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Does Geomagnetic Storm Magnitude Depend on Solar Flare Importance?

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Abstract—In order to predict space weather effects, solar flares are often used as precursors of magnetic storms on the Earth. In particular, possible relation between the solar flare importance and magnetic storm intensity is discussed in some papers. However, published results contradict each other. We compare the published results on the flare–storm dependence and discuss possible causes of this disagreement: (1) different intervals of observation, (2) differing statistics, and (3) different methods of identification of events and their comparison. Our analysis has shown that the fact of occurrence and the magnitude of a geomagnetic storm cannot be determined, generally, using only the solar flare importance. However, analyzing additional information on the coronal mass ejection (CME), associated with the geomagnetic storm, one can offer an algorithm for the storm magnitude prediction on the basis of flare importance.

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INTRODUCTION

One of the main purposes of solar-terrestrial physics is to study possible causes of geomagnetic storms on the Sun and in the interplanetary space. The basic factor resulting in magnetic storms is a large and long-lasting southward component of the interplanetary magnetic field (IMF) (see, e.g., [1, 2]), associated with interplanetary coronal mass ejections (ICME)—magnetic clouds and ejecta—and with compressed plasma in the region of interaction of fast and slow solar wind streams (corotating interaction regions—CIR) (see, for example, recent papers and reviews [3–7] and references therein).

Solar flares were the earliest powerful disturbances discovered on the Sun, and the researchers considered these events, for many years, as an important source of, virtually, all interplanetary and magnetospheric disturbances. For example, in the book "Physics of space: a small encyclopedia", published in 1986, in the section devoted to solar-terrestrial links [8], CME were not mentioned, but the role of solar flares was described. In early 1970-ties, another powerful solar process was discovered, coronal mass ejections (CME). In contrast to flare which manifests itself in the electromagnetic energy release, CME manifested themselves in ejecting a large plasma volume containing a rope of twisted magnetic lines, from the Sun into the interplanetary medium. The concept of CME effect on the interplanetary and magnetospheric disturbances, allowing one to satisfactorily explain many experimental results and physical processes, had attracted to its side ever growing number of researchers. A key point in prevalence of a dominating physical concept became Gosling's paper [9], whose publishing resulted in considering CME as an almost only source of all interplanetary and magnetospheric disturbances. Nevertheless, many researchers clearly understand the fact, that the flares and CMEs are merely different channels—electromagnetic and corpuscular (or MHD)—of one and the same process: the release of solar energy (see, e.g., [10–12] and references therein). Therefore, the solar flares, which are more easily observed technically than CME, are often considered as solar activity indicators and used for forecasting the interplanetary and geomagnetic disturbances (see, e.g., [13–18] and references therein).

It should be noted that the method commonly used for establishing the correspondence between solar phenomena and interplanetary phenomena near the Earth and in the magnetosphere and based on the delay time gives a formally calculated probability of relationship between these phenomena at the level of 30 % for any processes including random ones [3, 23]. Therefore, the geoeffectiveness of CME and flares at the level of 40–60 % and 30–40 %, respectively, found in the investigations [3, 16, 19], only slightly exceeds the level of random processes, and, so, one should be very cautious in accepting the results of such correlations.

The authors of a series of papers [20–26] tried to find the relation between the solar flare importance and the magnetic storm magnitude, since, if one would manage to find such a relation, then the solar flare importance could be used not only for forecasting the occurrence of a storm, but for forecasting its magnitude as well. However, the obtained results are not consistent

