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Dynamic aspects of the Solar Flare Effects and their impact in the detection procedures

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ABSTRACT
Although crochet shape is conceived as the common manifestation of Sfe, a lot of them present other different shapes and have a sparse variety of rising and ending times. That makes the detection tasks of the observatories difficult. In this work we analyzed the temporal response of the earth's magnetic field to these sudden large energy releases and we assess its consequences in the detection procedures.

We studied the driven mechanisms involved in the decay of the Sfe. The decrease in the ionizing radiation has been found to be one of the main drivers of this decay, which diurnal variation trends very often mask.

Another finding was that the decay time is strongly dependent on the balance in X and UV rays contributions. Finally, we identified the time constant as an important factor for visual detection because it restricts the detected events to those having sharp shape.

Keywords: Sfe, Dynamics, Detection, Time-constant, Decay-time.

INTRODUCTION

Solar flare effects (Sfe) are rapid magnetic variations which are related to the enhancement of the amount of radiation produced during Solar flare events (*Prölss, 2004*). Mostly X-ray and EUV emissions cause variations on the electronic density in the ionospheric layers (*Donnelly, 1976*). From the F to the D regions, there are electron density enhancements during solar flares (*Thome and Wagner, 1971*). On Earth, the magnetic signature of a flare is visible in the illuminated hemisphere (*Dmitriev et al., 2006*), having big amplitudes in the equatorial zone (*Rastogi, 2001*).

Spectral radiation changes from one flare to another. Not every spectral band in the flare contributes equally to the total emission, and radiation with different emission frequencies produce different magnetic effects. What Sfe-s have in common is that, during several minutes, the ionosphere is activated and electron densities, electric conductivities and electric currents are enhanced.

The main characteristics of Sfe can be summarized as: 1) morphology: «crochet» shape; 2) vision: simultaneously in the Earth's sunlit hemisphere; 3) beginning: simultaneous to the flare observation; 4) duration: few minutes (10-20 min); 5) amplitude: few nanoTeslas, about 10 nT.

In order to catalogue these events, the parameters characterizing the Sfe are: Amplitude (A_{sfe}), Rise Time (T_1) and Decay Time (T_2).

The service of Rapid Magnetic Variations (RMVs) was created by the International Association of Geomagnetism and Aeronomy (IAGA) with the aim of obtaining an overall view of the temporal and spatial distribution of RMV as a base for further study of these phenomena. The Ebre Observatory holds this service which has regular daily activities to provide reliable lists of events(Sfe and Sudden Storm Commencements (SSC)) which are published in the IAGA bulletin 32 series. Also, the Ebre Observatory creates normative prospects, aiming to focus the interest of the scientific community on this field and to promote the study of the physics of RMV.

We create lists of Sfe events (preliminary data) from a network of collaborating observatories which report candidate events after visual inspection on the magnetograms. For each event, the observers determine the starting time (T_s) and the ending time (T_e). Both, together with the time of the maximum (T_m) allow us determining T_1 (T_1=T_m-T_s) and T_2 (T_2=T_e-T_m).

DYNAMIC ASPECTS OF THE SFE

A_{sfe} Amplitude

Due to the vortex type of the Sfe current systems, at ground level, amplitudes of the Sfe magnetic variations depend on the latitude and the local time of the observer (*Villante and Regi, 2008*). Thus, just under the center of the vortex one can have nearly no magnetic movements while in observatories located one or two thousand kilometers far away of the focus, one can have variations of several tens of nT. So it is very difficult to establish a unique value of amplitude for an event. The superposed Sq variation being delayed with respect to Sfe variation also generates complex resultants because in some locations they coincide in direction and sense and in other locations they have even opposite senses (*Curto et al., 1994a*). Even for the same event, the configuration of the currents changes as the time goes by (*Gaya-Piqué et al., 2008*).

