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FEATURES OF MAGNETIC STRUCTURE OF SUNSPOTS GROUPS AT DEVELOPMENT OF SUSTAINED FLUXES HIGH ENERGY GAMMA RAY

Abstract. The research of magnetic structure of sunspots groups which were sources of three highest values of fluxes gamma ray with energy of photons >100 MeV for all the time of observations on Large Area Telescope (LAT), on board the Spacecraft (SC) Fermi Gamma-ray is conducted. At the same time observed fluxes of gamma ray had also the greatest duration of existence. For comparison, group of spots of similar magnetic class was attracted, but in the absence in it of events that are sources of gamma ray. As a result of the analysis, a characteristic feature of the structure of magnetic fields was revealed: it is that in these sunspots groups inside the region of one polarity there is a very close location of the magnetic field of the opposite polarity. This occurs in the consequence of the interpenetration of cores and umbrae, as concentrated magnetic field carriers, of one polarity inside the field of another polarity. Observations show the existence of a rather long neutral line with very high magnetic field gradients, which affect the growth of active processes in the sunspots regions and, most importantly, the growth of proton acceleration efficiency on high-speed shock fronts and shock waves of CME.

Therefore, groups of magnetic class sunspots BD and BGD, having a structure of close interweaving of magnetic fields of opposite polarities, exhibit extreme activity and are proposed to allocate them into special subclasses - BDe and BGDe (extreme). In the absence of such a property in the magnetic field structure, there is no significant enhancement of activity in the sunspots groups of BD and BGD classes.

Keywords: Structure of magnetic field of sunspots groups, high energetic gamma rays from flares, magnetic subclasses with extreme activity.

Introduction. The most powerful active phenomena in the Sun are solar flares which usually are accompanied by the coronal mass ejection (CME). On modern representations, the flare and CME are considered as the uniform process connected with violations of balance of magnetic structure in active region. Development of flare is connected with allocation of free magnetic energy in active region owing to her dissipation in current sheets because of magnetic reconnection with the subsequent action of stochastic acceleration at development of various plasma instability [1-3]. At development of active region its magnetic structure with the filaments which are located on the line of the section of polarities of magnetic field continuously becomes complicated. Over filaments the closed loops of magnetic field which create in general the closed magnetic configuration of all active region up to coronal heights are located. At continuous impact of shift movements on bases of magnetic loops along neutral line of magnetic field filament (prominence) loses stability and begins to rise up in an expedited manner, opening magnetic structure and forming "core" of ejection of CME [4].

Shock waves of CME are considered as the main source of the accelerated solar protons to energy> 500 MeV at their distribution, both in corona of the Sun, and in the interplanetary environment [5]. According to results [6], protons with the energy exceeding 300 MeV in interaction with substance of the solar atmosphere are capable to generate the neutral and charged pi mesons (peonies) at which disintegration is formed a gamma ray. In cases of acceleration of flare protons to energy Ek> 500 MeV,

neutral peonies become sources of ray of gamma photons of high energy >100 MeV which is registered devices FERMI LAT.

Thus, summarizing results of the researches conducted earlier, we come to a conclusion that very important factor in development of the flare process leading to education high-energy gamma ray is the structure of magnetic field of active region, as represents the purpose of further researches.

Properties of magnetic structure of sunspots groups for events with the most intensive and long fluxes high-energy gamma ray

The national Center NOAA publishes the observation data of solar active regions received on various observatories with the indication of magnetic classification of sunspots groups of: A – unipolar, B – bipolar, BG – bipolar with irregularly located polarities, BD – the delta the structure in which at least one spot includes umbrae of opposite polarity and the most complex – BGD includes in addition to previous irregularly located cores of opposite polarities. (stp_space-weather_solar-data_solar-features_sunspot-regions_usaf_mwl.html).

The numerous, earlier conducted researches showed that the active regions possessing the most complex magnetic structure (classes BD and BGD) are sources of overwhelming number of the highest powerful proton events with *pfu*>10^3 (the maximum value of flux of protons >10 MeV) [7].

