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Joan-Josep Curto, Christine Amory-Mazaudier, J.M. Torta, Michel Menvielle

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J. J. Curto,1 C. Amory-Mazaudier,2 J. M. Torta,1 and M. Menvielle3

Abstract. A great increase of the ionizing radiation during solar flares results in an immediate increase of the ionization production rate, electron densities and electric currents in the ionosphere, followed simultaneously by disturbances of the magnetic elements at ground level (solar flare effects (sfe)). In this paper an attempt is made to model sfe phenomena combining several semiempirical models derived from satellite and radar data obtained during the last two decades. The model allows us to quantify model values of the phase difference between the sfe and $\text{Sr}$ vectors, for comparison to the measurable quantity. It explains the cause of the change in magnetic perturbation during a flare at Ebre Observatory (40.8° latitude N, 0.5° longitude E). Large phase shift of the magnetic vector observed before noon, result from a descent of the "center of gravity" of the conducting mass, that, combined with a very different regime of neutral winds in the lower and in the middle parts of the dynamo region, produce a change in the direction of the integrated currents.

1. Introduction

A sudden increase of the solar radiation intensity as well as a change of the XUV radiation spectrum structure during a flare causes drastic changes of all photochemical processes in the ionosphere. These changes result in a variation of the geomagnetic field, the solar flare effect (sfe). The sfe have been the object of many studies since 1859, the year of its discovery by Carrington [Nagata, 1966].

In the past, attempts to model sfe used theoretical parameters due to the lack of direct observations [Onohio, 1964; Greenfield and Venkateswaran, 1968; Richmond and Venkateswaran, 1971]. At Ebre a long series of 33 years of magnetic solar flare effects have been analyzed by Curto et al. [1994]. These authors studied the time variations of the sfe and $\text{Sr}$ vectors ($\text{Sr}$ is the daily magnetic regular variation observed during a given day [Mayaud, 1965], while $\text{Sq}$ would be the mean of $\text{Sr}$ on magnetic quiet days; sfe is the magnetic perturbation induced by a solar flare). They found a local time dependence of the angle difference between the sfe and $\text{Sr}$ vectors, hereafter called phase difference. Reversed sfe (sfe with phase difference greater than 90°) concentrate between 1000 and 1200 LT and have a dominant equinoctial character. Curto et al. [1994] studied the global sfe and $\text{Sr}$ equivalent current systems. In the northern hemisphere the sfe system was about 1 hour in local time eastward of the $\text{Sr}$ system, and formed at a higher latitude (by 4°).

In order to understand Ebre observations and especially the mechanisms that produce reversed sfe, we developed a physical, integrated model of solar flare effects, presented here. This model, integrating the main physical processes involved in the sfe phenomenon, is based on empirical intermediate models derived from satellite and radar data obtained during the last two decades. Section 2 of this paper summarizes the leading processes involved in the genesis of a sfe and describes the intermediate models and the parameters considered for the Sun, ionosphere and Earth. In section 3 we compare the predictions of this physical, integrated model with the magnetic observations at Ebre. It is followed by the conclusions where is discussed the nature of the reversed sfe phenomena.

2. The Model

2.1. Physical Processes

This model integrates the most important physical processes involved in the genesis of a sfe. The global scheme is given in Figure 1.

Extra solar flare radiation produces increases of ionization, electric conductivity, and currents in the dynamo layer. By induction the ionospheric currents create magnetic field variations. All the ionospheric parameters involved in the definition of the currents are related by Ohm's law. The electric current and magnetic field variation are connected through Ampere's law. We computed the magnetic field variations produced by the regular radiation ($\text{S}q$ variation, left side of the figure) and the magnetic field variation produced by the sum of the regular and the sfe radiations ($\text{S}q + \text{sfe}$ variation, right side of the figure). Details concerning the computation model are given in the three following sections.

The semiempirical models used as input are (1) radiation flux from geophysical satellites (observations "in situ"), (2)
neutral atmosphere data (composition, densities, temperatures) from mass spectrometers in satellites and radar observations, (3) neutral winds, and (4) electric field. The neutral winds and electric field are deduced from measurements of the incoherent sounder of Saint-Santin which is located at 42.1° latitude N and 2.0° longitude E, that is, in a neighboring region from the Ebre Observatory. At Saint-Santin the observed electric currents produce mean diurnal magnetic variations very similar in amplitude and phase to those observed in Ebre. The use of semiempirical models, based on real data, allowed us to quantify the amplitude and phase of the magnetic perturbations. Table 1 summarizes the references of all the models.

