Ionospheric Currents Associated with Solar Flares: A Short Review

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Abstract

The enhanced radiation of the X-rays and the ultra-violets during a chromospheric flare can induce a qualitative change in the ionospheric current system. The observational results of this effect, popularly known as geomagnetic solar flare effect (s.f.e.), are briefly reviewed. Various theoretical formulations to explain the morphological results are described. The success as well as the shortcomings of the various theories are pointed out.

I. INTRODUCTION

The formation of an ionosphere in the earth's atmosphere is one of the direct effects of the interaction of the solar electromagnetic radiation with the terrestrial environment. The degree of ionisation at a particular ionospheric height is so sensitive to the spectrum as well as the flux of the radiation from the Sun that a change in the latter can qualitatively alter the various physical phenomena in the ionosphere. During chromospheric flares, the increased energy density of the emitted X-rays and the ultraviolets affect the ionosphere drastically. The resulting increased ionisation is manifested as various sudden ionospheric disturbances. In this article we shall confine ourselves only on a particular effect called the "geomagnetic solar flare effect" (s.f.e.) on the large scale ionospheric current system.

The ionising capability of the radiation of a particular wavelength, when it impinges the atmosphere at a particular height, depends on the chemical composition and the matter density at that point. These last two atmospheric parameters are height dependent. As a result, the number density of theelectrons and ions vary from height to height. Moreover, the electron-mobility is also affected by the matter density; consequently, the electrical conductivity σ in the inosphere is height dependent. This conducting plasma moves in the dynamo electric field $1/c\,(\mathbf{V}\times\mathbf{B})$ induced by the geomagnetic field **B** and the tidal velocity **V** of the neutral atmosphere. During quiet solar condition, the ionospheric currents are chiefly confined to the E-layer of the ionosphere at an approximate height of 100 to 110 km from the surface of the earth. The current density is maximum, quite obviously, in the neighbourhood of the local noon and decreasing both in the morning and in the evening sector. This Sq current system is clearly observed as a regular diurnal variation in the geomagnetic field recorded by a ground-based observatory. A typical Sq variation in the horizontal component of the geomagnetic field is shown in Fig. 1a. The geomagnetic solar flare effect is observed as a small but sharp bump in the magnetogram as shown in Fig. 1b which is sometimes referred to as a "chrochet".

In order to understand the response of the ionospheric currents to the solar flare radiation we shall first briefly describe the main characteristics of the Sq currents, since the s.f.e. currents are intimately linked with the Sq.

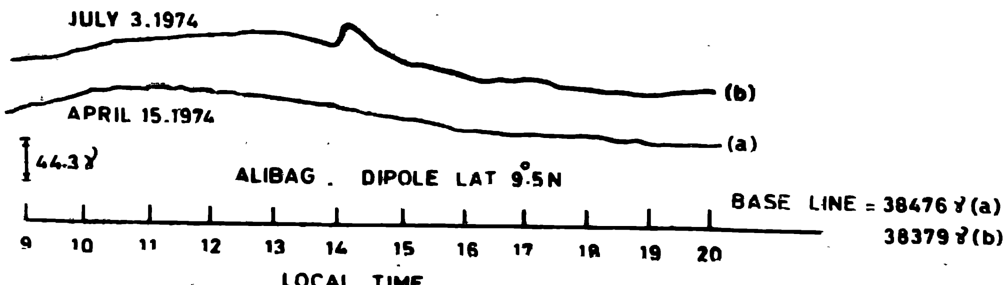

Fig. 1 a-b: The horizontal component of the magnetic field versus local time recorded at the magnetic observatory at Alibag (mag. lat. 9.5°N). The trace of April 15, 1974 represents a quasi-stationary Sq variation. For the July 3 trace the small bump near 14 U. T. indicates increased ionospheric currents caused by a solar flare.