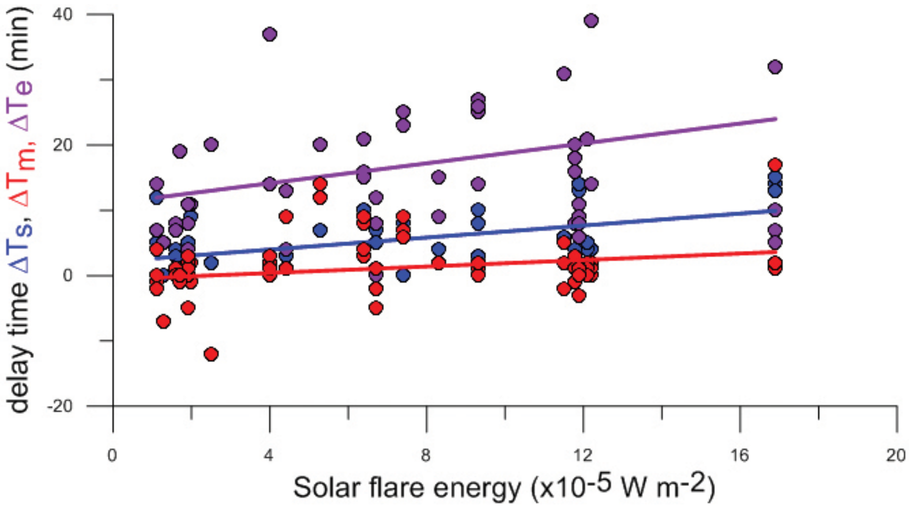

Figure 1. Delay time measured on the magnetogramsby the observers with respect to the corresponding times in the Xray monitors for several solar flares.

Table 1: Main equations ruling both processes: capacitor discharging in an electric circuit (on the left)and electron-ion recombination in the ionosphere (on the right).

$-\frac{Rdq}{dt}=\frac{q}{C}$	$\frac{dn}{dt}=-\alpha_{\mathrm{D}}\, nN_{\mathrm{e}}$
$\int_{q_0}^{q_1}\frac{dq}{q}=-(1/RC)\int_{t_0}^{t_1}dt$	$\int_{n_0}^{n_1}\frac{dn}{n}=-\alpha_{\mathrm{D}}N_{\mathrm{e}}\int_{t_0}^{t_1}dt$
$q=q_0e^{-\frac{t}{\tau}}$	$n=n_0e^{-\frac{t}{\tau}}$
$\tau=RC$	$\tau=\frac{1}{2\alpha_{\mathrm{D}}N_{\mathrm{e}}}$

T_s start time &T_e end time

In the reported lists from the collaborating observatories, there is rather unanimity in the T_s and T_m responses of the different observers, which are close to the corresponding times of the flare. However, there is great dispersion in the T_e given by the observers and a long delay (respect X-ray times) (Figure 1). Red points correspond to T_m (delay in the maximum). They are close to zero. Blue points correspond to T_s (delay in the start) they are bigger than Tm, but not much. Violet points correspond to T_e (delay in the end). They present the highest values, and they are much dispersed. Lines are the best linear fits. Delay times grow with the energy of the flares.

T_1 rise time & T_2 decay time

Summarizing, there are concordances in T_m but not in T_e so neither in T_2 (T_2=T_e-T_m). Thus we will concentrate in the study of the decay time to find the reasons of this discrepancy.

Some questions immediately arise: Is the decay time, T_2, conditioned by processes driven by the recombination process in the ionosphere? In that case, can the local conditions of upper atmosphere at the top of an observatory condition T_2?

THE IONOSPHERE AS AN AGENT IN THE DECAY PROCESS

Time constant, τ, in a decay process

To answer those questions, we first consider the main processes producing the ions concentration in the ionosphere. There, the continuity equation

$$\frac{dn}{dt}=Q-\alpha_{\mathrm{D}}\, nN_{\mathrm{e}}\text{-}\Delta.(N\nu)$$

accounts for the balance between creation and losses and transport. In the equation *n* is the ion density, *t* time, *Q* is the production term; *Ne* is the electron density and α_D the recombination coefficient, and ν is the electron

Table 2: Ionizing decrease during a recombination process.

$t = \tau$	$n = n_0/e^1 = 0.37\ n_0$
$t = 2\tau$	$n = n_0/e^2 = 0.13\ n_0$
$t = 3\tau$	$n = n_0/e^3 = 0.05\ n_0$
$t = 4\tau$	$n = n_0/e^4 = 0.02\ n_0$

velocity. During the occurrence of a flare, photochemical processes are much faster than transport (*Mitra, 1974*) so the transport term is negligible with respect to production and losses terms and we will not consider it.