Published data on the ”flare importance – storm magnitude” relation

No.	Number of flares	Solar event + interplanetary event	Magnetospheric event	Time interval	Relation	Reference
1	65	Opt. flare ≥1	K_p	1954–1976	No*	[27]
2	144	Opt. flare >1(F,N,B) + CME	A_p	1988–1993	Yes	[20]
3	325	X-ray flare ≥M5	$D_{st} < -60$	1976–2000	No	[18]
4	325	X-ray flare ≥M5	$D_{st} < -60$	1976–2000	No	[22]
	70	X-ray flare ≥M0 + SPE	$D_{st} < -60$	1976–2000	No	
5	121	H_α, X-ray flare	A_p	1978–1999	No	[24]
6	24	H_α, X-ray flare	$D_{st} < -100$	1986–1993	No	[25]
7	103(?)	X-ray flare >C0 + CME + Shock	A_p, D_{st}	1998–2004	Yes	[26]
8	235	X-ray flare ≥M5	D_{st}	1988–1993**	No	This paper***

Notes: * the result of our processing of the Krajcovic & Krivsky’s catalog, 1982 [27];
** a part of the data from the paper by Yermolaev & Yermolaev [18] corresponding in time to the data of paper by Shrivastava & Singh, 2002 [20];
*** the preliminary version is published in the archive of preprints (http://arxiv.org/abs/physics/0601197).

with each other. Therefore, the purpose of this paper consists in comparing various published results for better understanding of the question on the existence of the “flare importance–storm magnitude” relation.

OBSERVATIONS

The analyzed results on the “flare–storm” relation are presented in Table.

Krajcovic and Krivsky [27] have published a large catalog of optical solar flares and magnetic storms (identified by the K_p index value) for the period of 1954–1976. However, they did not draw any explicit conclusion on the existence of a relation between the flare importance and storm magnitude. We have processed mathematically this catalog’s data and could not find any significant relation between the optical importance of flares and the magnetic storm magnitude.

Shrivastava and Singh [20] have used simultaneous observations of optical flares and CME, as well as the measurements of magnetic storms identified by the A_p-index, and have found the relation between the optical importance of flares and the magnitude of magnetic storms. Recently, Howard and Tappin have published a statistical study of interplanetary shock waves and their accompanying phenomena on the Sun and in the magnetosphere in 1998–2004 [26]. In particular, the authors presented Fig. 7, which showed the dependence between the solar flares importance (X-ray measurements on the *GOES* satellites) and the magnitude of geomagnetic storms (estimated by A_p and D_{st} indices). The total statistics is 103 pairs of events. On the basis of these data, the authors have noticed “a tendency for large flares to be associated with very large storms”. Though the authors did not include this result into Conclusions of their paper and said in the Abstract, that “this casts doubt on the validity of using flare data alone as an effective space weather forecaster”, the data of Fig. 7 clearly indicate to the existence of the “flare importance–storm magnitude” relation.

Shrivastava and Singh [20] and Howard and Tappin [26] first selected the pairs of “CME–magnetospheric disturbance” events and only after this operation analyzed the relation between the importance of associated flares and magnetospheric disturbances. Howard and Tappin [26], in addition, selected the events accompanied by interplanetary shock waves. Though correlations between the optical and X-ray importances of flares and between various geomagnetic indices are

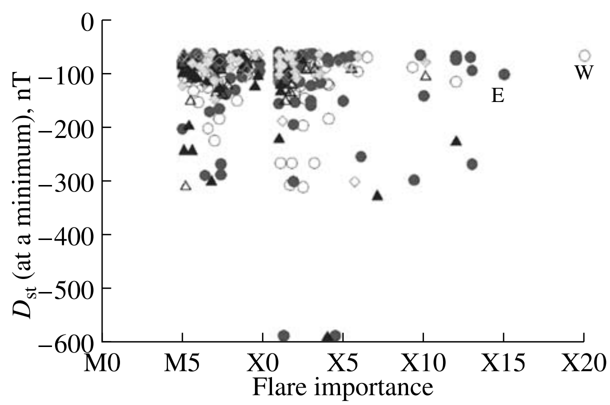

Fig. 1. Dependence of the minimum of the D_{st} index of magnetic storms on the X-ray importance of intense solar flares for the interval 1976–2000. (Figure is taken from the paper by Yermolaev & Yermolaev, 2003a). The data selection was carried out by: (1) flare position on the solar disk—the western (open symbols) and eastern (filled symbols) hemispheres, and (2) delay time between a flare and corresponding storm: 2–4 days (high probability of relation of events, triangles), 1.5–2 and 4–5 days (moderate probability, diamonds), and 1–1.5 and 5–6 days (low probability, circles).