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II. IONOSPHERIC CURRENTS UNDER NORMAL SOLAR CONDITION

The solar X-rays and the ultraviolet rays are the principal ionising agents in the earth's atmosphere. Generally the wavelength band 3 Å to 20 Å is chiefly responsible for the E-layer ionisation. X-rays below 3 Å is capable of ionising the deeper D-layer. A typical height profile of the electron density Ne for moderately quiet solar condition is shown in Fig. 2. Since the mass density in the atmosphere, and therefore the collision frequency of an electron (or ion) decreases with increasing height, the height dependence of the electrical conductivity does not necessarily follow the electron density height profile. The height variation of the Pederson and Hall (Meada and Kato 1966) conductivities σ_1 and σ_2 respectively for the above model atmosphere are also shown in the same Fig. 2.

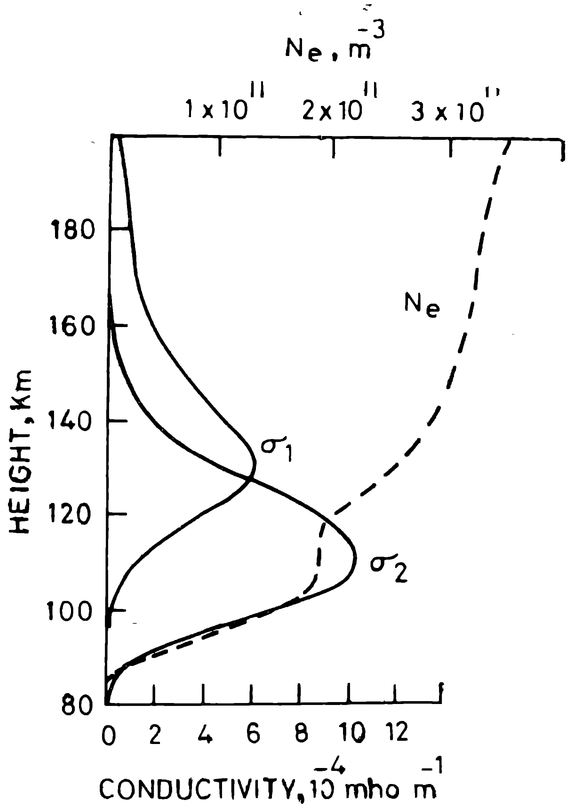

Fig. 2: The Pederson and Hall conductivity σ_1 and σ_2 respectively as a function of height. The dashed curve shows the variation of the number density of the electrons with height.

The ionospheric current, although height dependent, is confined in a narrow range of height around 100 km $\pm$ 10 km. A typical height profile of the current density measured by rockets (Sampath & Sastry 1979) is shown in Fig. 3. Therefore, it is reasonable to represent the current density by a two dimensional current vector,

$$\mathbf{J}(\Omega) = N(\Omega)\ \underset{\approx}{\sigma}(\Omega)\ [1/c\,(\mathbf{V}\times\mathbf{B}) + \nabla\Phi]. \qquad (1)$$

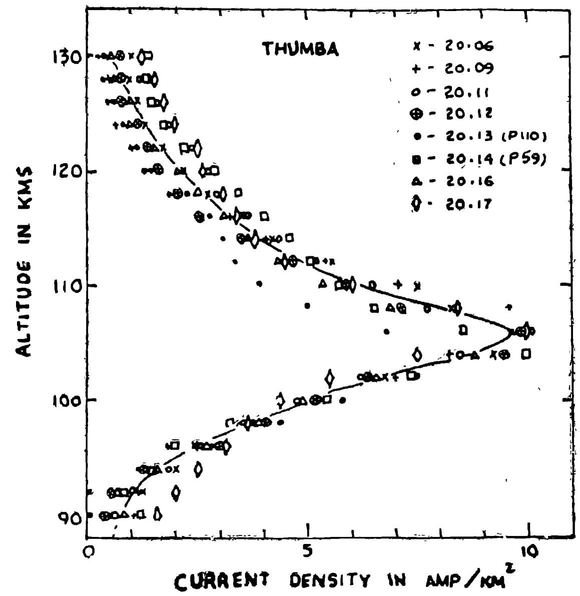

Fig. 3 : The vertical distribution of current density measured during eight mid day flights from Thumba (Sampath & Sastry 1979).

