер, Fe/O қатынасы.

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ОСОБЕННОСТИ ПРОЯВЛЕНИЯ FIP-ЭФФЕКТА В КОРОНАЛЬНЫХ ВЫБРОСАХ МАССЫ

Аннотация. Изучены особенности проявления FIP-эффекта в корональных выбросах массы. Для обработки использовались данные наблюдений на космическом аппарате ACE (прибор SWICS) в диапазоне энергий ионов (0.5-100) кэВ/е. Кроме значений относительного содержания Fe/O был привлечен показатель, характеризующий степень ионизации ионов железа и кислорода Q(Fe), Q(O). Для количественной оценки значений параметров Q(Fe) и Fe/O были рассчитаны их средние значения в шестичасовом интервале в период повышения временных профилей этих индексов. Сопоставление значений Q(Fe) и Fe/O показало, что при зарядах ионов Fe, меньших +13 практически не наблюдается изменений величины Fe/O с ростом Q(Fe). Но при Q(Fe) ≥13 резко усиливается проявление FIP-эффекта, связанное с увеличением относительных содержаний ионов Fe. Вероятно, благодаря проникновению энергичной вспышечной плазмы в тело выбросов, при их совместном развитии в короне Солнца, происходит значительное увеличение степени ионизации ионов Q(Fe). В результате, индекс Fe/O можно использовать в качестве индикатора возможного присутствия вспышечной плазмы в структуре коронального выброса.

Ключевые слова: солнечная активность, корональные выбросы массы, спектры энергии, FIP – эффект, отношение Fe/O.

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