In our research four events are used, three of which had the highest maximum values of flux gamma ray $9.0 \cdot 10^{-4}$ $\gamma \cdot cm^{-2} \cdot s^{-1} \leq F^{max}_{\gamma>100\text{MeV}} \leq 2.4 \cdot 10^{-3}$ $\gamma \cdot cm^{-2} \cdot s^{-1}$, (Fermi LAT Maximum Likelihood). At the same time, duration of fluxes of gamma photons with energy E_k >100 MeV was the largest - from 7 to 20 hours (figure 1). [https://hesperia.gsfc.nasa.gov/fermi/lat/qlook/LAT_qlook_plots.htm].

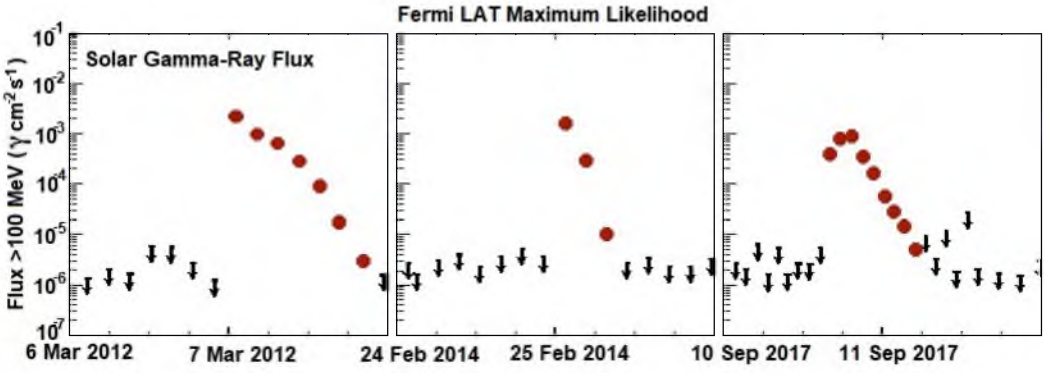


Figure 1 - Events of the highest intensity and the biggest duration
of fluxes gamma photons >100 MeV during observations of the Sun on telescope Fermi

