# A DOUBLE LAYER MODEL FOR SOLAR X-RAY AND MICROWAVE PULSATIONS

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## Abstract

The wide range of wavelengths over which quasi-periodic pulsations have been observed suggests that the mechanism causing them acts upon the supply of high energy electrons driving the emission processes. A model is described which is based upon the radial shrinkage of a magnetic flux tube. The concentration of the current, along with the reduction in the number of available charge carriers, can give rise to a condition where the current demand exceeds the capacity of the thermal electrons. Driven by the large inductance of the external current circuit, an instability takes place in the tube throat, resulting in the formation of a potential double layer, which then accelerates electrons and ions to MeV energies. The double layer can be unstable, collapsing and reforming repeatedly. The resulting pulsed particle beams give rise to pulsating emissions which are observed at radio and X-ray wavelengths.

## 1. Introduction

Most of the models for the quasi-periodic pulsations which are often observed at radio and X-ray wavelengths are based upon the modulation of synchrotron radiation by MHD wave modes in magnetic flux tubes, or by relaxation processes in wave/electron beam coupling. A summary of the observational data and models is given by Krüger (1979). The implicit assumptions embodied in these models is that the high energy electrons and mechanical disturbances required to drive the process are externally supplied by the flare.

However pulsations have been observed in the absence of flares (e.g. Kobrin et al., 1978; Kaufmann et al., 1980; Strauss et al., 1980; Gaizauskas and Tapping, 1980; papers by Kaufmann et al. included in these proceedings). In such cases modelling is more difficult. In addition to explaining the characteristic time-scales of the events, it is also necessary to identify the acceleration mechanism supplying the high energy electrons and how it is driven.

The wide frequency range over which the pulsations have been simultaneously observed, ranging from radio wavelengths to X-rays, implies that rather than modulation of the emissive process, for example by a time-varying magnetic field, it is more probably the variation of the supply of high energy electrons driving the various radiative processes that causes the pulsations. This may be due to a relaxation instability in the particle beams themselves, or by production of a pulsed electron beam by the accelerator. In this latter case the acceleration mechanism has to be highly efficient, accelerating the electrons from thermal to

relativistic velocities in time-scales of the order of seconds or less. Direct acceleration by field-aligned electric fields are the most viable ways of achieving this. The short time-scales indicate that the acceleration zone is spatially small, not larger than about $10^4$ km.

One candidate is the potential double layer. They have been extensively used in models for the acceleration of auroral electrons in the Earth's magnetosphere. They have also been used in at least one flare model (Alfvén and Carlquist, 1967, Hasan and Ter Haar, 1978). The formation, maintenance and dynamics of double layers have been discussed extensively (Block (1978); Torvén (1979); Torvén and Lindberg (1980-two references); Swift (1981); Davey (1983)).

Double layers are highly efficient electron accelerators, producing mono-energetic electron beams having small pitch angles. There is evidence that double layers exist in the laboratory and in the Earth,s magnetosphere; however there is as yet little evidence that such structures form in the solar atmosphere. This may be because of the difficulty in identifying structures of such small spatial extent.


## 2.   The Model

Evolutionary forces in solar active regions cause the overlying chromospheric and coronal magnetic fields to depart from simple, potential configurations, leading to the generation of electric currents. The current carriers are the ambient thermal electrons and ions. The complex magnetic structures contain sheared and curved magnetic field lines, giving rise to some motion of the current carriers across the field, from one loop structure to another. Therefore to at least some extent, the active region is a complex current circuit containing many interactive elements. Changes in one part of the region may modify the current system and so affect conditions in distant areas.

The formulation of model which is truly descriptive of the active region processes is very difficult if not impossible, yet the taking of one element of the region in isolation may not be realistic. This is particularly the case with double layers, where the formation criteria and the subsequent stability of the layer are defined by the external current circuit.

Consider the case of a magnetic flux tube forming part of an active region. It is firmly anchored at the ends by its connections to other structures, but is free to expand or contract in its middle section. It is always in pressure equilibrium with the surrounding magnetoplasma. Evolution of the active region leads to an increase of the current carried by the tube, causing it to contract radially.

As the cross-sectional area of the tube decreases, the current density is further enhanced. The variation in strength of the longitudinal magnetic field strength along the tube leads to mirroring of electrons at the tube throat, particularly at the centre, where the field is strongest. Since the mean free path of the electrons is much

larger than the dimensions of the trap, the current is carried only by electrons lying in the loss cones.

Finally, the number of available charge carriers becomes inadequate to carry the current. However the large self-inductance of the external current circuit forces the current to be maintained. The continuity of the current is achieved by the formation of a potential double layer in the throat. The layer's field-aligned electric field accelerates electrons into the loss-cones at MeV energies. These maintain the current at the required value. If the rate of energy supply to the double layer is less than the energy dissipation rate, the layer will collapse and reform, producing a pulsed beam of high energy electrons. The pulsations are due to the time-variation of the electron beam driving the various emission processes.