We compute ionospheric currents in the altitude range 80-160 km where the currents are able to induce detectable magnetic effects at ground level. We used the reference system (X, Y, Z) where X is the direction perpendicular to the magnetic field, B, and in the direction of the geographic north; Y is the direction perpendicular to B and in the direction of the geographic east; and Z is the direction parallel to B. We give values for the equinox season because it gives the greatest phase differences at the Ebre latitude [Curto el al., 1994].

2.2. Solar Radiation

Solar radiation is the first link of a chain that leads from the Sun to the Earth. Solar flares are complicated phenomena whose emitted spectra of the X and EUV radiation changes considerably from one flare to another. There have been no simultaneous measurements of the flare spectrum over the entire wavelength range. To estimate the flux of radiation from the solar flare, we used the empirical model of Donnelly [1976]. This model was prepared for ionospheric use and covers the EUV band and soft X rays, which produce most of the photoionization of the dynamo region. It is based on data from SMS 1, SMS 2, and ATM/Skylab satellite missions. Donnelly [1976] distinguished three classes of flares: M1, X1, and X25. For each flare class the model gives power density integrated in each band in the (1-1027 Å) spectral range. In Figures 2a and 2b, we display the spectral power for each flare class. To estimate the emission in the moments previous to the flare (which produces the regular variation), we used the Heroux et al. [1974] radiation model. It is represented by a dashed line in the Figure 2b and hereafter called Q0, for quiet conditions, or "without flare."

At flare time the overall power of the electromagnetic radiation increases. The greatest increase occurs at shorter wavelengths (hardening). The larger the flare, the more important the spectrum shift towards shorter wavelengths.

2.3. Ionospheric Processes

2.3.1. Photon absorption and ionization. At a given altitude the individual ion production rate of a neutral constituent species depends on the flux of incident solar...
Figure 2. (a) Power density for the different models of emitted radiation in quiet time (dashed line) and during a solar flare (solid line). (b) Detail showing relative enhancements for the less energetic flare classes.

We compute the contribution of the different spectral ranges to the atmospheric ionization, and then the altitudes where they are dominant (Figures 3a and 3b). We used the radiation model proposed in section 2.2, the neutral atmosphere model of Hedin [1987], and the absorption coefficients and the photoionization factors given by Okshio et al. [1966]. In general, short wavelengths penetrate deeper than longer ones and control the lower zones of the dynamo region, except some cases such as Lyα and C ii lines. For the X1 flare case (Figure 3b), production increases in all bands with respect to the undisturbed case (without flare) (Figure 3a). However, relatively, the biggest enhancement occurs in the lower zones of the dynamo region.

We used the photochemical model of Dymek [1989], which computes ionic densities by solving simultaneously an equation system for 38 species of ions. This model assumes that the chemical lifetimes of particular ions are considerably shorter than the characteristic time of changes in the incoming radiation so the equilibrium condition is fulfilled \(\frac{dN}{dt} = 0\). This model does not take into account the diffusion term, so real electronic densities above 200 km can differ from those computed. However, it does not affect current calculations because at these heights, the collision frequency of neutral ions is negligible in terms of the ionic gyrofrequency, thereby causing a decrease in the relative drift of electron and ions and the subsequent reduction of importance of the currents.

Figure 3. Production rate for different bands of wavelength. (a) Without flare and (b) with a X1 flare.
2.3.2. Electronic densities. For each flare class of the radiation model, calculations were done for the altitude range 80-260 km for a mean quiet equinoctial day and for the different zenith angles. Electron density profiles computed for M1, X1, and X25 classes of solar flares under a zenithal angle of \( \chi = 40^\circ \) are shown in Figure 4. The biggest changes compared with the quiet conditions (Q0) are caused by the strong X ray flare X25 changing \( N_e \) in the bottom of the dynamo layer by 2 orders of magnitude. This flare class produces slightly weaker electron enhancement in the middle of the \( E \) region, and minor enhancements in the \( F \) region. The flare X1 disturbs the lower zones, whereas M1 produces only modest electron enhancements.

2.3.3. Conductivities. In the dynamo region the effective collision frequency of the electrons with the neutral is very small in comparison with the electron gyrofrequency. The conductivity tensor is then a simple function of the electron density and of the effective ion-neutral collision. To model the effective ion neutral collision frequency profile we used the atmosphere model MSIS-86 [Hedin, 1987] with an exospheric temperature of 1000 K. We also used the ionic composition derived from Saint-Santin data [Oliver, 1975] and the expression of Stubbe [1968] for the individual ion-neutral collision frequencies.

