Heating of solar filamentary magnetic flux tubes

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The sunspot regions are well-known sources of energetic charged particle emissions and numerous wave mode generations. It is shown that the high frequency electromagnetic waves generated by synchrotron process, at times, could be cross-modulated by low frequency *p*-mode oscillations. The analyses of recorded electromagnetic field strength and seismic waves would depict interesting features of the originating sunspot regions.

THE sun in our galaxy is the best-studied star. Despite this we feel, at times, that our knowledge is limited and is far from adequate. Our sun is a source of many wave mode generations and their radiation. Study of some of these radiations provides important information about the sunspot regions over the solar surface. In this paper, we study certain features of low frequency *p*-mode oscillations[1–3] and the high frequency electromagnetic waves generated by the synchrotron process[4–6] in the magnetic flux tubes extending to solar coronal region. The growing solar magnetic flux tubes are a source of generation and interaction of these waves. The detailed features of these flux tubes vary as they grow and at a certain instant of time and space, the magnetic flux tubes depict nonlinear variation of solar plasma confined in the filamentary magnetic flux tubes. It is shown that *p*-mode oscillations in the nonlinear region of the solar magnetic filamentary flux tubes modulate the high frequency electromagnetic waves generated by synchrotron and other radiating processes. It is shown that the study of some features of cross-modulated signal may prove to be of great diagnostic value and may also exhibit remote sensing features of the solar regions. This subject is still in the growing stage and reported new features may lead to further interesting results.

The solar chromospheric and coronal magnetoplasma is subjected to varying magnetic field and plasma temperature. These regions invariably acquire complex character and the degree of complexity varies from the lower region to the upper region of the sun. The drastic changes take place in the sunspot regions and the extended region above the sunspots exhibit varying degree of plasma density and temperature changes, resulting in nonlinearity of varying degree. However, we have not gone into the details of parametric decay processes generating various wave modes and wave frequencies[7]. It is well known that the sun is a source of extended electromagnetic wave radiations. In this paper, we discuss certain features of low frequency waves generating in the chromospheric and coronal magnetic flux tubes. Reference is made to long-period oscillations of magnetic flux tubes generated in the solar active regions. The physical features of the five-minute and three-minute oscillations have been studied intensively since their discovery by Leighton *et al.*[8]. In the sunspot regions these oscillations exhibit interesting features and are dominant in the photospheric and lower chromospheric and coronal regions[9–11]. These oscillations are not capable of propagating outward to farther distances. Therefore, their detailed study is limited to various indirect measurements and theoretical analyses of some of the interrelated physical phenomena and many of their observed features.

The sunspots are randomly distributed over the solar surface and are known to be concentrated near the poles. The details of processes determining the build-up of active sunspots are not fully understood. The build-up and decay phases are characterized by solar winds emitted from these regions. The solar wind variational features, namely the velocity, charged particle flux and composition of charged particles in the solar wind provide diagnostic features of the solar wind build-up and emission process. The source region below the solar surface starts growing and building-up in the magnetic field strength when the sun executes its normal rational process. The schematic of a fully developed sunspot region depicting extended magnetic field emanating from the active sunspot region is shown in Figure 1. As the sunspot's region of magnetic field builds up, the magnetic field grows freely and is not significantly affected at lower altitudes above the solar surface. Higher up in the chromosphere and coronal regions, plasma is fully ionized and temperature is very high. The growing solar magnetic field configuration is completely frozen in the hot solar plasma of the coronal region. The magnetic field is extended as the solar plasma expands and rotates around the sun.

An important phenomenon takes place in the coronal region and beyond. The flow of solar plasma stretches the embedded magnetic field forming an oppositively-directed parallel magnetic field configuration. The solar wind hot plasma is frozen in this extended magnetic field region. With varying activity of the sunspot region, the solar magnetic field configuration undergoes a change and according to the enhanced plasma pressure, the neutral region of the extended coronal region is further compressed. In so doing, the separation between the oppositively-directed solar magnetic fields is reduced and the magnetic field flux is enhanced. According to frozen-in field-plasma condition, the enhanced magnetic field gives rise to enhanced plasma energy. With enhanced compression of solar magnetic field at larger distances, the oppositively-directed solar magnetic field lines tend to