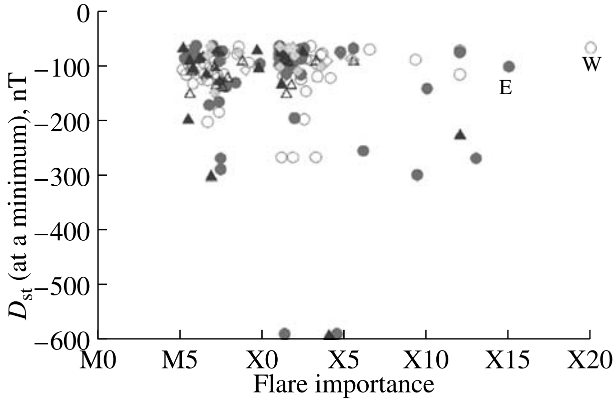

Fig. 2. The same as in Fig. 1, but for the interval 1988–1993 corresponding to observations by Shrivastava and Singh, 2002 [20].

rather low, since they describe different physical processes on the Sun and in the Earth magnetosphere [23, 3], these papers testify that there exists some connection between the flare importance and storm magnitude.

We have carried out a similar analysis of solar, interplanetary, and magnetospheric phenomena for the period of 1976–2000 [22] (see also the preliminary publication [21]), where the same dependence (see Fig. 5 in paper [22]) was presented. The dependence of magnitude of 325 storms with $D_{st} < -60$ nT on the X-ray importance (≥M5) of solar storms was presented on the upper panel of Fig. 5 (this panel is reproduced here as Fig. 1). The same dependence for 70 weaker flares (≥M0), but accompanied by arrival of solar energetic particles (Solar Particle Events, SPEs), was shown on the lower panel. On both panels the data were selected by (1) flare position on the solar disk—the western (open symbols) and eastern (filled symbols) hemispheres, and (2) the time of delay between the flare and corresponding storm: 2–4 days (high probability of relation between events, triangles), 1.5–2 and 4–5 days (moderate probability, diamonds), and 1–1.5 and 5–6 days (low probability, circles). No tendency of storm magnitude increase with growing solar flare importance was observed.

The H_α and X-ray classes of solar flares and the magnetic storms identified by the A_p index, were studied by Yadav and Kumar [24] for the interval of 1978–1999, while the same authors in another paper (Kumar and Yadav [23]) studied the relations between H_α and X-ray classes of solar flares and strong magnetic storms with $D_{st} < -100$ nT. In both cases the authors have drawn the conclusion, that "no significant correlation between the intensity of GMSs (abbreviation GMSs means "geomagnetic storms"—authors' remark) and importance of H_α and X-ray solar flares has been observed".

Thus, two radically different results are presented in the literature in different papers, namely: the existence and absence of the "flare importance–storm magnitude" relation. Possible causes of this distinction are discussed in the next section of the paper.

DISCUSSION

Two papers by the authors Shrivastava and Singh [20] and Howard and Tappin [26], which indicate to the existence of the "flare importance – storm magnitude" relation, have a common feature in the data selection technique (absent in the other papers), namely: the initial selection of pairs of "CME–magnetospheric disturbance" events and the subsequent analysis of the relation between the importance of CME-accompanying flares and magnetospheric disturbances. Thus, the necessary condition for existence of the "flare importance –storm magnitude" relation is, apparently, the existence of the initial "CME–storm" relation. This condition was implicitly formulated by Shrivastava and Singh [20] and Howard and Tappin [26]. On this basis, one can put forward a better-stated hypothesis that "if during the complicated active phenomenon on the Sun, resulted in the CME and flare appearance, the CME causes a magnetic storm, then these flare and storm can have relation of the type: "the higher flare importance – the higher storm magnitude"; otherwise no such relation exists" and take this hypothesis as a basis for further investigations.