Here Ω is the set of angular variable (θ, ϕ), $\underset{\approx}{\sigma}(\Omega)$ is the height integrated conductivity tensor per unit electron density and $N(\Omega)$ is the electron density itself. Φ is any electrostatic potential present. By demanding div $J = 0$ and assuming some models for $\underset{\approx}{\sigma}$ and $\mathbf{V}$, one can eliminate Φ from equation (1), and get an expression for the current function ψ defined by

$$\mathbf{J}(\Omega) = \hat{r} \times \nabla\ \psi(\Omega), \qquad (2)$$

where $\hat{r}$ is the radius vector in the current carrying layer. The geomagnetic field **B** is of course, known. This is the standard theoretical technique of drawing the large scale ionospheric current patterns. The quiet time Sq currents are more or less well understood under this theoretical frame-work.

III. IONOSPHERIC CURRENTS DURING A SOLAR FLARE

During a solar flare the change in the spectrum of the electromagnetic radiation is communicated to the earth much earlier than that of the corpuscular radiation which triggers a host of magnetospheric and ionospheric disturbances. If the change in the solar spectrum is such that there is an enhancement of the X-ray flux in the 3 — 20 Å band or below, the possibility of enhanced ionospheric currents is high. The magnetic variation recorded on a ground observatory can still be represented as if produced by a two-dimensional current system like Sq i.e.

$$\mathbf{J}(\Omega) = N(\Omega, t)\ \underset{\approx}{\sigma}(\Omega)\ [1/c\,(\mathbf{V}\times\mathbf{B}) + \mathbf{E}]. \ (3)$$

Here $N(\Omega, t)$ is the charge density which is modified by the solar flare and **E** is the electric field other than the dynamo field.

The ionising power of a particular solar radiation depends not only on the ionospheric height but also on the solar zenith angle (Mitra 1979). However, the magnetic field configuration in the ionosphere as well as the neutral particle density are not likely to change much during a flare. There is no reason why the tidal velocity field **V** should change within such a short time. Hence the change in the ionospheric conductivity comes only through the charge density term $N(\Omega,t)$. Since the current pattern is crucially dependent on the spatial distribution of the total conductivity $N\sigma$, the Sq current pattern (solution of equation (1) and the flare time current pattern (solution of equation(3) are distinctly different.

As an example we show in Fig. 4a, the Sq current pattern at 1500 UT on August 28, 1966 before a solar

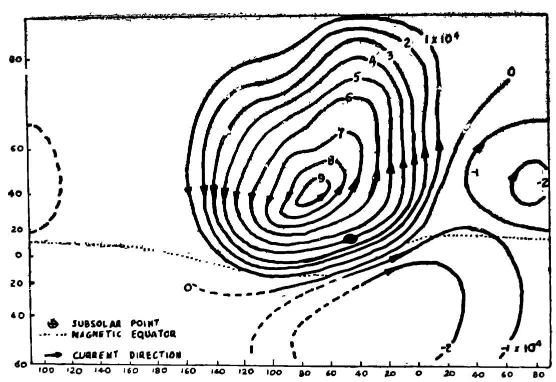

Fig. 4 a : The contours of Sq current pattern at 1500 U. T. on August 28, 1966. Fixed amount (104 amps) of current flows between the the consecutive lines.

flare which started at 1522 UT on the same day. The s.f.e. current system at 1539.5 UT on the same day is shown in Fig. 4b (Greenfield and Venkateswaran 1967).

The morphological analyses of the solar flare time current system in the ionosphere have been extensively done by Ohshio (1964), Greenfield and Venkateswaran (1967), Richmond and Venkateswaran (1971) and many others in the past. The main features out of these studies clearly indicate that the s.f.e. current system is not just an augmented Sq. The overall global current pattern is distinctly different. The focus of the current system is also not stationary even during various phases of a given solar flare (Greenfield and Venkateswarn 1966). It was suggested long time ago (Ellison 1950, 56; McIntosh 1951; Mitra and Jones 1953) that the s.f.e. current site is the lower D-region rather than the E-layer normally carries the Sq currents. The datailed time dependence of the observed current system of a few s.f.e.'s were analysed by Richmond and Venkateswaran (1971). They showed that the s.f.e. currents