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merge and convert all their magnetic energy into kinetic energy of the coronal plasma. This condition corresponds to

$$\frac{B_\mathrm{s}^2}{2\mu_0} = \frac{1}{2} nm V_\mathrm{s}^2, \qquad (1)$$

where B_s, V_s is the magnetic field in the solar plasma in the coronal region and V_s is the velocity of emanating solar wind charged particles. This condition is schematically illustrated in Figure 2. The oppositively directed parallel magnetic field configuration is shown in Figure 2 *a*. With enhanced sunspot activity, the parallel magnetic field region is further compressed, which maximizes, producing a neutral point. The magnetic field energy of the neutral region is slowly converted into the energetic charged particle beam emanating inward as well as outward as shown in Figure 2 *b*. The outside charged particle flux carries the embedded solar magnetic field and is known to form the energetic solar wind component. This region of the solar corona behaves as plasma bottles and radiates high frequency electromagnetic waves of decreasing frequencies with increasing altitudes. The energetic charged particle fluxes gyrating downwards along the closed loop magnetic field result in generation of high frequency electromagnetic waves by synchrotron and other plasma processes. The synchrotron process is one of the most potential processes generating electromagnetic waves at the higher harmonics of cyclotron frequency. The magnetic field configuration in the photospheric sunspot region develops slowly and extends beyond the solar coronal region. The sunspot magnetic field decreases away from the solar surface inversely as cube root of the normalized solar distance, i.e. $(R/R_\mathrm{s})^{-3}$ where R_s is the mean solar radius. The strength of the magnetic flux tubes, their cross-sectional area, plasma density and electron temperature are known to change from the solar surface to the apex of the closed magnetic field flux tubes. It is well known that the radiated electromagnetic wave power by synchrotron process at higher frequencies is confined to a narrower cone angle. It is therefore obvious that the low frequency *p*-mode waves generated in the photospheric sunspot regions are aligned along the solar magnetic flux tubes and propagate only over short distances. These low frequency waves are not capable of propagating outwards to longer distances. The high frequency electromagnetic waves generated by the synchrotron process are confined in the thin magnetic field filaments originating from the sunspot regions. The magnetic field flux tubes originating from the sunspot regions as such exhibit field strength variations with varying altitude. The plasma density and its temperature in the chromospheric and coronal regions also vary with changing altitudes. Therefore, the solar plasma frozen in the magnetic field depicts the nonlinear behaviour for propagating low frequency and high frequency waves. As a result of varying degree of nonlinearity, the large amplitude, high frequency waves are amplitude modulated by low frequency waves. This process seems to play an important role in transforming the solar phenomenon.

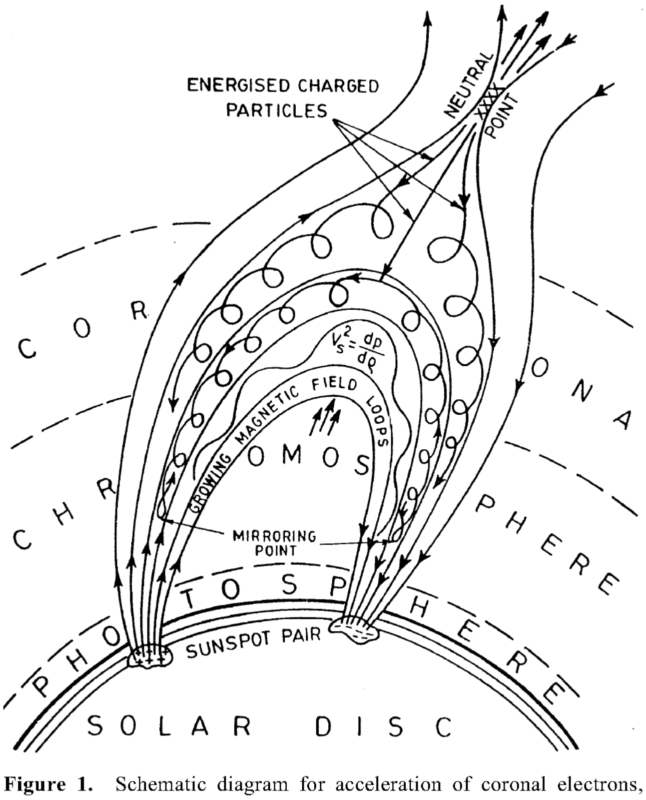

Figure 1. Schematic diagram for acceleration of coronal electrons, their entry into the magnetic filaments originating from sunspot region and giving rise to various causative effects.

The low frequency *p*-mode oscillations and high frequency electromagnetic waves propagate through the slowly increasing cross-sectional area of the sunspot's filamentary magnetic flux tubes. The plasma density and electron temperature change with increasing altitudes. For sake of simplicity the magnetoplasma is considered as linear. However, the magnetoplasma in the sunspot region acquires varying degrees of nonlinearity as a result of changing plasma and field parameters. In the region of maximum nonlinearity of the magnetoplasma in the flux