There is a formal equivalence in the equations ruling the temporal variations of the ions in the ionosphere and the discharge of a capacitor in a RC electric circuit as shown in Table 1. There, *q* is the electric charge circulating in the circuit; *R* is the resistance and *C* the capacitance. t_1-t_0 represents the time elapsed after the source has been removed (t_0).

Electrons circulating in the electric circuit decay following a power law when we disconnect the source (battery). Then, the main characteristic is the time constant which is proportional to the resistance and the capacitor values.

In analogy, in the ionosphere, ion density also follows a power law, whose main characteristic is the time constant which is inversely proportional to the electronic density, *Ne*, and the recombination coefficient, α_D.

It is worth to note that as in a Capacitor discharging, ionization is significantly reduced after one time constant (about 70%) and dramatically after 2 times the time constant (about 90%) (Table 2).

In the ionosphere several layers can be considered. Some of them (D and E) are directly related to the daily ionizing radiation and disappear at night. Around 100 km high, there is a dynamo region where there are electro-dynamic conditions to sustain electric currents which are able to induce magnetic variations on earth.

In the dynamo region of the ionosphere, the Time constant in the decay process can be computed using the equations given in Table 1 and introducing the usual values of α_D and N_e in this layer: $\alpha_D = 3 \times 10^{-7} s{\cdot}cm^3$ & $N_e = 10^5\ cm^{-3} \Rightarrow \tau_{ion} = 20$ s !. So the ionization extinguishes shortly after the radiation disappears.

Statistics of T_2

As it was said in the introductory section, Sfe use to have a life time of some minutes. After Curto et al. (1994a), T_2 for Sfe in EBR are: Mode = 7 min, Median = 12 min and Mean = 16 min. So $T_2(sfe) >> \tau_{ion}$. Therefore, although electron-ion recombination plays a role, it is a secondary actor and should be discarded as the main driver of the global decay process as regards the magnetic signature decay.

X-RAY AS IONIZATION DRIVER

Going back to the continuity equation, if the ionization decay process is not mainly driven by the loss term, then we should look at the production term, *Q*. In principle, the ionization is mainly generated by soft Xray radiation. But no every Xray flare has enough energy to ionize the ionosphere. M and X classes, the most powerful flares, are the main Sfe producers. Most X flares have also a crochet shape with a rapid increase and a slow decay.

After Veronig et al. (*2002*), T_2 for X-ray are: Mode = 3 min, Median = 6 min and Mean = 9 min. SoT_2 (sfe) ≥ T_2 (Xray). Although, now both decay times have the same order of magnitude, T_2 (sfe) is still bigger than T_2 (Xray). We have to search for another agent.

UV RADIATION AS ANOTHER IONIZATION DRIVER

In the dynamo region, in addition to the Xrays, other spectral bands contribute to produce ions (*Richmond and Venkateswaran, 1971*). Curto et al. (*1994b*) built a physical model integrating the main processes involved in the generation of a Sfe. Thus they could evaluate the impact of the different bands at the different highs. They found that, in the dynamo region, UV radiation has an important role, too.

A CASE STUDY: SFE 16/07/2004 AT EBRE (EBR)

To get a deep inside in the problem let's have a case study. Again we chose a Sfe event which happened in a magnetically quiet day: July 16th, 2004 at 13:53 UT. We focused on the Sfe time and compared the decay of the magnetic variation with those in Xray and XUV ray (Figure 2).

In the Xray band((a) panel of Figure 2), we observe a rapid decay with τ_1 = 9 min. In the XUV band ((b) pannel), the decay is much longer with τ_1 = 30 min. Finally, in the magnetogram ((c) pannel), τ_1 = 17 min. The Sfe has a rapid decay in the 10 first minutes following the Xray decay, but then a slower decay happens following the UV decay.