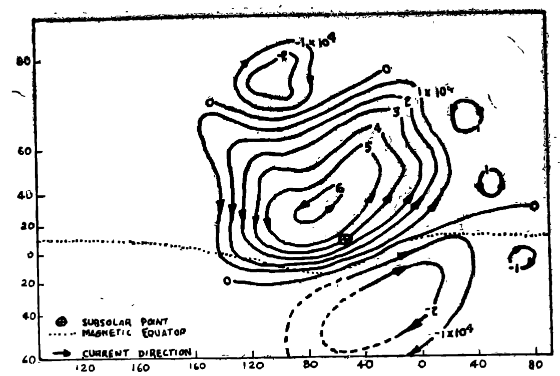

Fig. 4 b : The additional currents flowing in the ionosphere at 15 39.5 U.T. on the same day due to a solar flare which started at 15 22 U.T.

can be decomposed into two components whose time-dependences follow those of the electron densities in the E- and the D-layers respectively. Another morphological observation about the flare time current system is that the effect is occasionally felt even in the dark-hemisphere (Srivastava and Abbas 1975; Hanumanth Sastri 1975).

The first theoretical attempt to solve the dynamo equation during a solar flare was made by Pratap (1957) where he assumed that at the maximum phase of the flare the spatial dependence of the conductivity has the form

$$\frac{N(\Omega,\, t)}{N(\Omega, o)} \sim \exp\left(-\,\alpha\,[\,\phi - \phi_o\,]^2\right), \qquad (4)$$

where ϕ is the azimuthal coordinate and therefore is proportional to the local time, ϕ_o is the maximum of the "crochet" and α is a constant.

This calculation offers a fair agreement with the observation of the statistical distribution of the amplitudes of the flare time ionospheric currents as a function of latitude and longitude although it cannot still explain the change in direction of the flare time current so well.

The fundamental difference between the current equation (1) for Sq and (3) for crochet is not only the conductivity distribution $N(\Omega, t)\ \underset{\approx}{\sigma}(\Omega)$ but also the electric field **E**. For a quasi stationary Sq current the electric field is mostly electrostatic, $\nabla\Phi$. But a time-dependent current $\mathbf{J}(\Omega,t)$ will produce an induced field proportional to the time derivative $\dot{\mathbf{J}}(\Omega,t)$. This induced electric field was treated first by Nagata (1950) approximately and then by Rikitake and Yukutake (1962) in a more formal manner. Here of course they ignored the spatial dependence of the conductivity σ. In their model, σ is a constant in the sunlit portion of the ionosphere and zero in the dark hemisphere. They also assumed an exponential time dependence for N (Ω, t), i.e.

$$\sigma = \sigma_o \; (1 + \bar{e}^{\lambda t}),$$

$$\text{with } \sigma_o = 10^{-8} \text{ e.m.u.}, \lambda = 1/600 \text{ sec}^{-1},$$

Over the sunlit part of the hemisphere and σ is zero over the dark hemisphere. Here $t = 0$ is assumed to be the maximum phase of the s.f.e. Therefore, it describes the decay phase of the flaretime current system.

The theoretical current system described by this above model is shown in Fig. 5. Here the co-ordinate

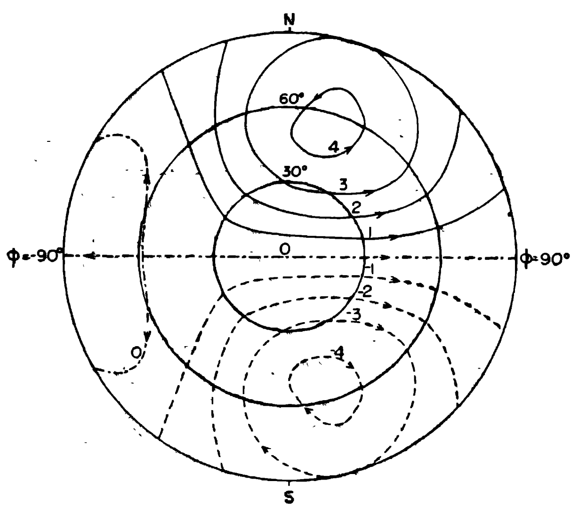

Fig. 5 The current system of s.f.e. (excluding the normal Sq) over the sunlit hemisphere at $t = 10$ sec. i.e. after 10 sec of the maximum phase of the s.f.e. Electric current amounting to 5×10^3 A is flowing between two adjacent lines.