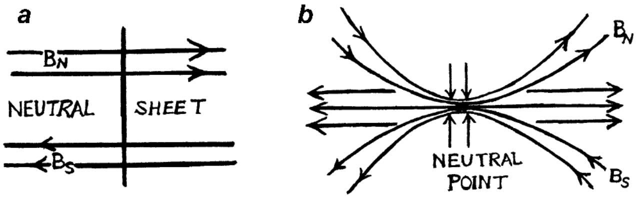

Figure 2. *a*, Ionized solar plasma bounded by oppositively directed parallel magnetic fields, which characterizes the field-free solar plasma; *b*, Enhanced solar plasma compresses the field-free region and forms a magnetically neutral point. The magnetic energy converts into two energized electron beams. One beam enters into the inner solar region and the other one is ejected outwards from the solar coronal region in the form of solar wind.

tubes, the electron component of plasma results in localized heating, wave mode interactions and transformation and enhanced inter-particle collision frequency. The theory of weak though nonlinear interaction of wave and plasma conforms with the following criteria: (i) The low frequency and high frequency electromagnetic waves are generated by various processes taking place in the solar chromosphere and corona; (ii) As a result of varying degrees of nonlinearity of solar magnetoplasma, the high frequency electromagnetic waves are cross-modulated by the low frequency waves and propagate outwards. (iii) $\Omega \ll G\nu$, where Ω is the modulating frequency, $G = 2M_e/M_p$ is the simplest form of energy transfer parameter and ν is the electron–proton collision frequency in Hz. The value of G is known to change depending upon the degree of nonlinearity and the temperature of the magnetoplasma. (iv) The electron heating $(T_e - T) < T$, where T is the average plasma temperature and T_e is the electron temperature as a result of electromagnetic wave interactions resulting into local heating (v) The energy content of solar coronal plasma is less than the electromagnetic wave energy, which introduces the nonlinearity in the solar plasma.

We consider the high frequency electromagnetic waves modulated with the low frequency waves that propagate through the solar plasma confined to the filamentary magnetic flux tubes. The temporal change in heating of the solar plasma frozen in the magnetic flux tube as a result of interaction of modulated electromagnetic waves is given by[12]

$$\frac{d(T_e - T)}{dt} + G\nu(T_e - T) = \frac{1}{3nK}\sigma_r E_o^2 (1 + \mu_o \cos \Omega t)^2. \tag{2}$$

σ_r is the real part of the plasma conductivity, E_o is the magnitude of high frequency unmodulated wave and μ_o is the index of amplitude modulation. This equation is similar to that for the amplitude modulation phenomenon. The second term on the left hand side depicts the energy transfer process from electrons heated by modulated electromagnetic waves to ambient electrons and the term on the right hand side of eq. (2) denotes the temporally changing Ohmic energy loss term. Equation (2) can be rewritten as

$$\frac{d(T_e - T)}{dt} + G\nu(T_e - T) = \frac{1}{3nK}\sigma_r E_o^2 \left(1 + \frac{\mu_o^2}{2}\right) \times$$
$$\left[1 + \frac{2\mu_o}{\left(1 + \frac{\mu_o^2}{2}\right)} \left(\cos \Omega t + \frac{\mu_o}{4} \cos 2\Omega t\right)\right]. \tag{3}$$

Equation (3) is a first-order linear differential equation and its solution is given by,

$$T_e - T = T\frac{E_o^2}{E_c^2}\left[1 + \frac{\mu_o^2}{2} + 2\mu_o \left(\cos \Omega \left(t - \frac{1}{G\nu}\right)\right)\right.$$
$$\left. + \frac{\mu_o}{4}\cos 2\Omega\left(t - \frac{1}{G\nu}\right)\right], \tag{4}$$

where E_c is the characteristic field of the interacting plasma system defined as

$$E_c^2 = 3mKTG(\nu^2 + \omega^2)/e^2 \quad (\text{Volt m}^{-1})^2. \tag{5}$$

Equation (4) clearly depicts that the electromagnetic waves interacting with the nonlinear plasma system result in heating and enhanced modulation by the low frequency intrinsic p-mode oscillations denoted by Ω. The solar coronal parameters chosen for this computation are $n_e = 10^8$ cm^{-3}, $T = 10^6$ K, $B = 20$ Gauss and the frequency of electromagnetic wave $\omega = 3.5 \times 10^{10}$ rad sec^{-1} and are typical of solar active regions[11]. Using eq. (4), the variation of electron temperature in the filamentary flux tube with time has been computed as a consequence of incidence and interaction of modulated high frequency electromagnetic waves. It is seen that the higher modulation index results in larger heating of the filamentary flux tubes of the solar plasma. The changing period of the modulating waves starts showing up with increasing interaction time of the waves as shown by the dotted and solid curves in Figure 3. Variation of heating of the solar plasma confined to the filamentary flux tube is shown in Figure 4. The solar plasma is heated up by generation of long-period and large-amplitude oscillations in the filamentary solar magnetic flux tubes. The index of modulation of propagating high frequency electromagnetic wave