In terms of deposited power (Table 3), the energy delivered in the X ray band reduces the importance of its

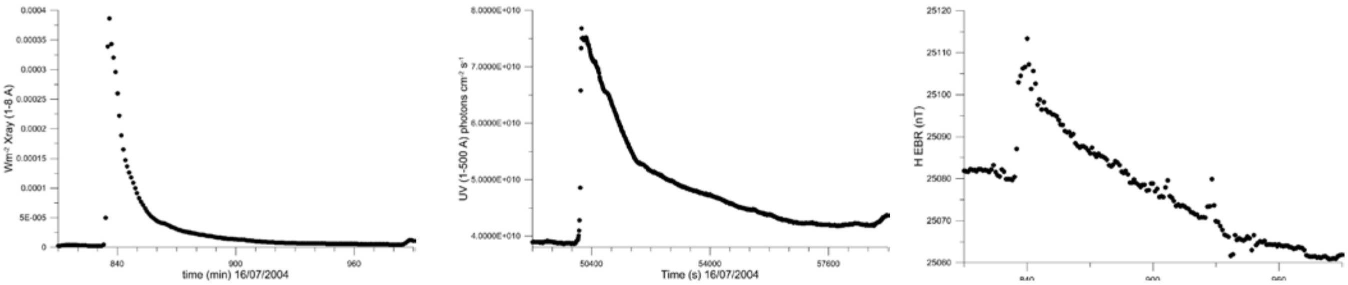

Figure 2. Panoramic view of the 16/07/2004 sfe event. Pannel a) Xray, b) XUV and C) Sfe.

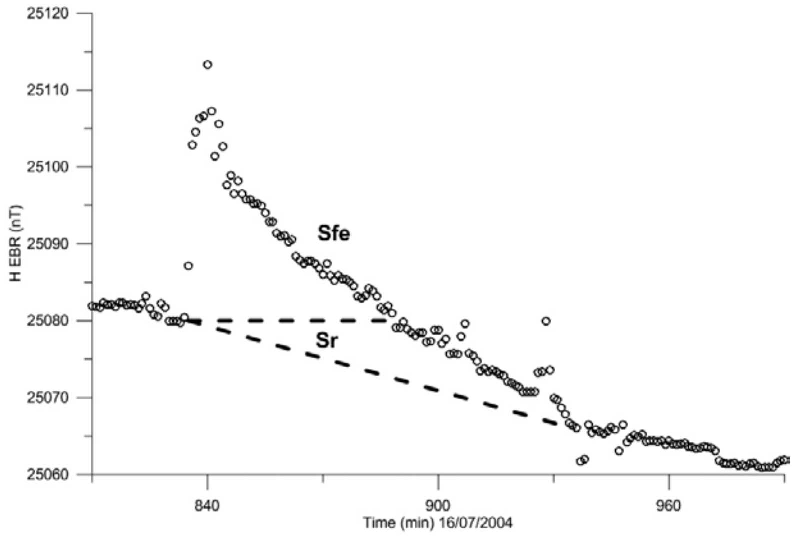

Figure 3. Sfe signature as can be seen in EBR magnetograms (16/07/2014). The starting time is clear enough to be easily determined (13:53). But the ending time depends on the different options of base line according to the Sr extrapolations (dashed lines in the figure).

Table 3. Deposited power rate at the moment of the maximum and ten minutes later for the whole band XUV and for the Xray sub-band.

	XUV ray (1-500 Å) band	X ray (1-8 Å) band
$t = t_0$ (at Sfe maximum)	$P_0 = 5 \cdot 10^{-2}$ W m^{-2}	$P_0 = 4 \cdot 10^{-4}$ W m^{-2} (1%)
$t = t_1 = t_0 + 1_0$ min (after τ_1 Xray)	$P_1 = 4 \cdot 10^{-2}$ W m^{-2}	$P_1 = 1.25 \cdot 10^{-4}$ W m^{-2} (0.3 %)

contribution to the whole XUV band (X+UV) (1-500 Å) as the time goes by. This contribution goes from the 1 % at the moment of the maximum to 0.3 % ten minutes later, when the Xrays have decayed for less than 40% of its value at the moment of maximum.

OTHER CONSIDERATIONS.

Diurnal variation, a quiz

The Diurnal Variation, Sr, is always superposed to the Sfe event. The Diurnal Variation trend very often masks Sfe decay and gives a misleading base level. One should see not only the level at the moment previous to the event but also how the Sr evolves after the event to infer the Sr trend (Figure 3). Having a wrong base line could result in a large error in the T_e determination.