The computed transverse conductivities for the given flare classes are superimposed in Figures 5a and 5b. Hall conductivity is dominant in the middle and lower zones, and Pedersen conductivity, in the higher zones. Conductivities increase with the importance of the flare. However, the greatest increasing occurs in the lower zones, especially for Hall conductivity.

2.3.4. Neutral winds. The regular \( E \) region winds are mainly produced by tidal oscillations of the neutral atmosphere. The temporal evolution of the neutral wind, at each altitude, can be represented by a Fourier development with mean period of 24 hours.

From Saint-Santin radar data, Bernard [1978] modeled the meridional component of the neutral wind from the measure of the ion drift component quasi parallel to the magnetic field, for different altitudes in the \( E \) layer. Bernard [1978] deduced amplitudes and phases from least squares fits to the data for each individual daytime period, and subsequently established an average model of these parameters.

The tidal zonal components for the neutral wind were deduced from the meridional component, assuming that atmospheric tides have a circular polarization. The mean zonal wind was modeled on the basis of the meteoric radar data.

The diurnal variation of the wind velocities in the dynamo region can be seen in Figures 6a and 6b. For both east and north components the wind regime in the lower part of the dynamo layer (90-100 km), region A, is very different from the wind regime in the middle part of the dynamo region (120-130 km), region B. In both A and B regions, between 1000 and 1100 LT, winds have maximum amplitude, pointing north-westward in the region B and eastward in the region A. At 1400 LT, in both regions, winds have smaller amplitudes and their directions are almost coincident.

2.3.5. Ionospheric electric field. Until now, there is not any model of electric field for flare time conditions. The
2.3.6. Current density. The ionospheric Ohm's law

\[ j = \frac{\alpha(E_x + V_n B)}{\rho} \]  

is used to determine the profile of the electric current density \( j \) \([Mazaudier and Blanc, 1982]\). The main magnetic field of the Earth plays the role of the stator in the ionospheric dynamo. We estimated its values using a centered dipole model. In the reference system that we use \( (X_s, Y_s, Z_s) \), the altitude profile of the \( j_x \) and \( j_y \) components of the current density are given by the expressions

\[ j_x = \sigma_j (E_x + V_n B) + \sigma_k (E_y - V_n B) \]  

\[ j_y = -\sigma_j (E_x + V_n B) + \sigma_k (E_y - V_n B) \]  

The total current density is obtained by integration over the layer between 80 and 160 km (boundaries of the dynamo region), using the Gauss calculation.

From Saint-Santin measurements it was only possible to compute perpendicular currents \( (J_{x_p}, J_{y_p}) \). However, they enable us to estimate horizontal currents according to certain hypothesis \([Mazaudier, 1982]\): (1) the dynamo region has a very broad horizontal area and a modest vertical dimension; (2) in the lower part of this region, currents disappear. The following relationships between perpendicular currents \( (J_{x_p}, J_{y_p}) \) and horizontal currents \( (J_x, J_y) \) are thus useful since the vertical currents may be ignored in comparison with horizontal currents.

\[ J_x = \frac{J_{x_p}}{\sin I} \]  

\[ J_y = J_{y_p} \]  

The differential currents at each height, calculated for the different flare classes at 1100 LT, can be seen in Figure 7. At all heights there is an increase of the current intensities related with the importance of the flare. The increase is bigger in the lower zones than in the higher ones. This is equivalent the "center of gravity" of the currents moving down. If a flare occurs around 1100 LT, the resulting ionospheric electric current under the zenith of Ebre will turn in the sense of the lower current elements, that is to say, toward south-southeast. Therefore the magnetic vector and the focus will shift towards east-northeast.

3. Magnetic Field Variations and Comparisons

Ampere's law applied to a thin sheet "connect" the ionospheric current density \( J \) to the induced magnetic variations at ground level, \( \Delta B \), through the following expression \([Veldkamp and Van Sabben, 1960]\):

\[ |\Delta B| = \left| \frac{2\pi J}{10 f} \right| \]  

where \( J \) is measured in milliamperes per meter and \( \Delta B \) in
nanoteslas and $f$ is a factor representing the fraction of magnetic variation produced by ionospheric currents; the remaining variation is produced by induced ground currents. The $f$ factor ranges from $f=1$ (for a nonconducting Earth) to $f=1/2$ (for an infinitely conducting earth [Kamide and Brekke, 1975]). In a non still published study, we performed an Harmonic Analysis on $Sq$ in our geographic area. We found that $f=0.6$ was dominant. This value is generally admitted and used by researchers in sfe [Van Sabben, 1961] and found in $Sq$ studies [Campbell and Masushita, 1982]. An eastward ionospheric current induces a variation in the northward component of the magnetic field, whereas a southward current induces an eastward variation in the magnetic field. Therefore

$$\Delta B_E = -J_N$$  \hspace{1cm} (7)

$$\Delta B_N = J_E$$  \hspace{1cm} (8)

because $2\pi/10f=1$ as $f=0.6$. According this we computed the amplitude and direction of the magnetic vectors.