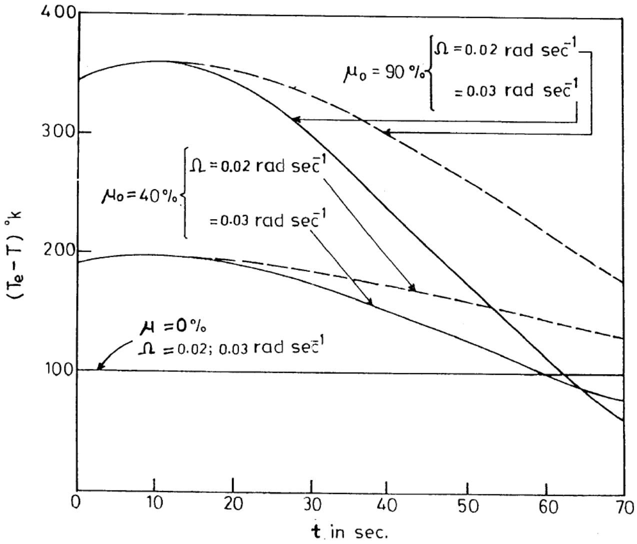

Figure 3. Variation of electron heating with the interaction time for a plasma characterized by $E_c = 4.248 \times 10^4$ V/m and the interacting wave electric field of $E_o = 4.248 \times 10^2$ V/m.

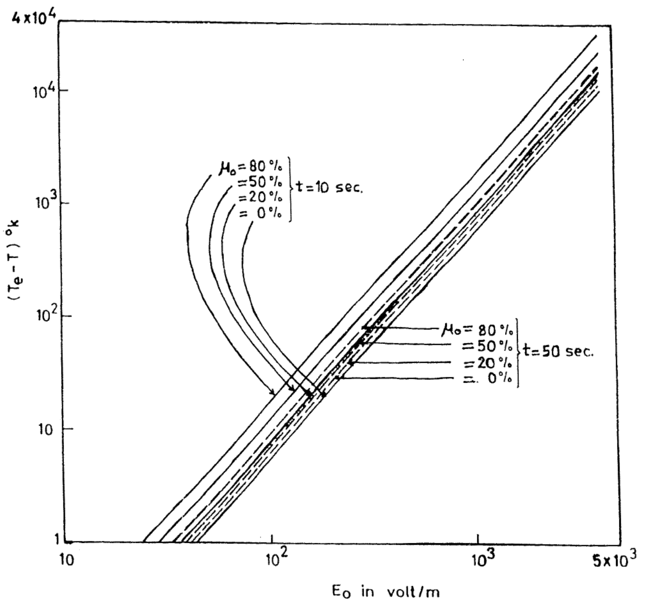

Figure 4. Variation of electron temperature with electric field strengths for different modulation indices for $\Omega = 0.03$ rad $\sec^{-1}$.

of constant amplitude is seen to increase with enhanced heating of the filamentary solar plasma. The electron temperature is found to increase with increasing amplitude of the high frequency waves and is also affected by the changing index of amplitude modulation of long-period waves.

The present analysis clearly shows that the high frequency electromagnetic radiations, at times, could be modulated by the long-period *p*-mode oscillations associated with the growing filamentary solar magnetic flux tubes. Careful recording of the high frequency signal strength over a long period is required for ascertaining its origin in the sunspot regions. The modulation of high frequency waves by long-period oscillations can be best seen by time compression of the long-period modulation. The depth of modulation index of high frequency signal is governed by the varying solar conditions and has inbuilt potential for diagnostic studies of sunspot processes.

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Relationship between the reference value of young people's haematocrit and geographical factors in China

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This paper provides a scientific basis for a unified standard of the reference value of healthy young people's haematocrit in China. It studies the relationship between the reference values of healthy young people's haematocrit, tested according to the Wintrobe Laws and five geographical factors. It is found that the altitude is the most important factor affecting this reference value. As the altitude gradually increases, the reference value also increases, the relationship is quite significant. By using the method of stepwise regression analysis, two multivariate regression equations are deduced. If the geographical index values in a particular area in China are known, the reference value of haematocrit in this area can be established by means of the regression equations. Furthermore, China can be divided into six districts: Qingzang, Southwest, North-west, South-east, North and North-east.

HAEMATOCRIT is an important index of haemorheology. At present, it is difficult to achieve accuracy in clinical practice, because of the lack of a unified standard of the reference value of young people's haematocrit in China. Many researchers have measured the reference value (Wintrobe) of local young people's haematocrit[1–47]. No reports on the relationship between this reference value and geographical factors were found. By means of correlation and stepwise regression analysis, research on this relationship has showed that there are certain regular patterns between the reference value of young people's haematocrit and geographical factors.

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