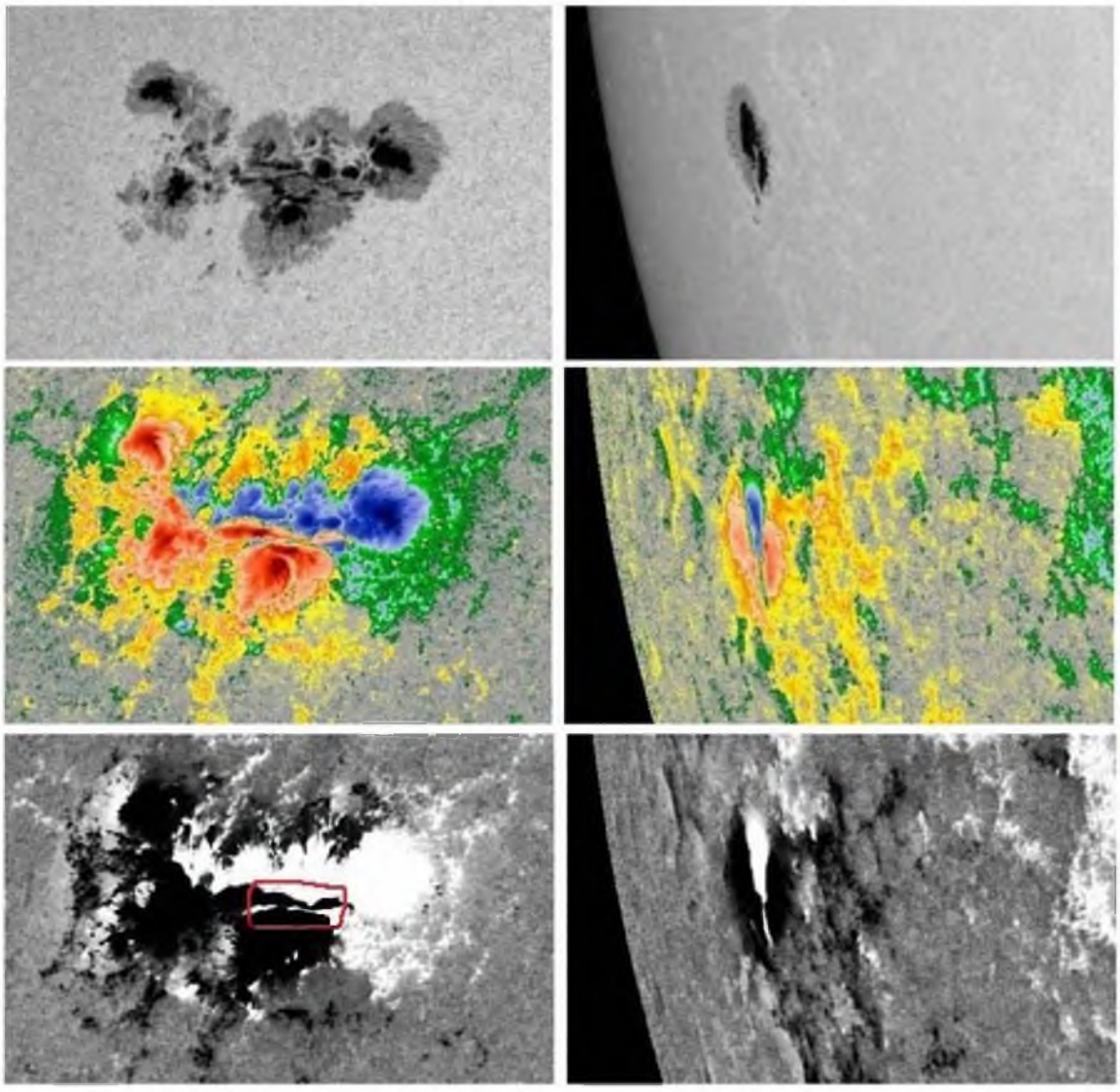
Especially for comparison the fourth event which occurred in the group of spots of a BGD class is attracted, but in it there were no flux of gamma ray. The main characteristics of the considered flare events are presented in table 1.

Table 1

Data, Location yyyy/mm/dd, deg	GOES X-Ray Class, Start	SEP Flux (pfu)	CME Speed, km s^{-1}	Duration $F_{\gamma>100\text{MeV}}$ hours	$F^{max}_{\gamma>100\text{MeV}}$ γ cm^{-2} s^{-1}
2012/03/07, N17E15	X5.4, 00:02	6310	2684	20	$2.4 \cdot 10^{-3}$
2014/02/25, S12E82	X4.9, 00:39	103	2147	7	$1.8 \cdot 10^{-3}$
2017/09/10, S08W83	X8.2, 15:35	1490	3163	12	$9.0 \cdot 10^{-4}$
2014/10/24, S12W22	X3.1, 21:07	-	184	-	-

Necessary to make a remark concerning rather low observed *pfu* value for powerful SEP - event on February 25, 2014. It is connected about arrangement of flare on longitude - actually east edge of disk the Sun. Therefore, in near-earth space of SC GOES were registered only an insignificant part of a flare flux of protons (table 1, the 3rd column).

Pictures with of SC Solar Dynamics Observatory are given below: a photosphere, color and black-and-white magnetograms for four considered groups of spots (figure 2,3).



a) b)

Figure 2 - a) On March 7, 2012 00h AR 1429; S=1310 millionths of the solar hemisphere (msh); N17 E15; group of spots of the class BGD; The area border with close located four layers of the alternating umbrae of opposite polarities is marked in red color on a black-and-white magnetogram. b) On February 25, 2014 00h AR 1990; S=250 msh; S12 E82; group of spots of the class BD