system is such that the earth-sun line is the X-axis. Hence the region bounded by $0 \leq \phi \leq \Pi/2$ is the sunlit hemisphere. This is the additional current due to the solar flare. Therefore, total observed current will be the superposition of this and the Sq current. It should be noted that the current lines 2 and 4 in Fig. 5 actually complete the circuit through the dark hemisphere. This shows that it is the induction effect which drives the current in the dark hemisphere to explain the observed night time crochet, although weak. This model thus demonstrated the importance of the ionospheric induction effect of modifying the flare time current pattern substantially from that of the Sq pattern. The time lag between the maximum phase of the charge density $N(t)$ and the maximum phase of the current density $J(t)$ was also shown to be the effect of induction. However, the observed time lags between the maximum phases of the current density $J(\Omega, t)$ at various points cannot be explained by this model. It was shown by Roy (1978) that the inclusion of the inductive electric field as well as the spatial dependence of the conductivity $\underset{\approx}{\sigma}(\Omega)$ in the dynamo equation (3), can indeed explain this time lag phenomenon better.

In all the above theoretical investigations a single layer model was invoked although it was known long time ago that the flare time current extends upto the lower D-layer. A two layer concept of the flare time current was first incorporated in solving the current equations by Roy (1977, 1979). This model assumed that the flare time currents are the super position of the two mutually coupled current systems ψ^E in the E layer (at about 105 km) and ψ^D in the D layer (at about 75 km) respectively. The dynamo equations are as follows :

$$\mathbf{J}^{E,D}(\Omega, t) = \hat{\gamma} \times \nabla \psi^{E,D}(\Omega, t),$$

$$\mathbf{J}^{E,D}(\Omega, t) = N^{E,D}(\Omega, t)\, \underset{\approx}{\sigma}^{E,D}(\Omega)\, [(1/c)\, \mathbf{V}^{E,D} \times \mathbf{B} + \nabla\Phi^{E,D}$$

$$+ (1/c) \int d^3\gamma' \frac{\partial \mathbf{J}(\gamma', t)}{\partial t} \quad |\gamma - \gamma'|]. \quad (6)$$

The superscripts E and D represent the variables for the E and D— layers respectively. The third term on the r.h.s. of equation (6) is the induced electric field. Both J^E and J^D will contribute to the E-layer (D-layer) current. Thus ψ^E and ψ^D are coupled through this induction term.

The spatial dependence of the conductivity $\sigma(\Omega)$ is assumed to be of the form :

$$\sigma \backsim 1 + \alpha_1 \cos\chi + \alpha_2 \cos^2\chi,$$

where α_1, α_2 are constants and χ is the solar zenith angle. The theoretical current pattern for the flare of May 21, 1967 is shown in Fig. 6. The lines of constant potential represent the total (Sq + s.f.e.) current at that instant. The temporal developments of the conductivities for both the E and the D-layers are deduced from the observed conductivity profiles (Richmond and Venkateswaran, 1971) during this flare. These calculations showed that the time development of the two current systems, one in the E- and the other in the D—layer respectively, being different, the superimposed current pattern is indeed distinctly different from the Sq pattern. It also shows how the focus of the current system moves away from the Sq focus during the initial phase of the flare but tends to coincide with Sq focus at the maximum phase of the flare. This effect is attributed to the mutual induction between these two layers.

The solar flare effect is generally confined to the low and the mid latitude ionosphere. It is very difficult to identify the geomagnetic solar flare effect