Along with the aforementioned feature of method (the initial selection of pairs of "CME–magnetospheric disturbance" events), there exist 3 other possible basic causes of distinction in the published results: (1) different intervals of observations in the solar activity cycle, (2) different numbers (statistics) of considered events, and (3) different methods of identification of events and their comparison. These causes are considered in more detail below.

Yermolaev and Yermolaev [22] have studied 25-year interval (more than 2 solar cycles since 1976 to 2000), Krajcovic and Krivsky [27] considered 23-year interval, and Yadav and Kumar [24] 12-year interval, while others have studied the intervals shorter than a solar cycle: Howard and Tappin [26] dealt with 7-year interval at the maximum of the 23-rd solar cycle (1998–2004), Shrivastava and Singh [20] considered 6-year interval, and Kumar and Yadav [25] 8-year interval near the maximum of a previous solar cycle. It is well-known that the relationship between the geoeffective solar phenomena (ICME-generating CMEs and CIR-generating coronal holes) changes during a solar activity cycle (see, for example, [28]). Therefore, one can suppose that the existence of the "flare importance–storm magnitude" relation is typical only for the solar cycle maximum, as in papers by Howard and Tappin [26] and Shrivastava and Singh [20], it is absent in the other solar cycle's phases and is masked at averaging over large intervals, including both the intervals on which the relation exists and the intervals on which it is absent. In order to verify this supposition, the data of paper by Yermolaev and Yermolaev [22] were restricted to the same time interval, as in the paper by Shrivastava and Singh [20] (see Fig. 2 of the present paper). However, no relation is seen in this case as well. On the other hand, a higher statistics of observed events in the paper by Yermolaev and Yermolaev [22] testifies the fact that the conclusion on the absence of the "flare importance – storm magnitude" relation is statistically reliable. In this connection, of interest is to note that our statistics includes the case of the strongest magnetic storm in the space era (in March, 1989), with a minimum of D_{st} = –589 nT. This storm can be compared with large (but not extremely large) flares of X1–X5 importances, and it is not consistent with the supposition on the "flare importance – storm magnitude" relation.

The Table demonstrates a great variety of used techniques and criteria for identification and classification of analyzed events. As it was shown in our papers [3, 16, 22], the results of comparison of various phenomena on the Sun, in the interplanetary space and in the magnetosphere strongly depend on the techniques of identification of phenomena and on the procedures of their comparison. Unfortunately, the issues of method related to the studied problem were very schematically discussed in papers by Yadav and Kumar [24], Kumar and Yadav [25], and Howard and Tappin [26], which makes it impossible to compare in detail the techniques and to search for possible causes of distinction in the results.

The available data allow one to discuss only the question on selecting the flares with different importances for their comparison with magnetic storms. In contrast to the paper by Yermolaev and Yermolaev [22], in which the analysis included the flares with importances ≥M0 and ≥M5, Howard and Tappin [26] included into their analysis some weaker flares of C importance as well. As is well-known, precisely CMEs (rather than flares) excite the interplanetary disturbances and, then, magnetic storms (see, e.g., Gosling [9]), and the flares can be used only as solar activity indicators, which can be accompanied by CMEs and interplanetary disturbances. On the other hand, the association between flares and CMEs decreases with decreasing importance of the flares (see, for example, Kahler et al., [29]). In recent paper by Yashiro et al. [30] it was shown that the "flare–CME" association is observed, respectively, in 15 and 30 % of cases for the disk and limb flares, when weak flares are studied in the range of C3–M1. Thus, the flares of C importance, included into the analysis by Howard and Tappin [26], cannot improve correlation between the flare importance and the magnitude of magnetic storms.