Comparison of structure of a magnetic field of four active regions which groups of solar spots have the complex magnetic configuration (classes BD and BGD) indicates presence in three cases of her additional very important property (figure 2a, and figure 3a). It is that in these groups of spots in region of one polarity the magnetic field of opposite polarity is observed. It results from interpenetration of umbrae of spots and pores as concentrated carriers of a magnetic field of one polarity in the field of other polarity. Only the close arrangement of two separate cores and large-scale magnetic fields of different polarities is characteristic of the fourth event (figure 3b) that didn't lead to very noticeable strengthening of the activity processes in AR2192. Quite compact AR2192 (class BGD) considerably exceeded other considered groups on the area. During passing on a disk of the Sun in it there were 95 flares of X-ray Class C, 33 flares of Class M and 6 flares of Class X. But at the same time, not a single proton event and not a single geomagnetic storm have been registered. Flares were accompanied by several Coronal Mass Ejections with very small speed.

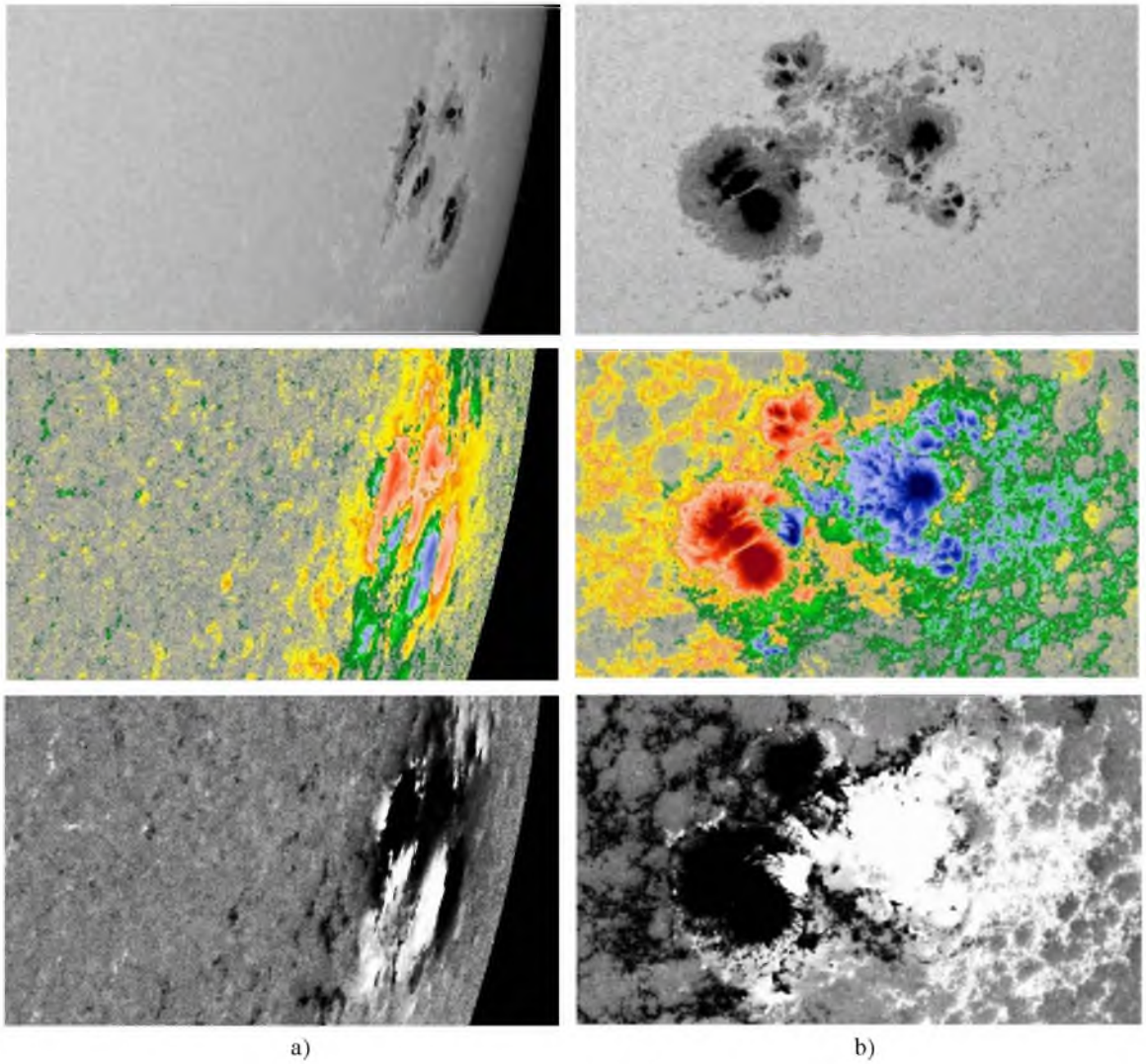


Figure 3 - a) On September 9, 2017 00h UT; AR 2673; S=1000 msh; S08 W74; group of spots of the class BGD; b) On October 25, 2014 00h UT; AR 2192; S=2500 msh; S12 W22; group of spots of the class BGD. The delta structure of group is defined by presence of umbrae of opposite polarities at the western part of a penumbra of the main multicores spot

It should be noted one more characteristic property of sunspots groups with the mixed polarities – very high gradients of a magnetic field on quite long part of the neutral line in the active regions.

Possibly, very high speeds of coronal mass ejections which accompanied development of flares were affected by the complex structure of magnetic field in first three (table 1) the considered active regions. The additional research showed that in the period of 2010-2017 on SC SOHO at development of 9 flare events coronal mass ejections which linear speeds exceeded 2000 km/s were observed. And only for 6 CME them sources (the active regions) were on a visible disk of the Sun. Thus, three more were added to three already considered events with high-speed