Sfe starts later than the X-ray flare

In general, only the most energetic period of an X-ray flare is Sfe productive. At the moment of the start time, the flare delivers small energy and, only after certain amount of time, it reaches a level of energy sufficient (M or higher) to produce appreciable electric conductivity enhancement which finally manifests itself as a Sfe. This can be seen as a positive delay in Ts (Figure 1). Vice versa, something like this, but in the opposite sense, should happen in the decay time. However, at that moment the UV rays control

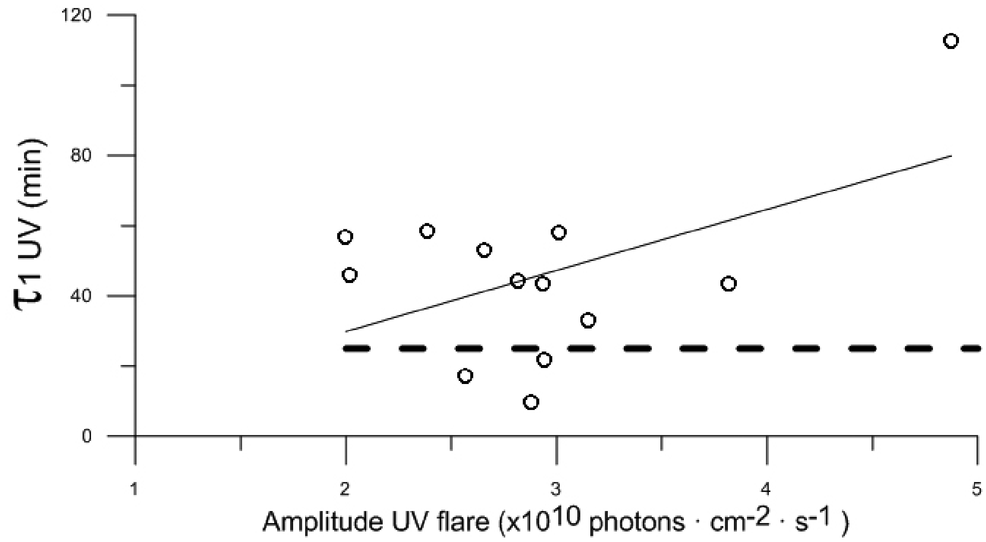

Figure 4. τ_1 versus Amplitude for several UV flares. Only the sfe events under the threshold level (dashed line) were detected and reported in the lists. The best fit (solid line) suggests some kind of dependence between the amplitude of the flare and the value of the time constant.

the ionization and as they have a long recovery, T_e(sfe) takes place much later than T_e(X-ray).

Big X ray flares not always produce Sfe

Other surprising fact is that having big X ray flares is not equivalent to have big Sfe. Even, in many cases, no Sfe is detected!

According to Curto and Gaya-Piqué (*2009a*), when a flare is only important in X-ray emission, the probability to produce a Sfe is only around 50%. In that study, the authors concluded that other spectral bands contribute and sometimes have more relevance than Xray one. Also Tsurutani et al. (*2005*) have shown that solar flare of 28 October 2003 (X17) produced TEC increase of ~25 TECU whereas a much intense solar flare on 4 November 2003 (X28) produced only an increase of ~5-7 TECU. The cause for such a phenomenon was that EUV flux was nearly double for the 28 October flare as compared to 4 November flare. That study emphasized the importance of the spectra of solar flares for Sfe. Similarly, the solar energetic particles (SEP) associated with some flares can reach the Earth's high latitude ionosphere a little later than the energetic solar photons produced during solar flares (Tsurutani et al., 2009). They can produce extra ionization affecting the Sfe amplitudes, too.

Steepness, a key factor

Going on with this paradoxical fact that most of the biggest XUV flares apparently produce small or no effect in magnetism (Sfe), we compute the time constant of several flares (Figure 4). There, the right most point suggests a kind of dependence between the amplitude of the flare (energy deposited in the ionosphere at the moment of the maximum) and the value of the time constant. The dashed line in the figure separates the events producing Sfe (those under the line) from those events not producing Sfe (those over the line). Only the flares having small τ produced Sfe. The explanation could be that our eyes look for sharp increases of the magnetic field detecting only those with small τ.

CONCLUSIONS

The start and ending times of Sfe are difficult to precisely determine. Very often, ending times of a Sfe event given by the different observatories are very scattered.

The decay in the Sfe is mainly driven by the decrease in the ionizing radiation. In the decay time, after 2 or 3 times the time constant, τ, the signal is reduced drastically to only few % of the total, very close to the "natural" noise level. Moreover, the diurnal variation, Sr, is always superposed to the Sfe event. Diurnal variation trend very often masks Sfe decay.