As it was noted in the Introduction, the geoeffectiveness of flares is very low, of about 30–40 % [3, 16], and only slightly it exceeds the level of correlation for random processes [22]. This implies that, in the modern techniques of solar phenomena comparison with geomagnetic storms, only a small part of flares has real cause-and-effect relations with corresponding storms, while the other pairs of "flare – storm" events occur to be physically independent, i.e., random. Therefore, the possible "flare importance – storm magnitude" relation, sought for in the total data set, can occur to be highly noised by random processes and could not be found on their background. For increasing the probability of its detection, it is necessary to use the procedures of decreasing the fraction of random processes in the total data set. This can be done partly due to the use of additional information on CMEs, because their geoeffectiveness is higher than that of flares, and equals 40–60% [3, 16, 19]. That is, the fraction of solar events having a real cause-effect relation with storms is higher for CMEs than for flares. Probably, this is the reason of observing positive "flare importance – storm magnitude" correlation in papers by Shrivastava and Singh, [20] and Howard and Tappin, [26], where the additional "CME – storm" relation is used in analyzing the required dependence. However, one should remember here that, having included CMEs into consideration, we added into our chain of events the additional "flare–CME" link, whose description contains the greater random component, the lower the flare importance (see Yashiro et al. [30]). This implies that the probability of finding the possible "flare importance–storm magnitude" relation is higher for stronger flares. And this "tendency for large flares to be associated with very large storms" was noticed by Howard and Tappin, [26].

It should be noted that solar energetic particles (SEP) observed near the Earth can serve as a CME generation criterion, since they can be formed on the shock waves generated by CMEs. This is confirmed by our observations, when in flares of importance ≥M0, accompanied by SPEs, the geoeffectiveness of generation of magnetic storms with D_{st} < –60 nT by these flares was 44 %, wheilr for stronger flares of importance ≥M5 (i.e., more geoeffective due to higher importance), but not accompanied with SPEs, the geoeffectiveness of generation of the same magnetic storms with D_{st}< –60 nT was 40 % only [3, 18, 22]. Nevertheless, this rather small increase of geoeffectiveness due to accounting for SPEs occurred to be insufficient to allow one to reveal the "flare importance – storm magnitude" relation.

CONCLUSIONS

Thus, the analysis of published results allows one to draw the following conclusions.

1. If one takes an arbitrary solar flare and a magnetic storm, separated by the time of solar wind propagation from the Sun to the Earth, then the "flare importance–storm magnitude" relation is statistically at the "noise" level; that is, the answer to the question at paper's heading is negative. This is related, first of all, with a low geoeffectiveness of flares; that is, the probability of the

fact that the cause-and-effect relation really exists for a chosen pair of events is very low.

2. If one takes a non-arbitrary solar flare, associated with a CME moving towards the Earth, then for such a flare and storm, separated by the time of disturbance propagation to the Earth, a statistically weak, positive "flare importance–storm magnitude" correlation is observed; that is, the answer to the question at paper's heading is "possibly, yes". This result is explained by a higher CME geoeffectiveness, since the major part of the flares chosen in such a manner have a real cause-and-effect relation with storms.

Hence, we have an obvious conclusion for forecasting the space weather: the magnitude of a predicted magnetic storm can be judged by the solar flare importance only after recording the CME, associated with this flare, which moves towards the Earth (i.e., the halo CME). For example, close algorithms of magnetic storms prediction on the basis of observations of solar flares and CMEs (or radio-bursts of IV and II types, associated with CME and a shock wave in front of it, respectively) are proposed in the literature (see, e.g., papers by Song et al. [31], Valach et al. [32], and Prokudin et al. [33])[1]. The forecast constructed without the CME data has, in essence, random character and cannot have practical value. The increase of quality of a similar forecast should follow two directions: (1) introduction into consideration of a quantitative description of interrelations between flare and CME parameters, (2) increase of the probability of forecast of CME interaction with the Earth's magnetosphere.

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