CME. For them the following data are revealed: On January 23, 2012, V_{CME} =2175 km/s, M8.7, $F^{max}_{\gamma>100\text{MeV}}=2.3\cdot10^{-5}$ $\gamma\cdot см^{-2}\cdot с^{-1}$; On January 27, 2012, V_{CME} =2508 km/s, X1.7, $F^{max}_{\gamma>100\text{MeV}}=3.0\cdot10^{-5}$ $\gamma\cdot см^{-2}\cdot с^{-1}$; On May 13, 2013, V_{CME} =2625 km/s, X3.2, $F^{max}_{\gamma>100\text{MeV}}=3.5\cdot10^{-5}$ $\gamma\cdot см^{-2}\cdot с^{-1}$. Duration of fluxes gamma ray with energy of photons > 100 MeV according to observations on Fermi LAT (Maximum Likelihood) is from 2 to 5 hours. And the most important – sunspot groups had the complex magnetic structure with the mixed opposite polarities. That is, the assumption of relations of the linear speed of coronal mass ejections at development of flares with structure of a magnetic field of the active region is confirmed. To quantify the complexity of the magnetic structure of the active region the parameter can be used - the length of the neutral line of the magnetic

field, only those pieces where they pass between the cores and the umbrae of opposite polarities. So for the considered four events, length of pieces of the neutral line with the specified properties is respectively: On March 7, 2012 – 6.9 degrees., on February 25, 2014 – 3.2 degrees., on September 10, 2017 – 5.8 degrees, on October 25 2014 – 1.0 degree.

In areas of the active region with closely spaced umbrae of opposite polarities, the neutral line has many bends and the magnetic field has very high gradients. The length of the neutral line in such a complex magnetic field structure clearly characterizes its effect on the size of the eruptive filament, its mass, and the speed of coronal mass ejection in the further development of the active processes.

As a result of the unique location of the umbrae of different polarities in the active region of March 7, 2012, an area was formed, where a number of four layers were located, representing a sequential alternation of magnetic fields of opposite polarities (see Fig.2a). It is remarkable that the similar structure remained during all development of fluxes high energy gamma ray (20 hours). At the same time, in the gamma ray of solar flare March 7, 2012 on Fermi LAT the maximum values of energy of quanta of 4-4.5 GeV were registered [8].