In Figure 8 the temporal evolution of the incremental currents due to the sfe perturbation (current during the flare minus current without the flare) is drawn. We notice that the absolute intensities (moduli) increase with the importance of the flare. The modulus of the sfe magnetic variation lies between 10 nT (8 hours) and 25 nT (13 hours) for M1 and X1 flares, and between 26 nT (8 hours) and 44 nT (13 hours) for X25 ones. These values are consistent with those found in the statistical analysis [Curto et al., 1994]. In general, the direction of the current density vector $J$ rotates from the east to the northeast during the central
Figure 10. Local time variation of the phase difference between sfe and $S_q$ vectors at equinox. Dashed line represents theoretical values predicted by the model for a X25 flare class, and solid line represents the mean of the observed data.

hours of the day so the direction of the magnetic variation vector $\Delta B$ rotates accordingly from the north to southwest.

For each hour between 0800 and 1300, and for each flare class, we computed the phase difference between the sfe and $S_q$ vectors with the mean seasonal values of the parameters (Figure 9).

The model reproduces the basic characteristics of Ebre data [Curto et al., 1994]: (1) Between 1000 and 1200 LT, we have negative phase differences between $S_q$ and sfe. The phases differences for all flare classes peak at 11h. The absolute value of the phase difference increases slightly with the flare importance. X25 flares reach -80°, hardly any difference with the -90° of reversed sfe. (2) In the hours preceding (0800-1000 LT) and following (1200-1300 LT) this large phase difference zone, values are small (close to zero).

Figure 10 compares the computed values of phase differences for a X25 flare class (dashed line) against the mean of the experimental data (thick solid line). Experimental data were collected from 40 sfe events observed at Ebre Observatory which occurred at equinox in magnetic quiet days [Curto et al., 1994]. They reflect the high day-to-day variability in $E$ fields and neutral winds. So, only comparisons of mean behaviour could be attempted. High dispersion at 0900 could be explain by the scarcity of observations at this hour together with the existence of twilight counterloops [Curto et al., 1994]. Except at 1200, the magnitude of the model and observed data are in reasonable agreement. The agreement is especially good between 1000 and 1100 LT (zone of maximum probability of reversed sfe appearance).

4. Conclusions

This physical, integrated model reproduces the main characteristics of the sfe at Ebre and allows us to give an explanation of the reversed sfe occurrence. A reversed sfe scenario could be the following:

1. Electromagnetic radiation delivered during flare time, in comparison with the regular radiation (responsable of $S_q$), is comparatively more rich in "short wavelengths" (soft X rays) than in "long wavelengths" (extreme ultraviolet);

2. In the X-ray band the ionization efficiency of the radiation increases with decreasing wavelengths (penetrates deeper). Flares ionize zones of lower altitude than regular radiation does. The center of gravity of the conducting mass descends provoking the same effect in the conductivity distribution;

3. The neutral winds, motor of the ions in the dynamo region, have a velocity profile variable in altitude. In the dynamo region exists a clear difference between the winds in the middle of the region (120-130 km) and these in the lower part (90-100 km). This difference has its maximum between 1000 and 1100 LT reaching then close to a phase opposition;

4. During a solar flare the extra radiation strongly modifies the current density at the lower level of the dynamo layer. This, combined with the wind action, produces a change in the direction of the integrated current density. Therefore the sfe equivalent current system appears turned compared to the $S_q$ current system. This rotation is maximum before noon when the wind phase difference is maximum.

5. Variations in the ionospheric current induce magnetic variations at ground level. So the rotation of the density current vector translates into a phase difference between the sfe and $S_q$ vectors. When this phase difference is greater than 90°, we have a reversed sfe.

This study shows the consistency of the various models with the observed sfe at Ebre. However, more data would be necessary to make a definitive test of the model. An improvement of this work would be to extend the model for the more general case of a variable electric field. This would involve to model the dynamo mechanisms at global scale.

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C. Amory-Mazaudier, CRTP 4, Avenue de Neptune, 94107 Saint-Maur-des-Fossé's, France.


M. Menvielle, Laboratoire de Physique de la Terre et des Planètes, Université Paris Sud. 91405 Orsay Cedex, France.

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