The decay time is very dependent on the balance in X and UV rays contributions. Only the most energetic period of the Xray enhancement is active producing Sfe.

Finally, visual detection restricts the detected events to those having sharp shape. Very often big XUV events don't appear in the lists because they have large τ.

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REFERENCES

Curto, J.J., Amory-Mazaudier, C., Cardús, J.O., Torta, J.M. and Menvielle, M., 1994. Solar flare effects at Ebre: Regular and reversed solar flare effects, statistical analysis (1953 to 1985), a global case study and a model of elliptical ionospheric currents, J. Geophys. Res., vol. 99, nº A3, p. 3945-3954.

Curto, J.J., Amory-Mazaudier, C., Cardús, J.O., Torta, J.M. and Menvielle, M., 1994. Solar flare effects at Ebre: Unidimentional physical, integrated model, J. Geophys. Res., vol. 99, nº A12, p. 23289-23296.

Curto, J.J. , Gaya-Piqué, L.R., 2009. Geoeffectiveness of Solar Flares in magnetic crochet (sfe) Production: I - Dependence on their spectral nature and position on the solar disk, J. Sol. Atmos. Terr. Phys., 71, 1695-1704. DOI. 10.1016/j.jastp.2008.06.018.

Curto, J.J. , Gaya-Piqué, L.R., 2009. Geoeffectiveness of Solar Flares in magnetic crochet (sfe) Production: II - Dependence on the detection method, J. Sol. Atmos. Terr. Phys., 71, 1705-1710. DOI: 10.1016/j.jastp.2007.12.003.

Dmitriev, A. V., H.-C. Yeh, J.-K. Chao, I. S. Veselovsky, Su, S.Y. and Fu, C. C., 2006. Top-side ionosphere response to extreme solar events, Ann. Geophys., 24, 1469,

Donnelly, R. F. 1976. Empirical models of solar flare x-ray and EUV emissions for use in studying their E and F region effects, J. Geophys. Res., 81, 4745, doi:10.1029/JA081i025p04745, 1976.

Gaya-Piqué, L.R., Curto, J.J, Torta, J.M., Chulliat, A., 2008. Equivalent ionospheric currents for the 5 December 2006 solar flare effect determined from spherical cap harmonic analysis, J. Geophys. Res., 113, A07304, doi:10.1029/2007JA012934,

Mitra, A. P., 1974. Ionospheric Effects of Solar Flares, Springer, New York

Prölss, G., 2004. Physics of the Earth's Space Environment, Springer, Heidelberg, Germany.

Rastogi, R. G., 2001. Electromagnetic induction due to solar flares at equatorial stations, JASTP, 63, 599-604

Richmond, A.D., Venkateswaran, S. V., 1971. Geomagnetic crochets and associated ionospheric current systems, Radio Sci., 6, 139-164.

Thome, G. D., and Wagner, L. S., 1971. Electron density enhancements in the E and F regions of the ionosphere during solar flares, J. Geophys. Res., 76, 6883, doi:10.1029/JA076i028p06883.

Tsurutani, B. T., Judge, D. L., Guarnieri, F. L., Gangopadhyay, P., Jones, A. R., Nuttall, J., Zambon, G. A., Didkovsky, L., Mannucci, A. J. Iijima, B., Meier, R. R., Immel, T. J., Woods, T. N., Prasad, S., Floyd, L., Huba, J., Solomon, S. C., Straus, P. and Viereck, R., 2005. The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille day event, Geophys. Res. Lett.,32, L03S09, doi:10.1029/2004GL021475

Tsurutani, B. T., Verkhoglyadova, O. P., 2009. Mannucci, A. J., Lakhina, G. S., Li, G. and Zank, G. P., A brief review of "solar flare effects" on the ionosphere, Radio Sci., 44, RS0A17, doi:10.1029/2008RS004029.

Veronig, A., Temmer, M., Hanslmeier, A., Otruba, W., Messerotti, M., 2002. Temporal aspects and frequency distributions of solar soft X-ray flares, Astronomy & Astrophysics, 382, 1070-1080.

Villante, U., Regi, M., 2008. Solar flare effect preceding Halloween storm (28 October 2003): Results of a worldwide analysis, J. Geophys. Res., 113, A00A05, doi:10.1029/2008JA013132.