Conclusion. Thus, the sunspots groups possessing most the complex structure of a magnetic field (classes BD and BGD) show extreme activity in cases of mixed of umbrae of opposite polarities. In such magnetic structures, there are extended neutral lines with very high magnetic field gradients. Therefore, the active regions having such unique magnetic structure feature should be allocated in special subclasses - BDe and BGDe (extremal). In the absence of such property in structure of a magnetic field, significant strengthening of activity in sunspots groups of the classes BD and BGD isn't observed.

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ЖОҒАРЫ ЭНЕРҒИЯЛЫҚ ҒАММА-СӘУЛЕЛЕНУІНІҢ ҰЗАҚ МЕРЗІМДІ АҒЫМДАРЫН ДАМЫТУДАҒЫ ДАҚ ТОПТАРЫНЫҢ МАГНИТТІК ҚҰРЫЛЫМЫНЫҢ ЕРЕКШЕЛІКТЕРІ

Аннотация. Күндегі көптеген белсенді құбылыстардың ішінде ең қуатты энергиялы жарқылдар және күн тәжімен байланысты шығарулар болып саналады. Олар жогары жылдамдықты бөлшектер агындарының және әртүрлі спектрлік аймақтардағы, соның ішінде гамма аймағындагы энергетикалық сәулеленудің көзі болып табылады.

Жарқыл проңесінің негізі тікелей бөлшектердің үдеуі болып табылады. Себебі, көптеген зерттеулер магниттік құрылымы ең күрделі аймақтар (BD және BGD кластары) жогары рентген сәулелері мен жогары энергиялы протондардың максималды ағындары бар ең қуатты жарқылдың басым көзі болып табылатындыгын көрсетті. LAT FERMI гамма телескопы арқылы бүкіл уақыт бойы бақыланган >100 МэВ кванттық энергиялы ең жогары үш гамма-сәулелену ағынының көзі болган күннің белсенді аймақтарының магниттік құрылымдары зерттелді. Сонымен қатар, бақыланган гамма-сәулелік ағындары өмір сүру уақыты ұзақ болды. Салыстыру үшін ұқсас магниттік кластың белсенді аймагы таңдалып, бірақ онда гамма-сәулеленудің пайда болуына әкелетін ерекшеліктер болмады.Орындалган талдау нәтижесінен белсенді энергетикалық оқигалары бар белсенді аймақтарга тән магнит өрісі құрылымының қасиеті - қарама-қарсы полярлы жақын орналасқан ядролар және дақтар көлеңкесін бөлетін жеткілікті ұзын бейтарап сызықтың болуы анықталды. Бұл басқа полярлық өрістің ішіндегі бір полярлы магнит өрісінің шогырлануының тасымалдаушылары ретінде ядролар мен көлеңкелердің өзара әсерлесуі нәтижесінде пайда болады. Бұл

жағдайларда жүргізілген бақылаулар бейтарап сызықтардың көлденең магнит өрісінің градиентінің өте жоғары мәндері бар, дақтар көлеңкесіндегі тік өріс градиентінің мәндерінен 5 есе жоғары бөліктерінің бар екендігін көрсетеді. Мүмкін, бұл магнит өрісінің осындай күрделі құрылымы энергияның таралуы кезінде бос магниттік энергияны тиімді шығаруға мүмкіндік береді (қайта қосу процесі) және бұл өте маңызды, жоғары жылдамдықты соққы фронттары мен күн тәжі шығарылымдардың соққы толқындарында протонды үдетудің тиімділігінің едәуір артуына әкелуі мүмкін.

Белсенді аймақта әртүрлі полярлықтардың көлеңкелерінің бірегей орналасуы нәтижесінде 2012 жылғы 7 наурызда қарама-қарсы полярлықтары бар магнит өрістерінің тізбектей ауысуын білдіретін төрт қабат бір-бірінің қасында орналасқан аймақ пайда болды. Бір ерекшелігі, ұқсас құрылым жарқылдағы гамма-сәулелік ағындардың бүкіл дамуы кезінде сақталды (20 сағат). Сонымен бірге, жарқыл процесінің жоғары энергиялы гамма-сәулесінде, Fermi LAT-да максималды кванттық энергия 4 ~ 4,5 ГэВ тіркелді.