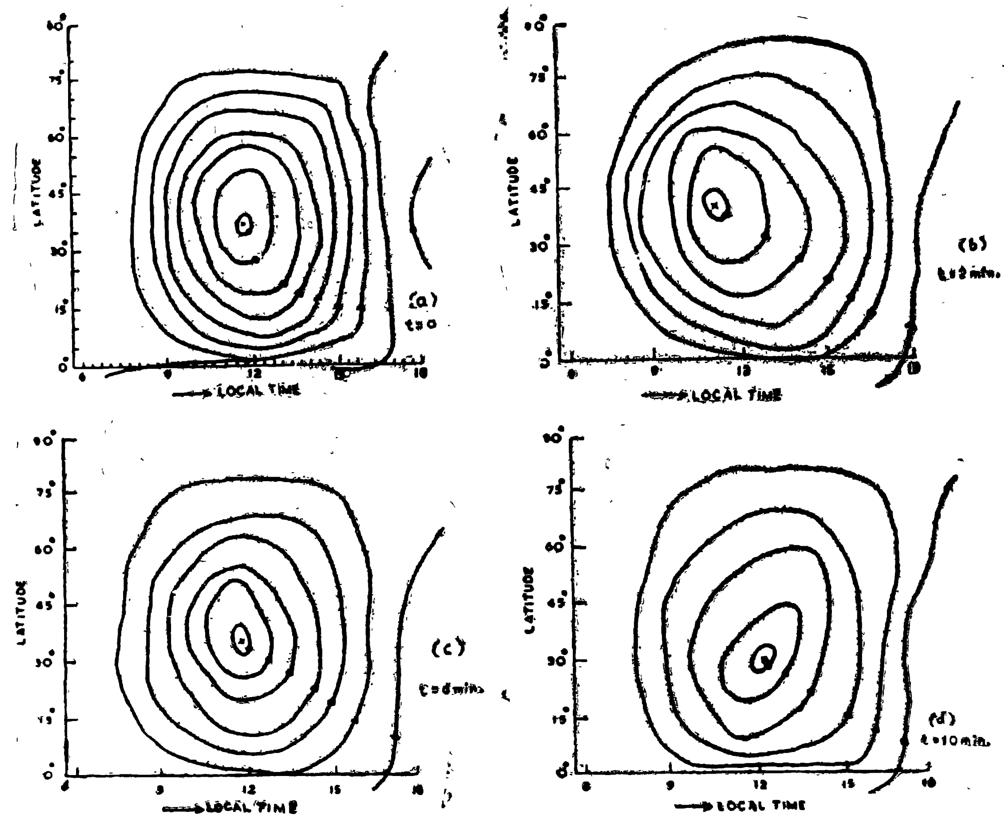

Fig. 6 The contours of the constant potentials obtained from $\psi E + \psi D$ at a few instants starting from $t = 0$ which represents the onset of the flare. (a) Resultant current system with total current of 3.0×10^5 A. associated with the main vortex, at $t = 0$ i. e. the Sq current. (b) Current system at $t = 2$ min, total current being 1.35 times, the tota l Sq current. (c) The same at $t = 6$ min; total current is 2.38 times the Sq current. (d) The same at $t = 10$ min with 2.15 times Sq current associated with the main vortex.

in the high latitude stations because of the high variability of existing magnetic field. Still, the study of the current systems of some intense chrochets (Sergeyev 1977) made it possible to obtain, under certain conditions, an approximate global picture of the distribution of the electric fields in the sunlit high-latitude ionosphere.

In all the past theoretical formulations of describing the flare time ionospheric currents it was implicitly assumed for the sake of mathematical simplicity, that the time dependence of the electron density all over the sunlit part, is similar i.e., $N(\Omega,t)/N(\Omega,0)$ is represented by a single function f (t). In practice, of course, this is not so. Therefore, a complete solution of equation (3) is necessary incorporating the spatial dependence of $N(\Omega,t)$ which faces rather computational hazards.

The basic difficulty in treating the flare time currents in more details is that the only observational global informations (as a function of short interval of time) available are those by the ground-based magnetograms which project the equivalent current system and not its multiple structure. Since the flare time currents are multilayered, it is essential to know the relevant parameters like electric field, wind distribution, electron density for the D—layer also not only during the flare but also during the quiet times when this layer carries negligible, nevertheless finite, current. Although the incoherent back scatter experiments (Mitra 1974) and the rocket experiments (Mitra 1974) aim at gathering the detailed ionospheric parameters and their height dependence, even during solar flares, they hardly project a simultaneous global picture of the transient state of these parameters. The characteristic spectrum and the intensity of the solar radiation vary from flare to flare. As a result, their ionospheric responses are also variable. Hence simultaneous global observations are necessary to sort out and understand the detailed structure of the geomagnetic solar flare effect. This can be achieved only by coordinated probing of the ionosphere by the ground and the satellite magnetometers as well as by the back scatter experiments simultaneously at as many stations as possible.

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