Сондықтан, қарама-қарсы полярларлы магнит өрістерінің тығыз орналасуы құрылымы бар BD және BGD магниттік кластар дақтары өте белсенді және оларды арнайы ішкі кластарға бөлуі ұсынылады - BD және BGD (extreme). Магнит өрісінің құрылымында мұндай қасиет болмаган жагдайда, BD және BGD кластар топтарында белсенділіктің айтарлықтай өсуі байқалмайды.

Түйін сөздер: Дақтар топтарының магниттік өрісінің құрылымы, жарқылдардан жоғары энергиялы гамма-сәуле шығару, экстремалды белсенділігі бар магниттік класс тармақтары.

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ОСОБЕННОСТИ МАГНИТНОЙ СТРУКТУРЫ ГРУПП ПЯТЕН ПРИ РАЗВИТИИ ДЛИТЕЛЬНЫХ ПОТОКОВ ВЫСОКОЭНЕРГИЧНОГО ГАММА-ИЗЛУЧЕНИЯ

Аннотация. Среди многочисленных активных явлений на Солнце событиями с наиболее мощной энергетикой считаются вспышки и связанные с ними корональные выбросы. Они являются источниками как высокоскоростных потоков частиц, так и энергичного излучения в различных областях спектра, в том числе и в гамма – диапазоне.

Основой вспышечного процесса является прямое ускорение частиц. Многочисленные, ранее проведенные исследования показали, что активные области, обладающие наиболее сложной магнитной структурой (классы BD и BGD), являются источниками подавляющего числа самых мощных вспышек с высокими рентгеновскими баллами и максимальными значениями потоков высокоэнергичных протонов. В представленной работе изучены события, магнитные структуры активных областей которых были источниками трех самых высоких максимальных потоков гамма-излучения с энергиями квантов >100 MeV за все время наблюдений на гамма-телескопе LAT FERMI. При этом наблюдаемые потоки гамма-излучения имели также наибольшую продолжительность времени существования. Для сопоставления была привлечена активная область подобного магнитного класса, но с отсутствием в ней особенностей, приводящих к появлению гамма-излучения. В результате выполненного анализа выявлена характерная особенность структуры магнитных полей: она заключается в том, что в этих группах пятен внутри области одной полярности наблюдается очень близкое расположение магнитного поля противоположной полярности. Это происходит в результате взаимопроникновения ядер и теней как концентрированных носителей магнитного поля одной полярности внутрь поля другой полярности. Наблюдения в этих случаях показывают существование довольно протяженных участков нейтральной линии с очень высокими значениями градиента горизонтального магнитного поля, более чем в 5 раз превышающими значения вертикального градиента поля в тени пятен. Вероятнее всего, такая сложная структура магнитного поля позволяет эффективно освобождать свободную магнитную энергию в ходе диссипации энергии в токовых слоях (процесс пересоединения) и, что особенно важно, может приводить к существенному росту эффективности ускорения протонов на высокоскоростных ударных фронтах и ударных волнах корональных выбросов.

В результате уникального расположения теней разных полярностей в активной области 7 марта 2012 г. образовалась область, где рядом располагаются четыре слоя, представляющие последовательное чередование магнитных полей с противоположными полярностями. Примечательно, что подобная структура сохранялась в течение всего развития потоков гамма излучения во вспышке (20 часов). При этом, в высокоэнергичном гамма-излучении вспышечного процесса на Fermi LAT были зарегистрированы максимальные значения энергий квантов ~ 4-4.5 GeV.

Поэтому группы пятен магнитного класса BD и BGD, обладающие структурой тесной переплетенности магнитных полей противоположных полярностей, проявляют экстремальную активность и их предлагается

выделить в особые подклассы – BDe и BGDe (extreme). При отсутствии такого свойства в структуре магнитного поля не наблюдается существенного усиления активности в группах пятен классов BD и BGD.

Ключевые слова: структура магнитного поля групп пятен, высокоэнергичное гамма излучение вспышек, магнитные подклассы с экстремальной активностью.

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