## (1)  Radial Contraction of a Magnetic Flux Tube

Consider the case of an infinitely long, thin, straight magnetic flux tube. It carries a current driven by an external source. The current density is assumed to be uniform across the tube cross-section. The ends of the tube are fixed but the rest of the tube is free to move. It is in pressure equilibrium with the external plasma. Initially it assumed to be a uniform cylinger of radius $R_0$, containing a longitudinal magnetic field of strength $B_0$. The configuration is shown in Figure (1). All changes in the quantities dictating the tube structure are assumed to take much longer than any of the characteristic time-scales of the tube. In the force-free case, the tube equilibrium is described by the equations:
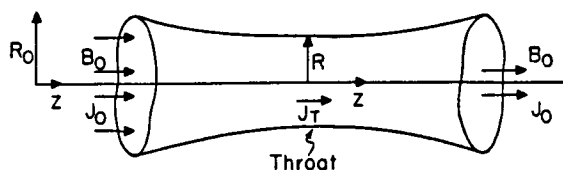
$$\text{Curl } (\vec{B}) \times \vec{B} = 0 \qquad (1)$$

$$\mu \vec{j} = \text{Curl } (\vec{B}) \qquad (2)$$

where $\mu$ is the permeability of free space.

Figure 1:  The Collapsing Flux Tube.

In the axisymmetric case these equations become:

$$B_z \cdot \partial B_z / \partial r + B_\phi \cdot \partial B_\phi / \partial r + B_\phi^2 / r = 0 \qquad (3)$$

$$j_z = \mu/r \; \partial(r B_\phi) / \partial r \qquad (4)$$

where r, $\phi$, Z represent the usual cylindrical coordinate frame.

If the current density is assumed to be uniform across the

tube cross-section then $j_Z$ can be replaced by

$$j_Z = j_0(R_0/R)^2 \qquad (5)$$

where $R_0$ and R are respectively the radius of the tube at the (fixed) ends and R the radius of the tube elsewhere along the length of the tube. The quantity $j_0$ represents the current density at the tube end.

Using (5) and (4), equation (3) may be solved for $B_Z$ as a function of r. At the tube periphery (r=R), there must be pressure equilibrium with the external plasma. Also, since the total longitudinal magnetic flux is conserved:

$$\Pi.R_0^2.B_0 = 2\Pi \int_0^R B_Z(r).r.dr \qquad (6)$$

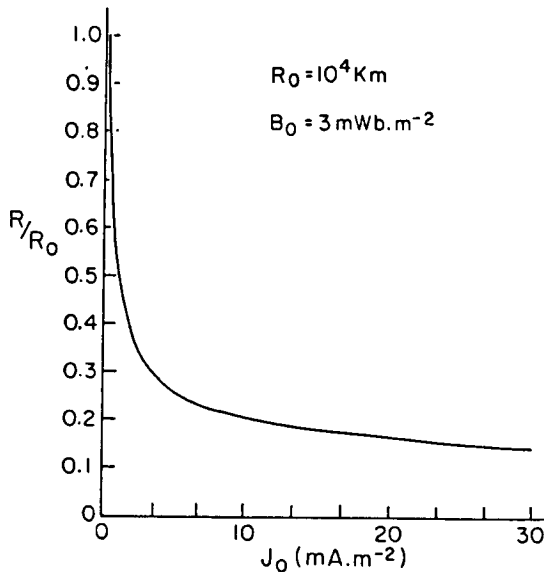Where $B_0$ = Magnetic field strength in un-perturbed tube.

Solving (6) gives the variation of tube radius as a function of the longitudinal current density, $j_0$, and can be used to calculate the throat current density (Equation (5)). The radial shrinkage of a tube of radius $10^4$ km and an initial magnetic field strength ($B_0$) of 2.5 mWb.M$^{-2}$ is shown as a function of current density in Figure (2). The maximum limit of the x-scale is equivalent to tube twist pitch of about unity.

$R_0 = 10^4$ Km

$B_0 = 3$ mWb.m$^{-2}$

Figure 2: The Relative Change in Tube Radius as a Function of Current Density for a Tube of Radius 10,000 km.

(ii)   The Formation of the Double Layer

As the current density increases, a point is reached where there are insufficient available charge carriers to carry the required current. If the charge carriers initially have an isotropic pitch angle distribution, the fraction lying the loss cones is given by:

$$\eta = 1 - (1 - B_0/B_Z)^{\frac{1}{2}} \qquad (7)$$

Only electrons lying in the loss-cones can contribute to the carrying of the current, so using equation (7), the maximum allowable current density in the throat is:

$$j_{max} = N.u_T.e.[1 - (1 - B_0/B_Z)^{\frac{1}{2}}]$$ (8)

Where N = Number density of thermal electrons;
$u_T$ = Mean thermal velocity of electrons;
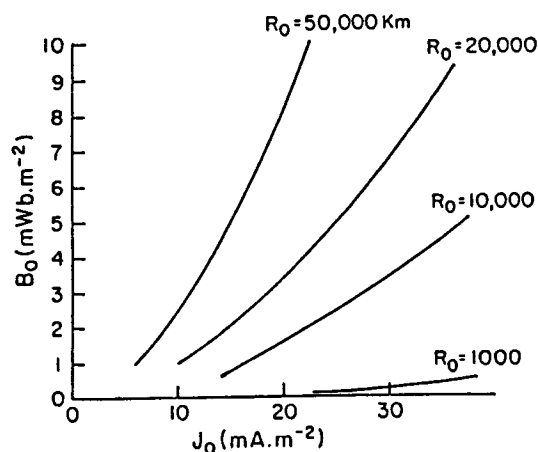e = Electronic charge



Figure 3: The Values of and Satisfying the Double Layer Formation Criteria for Various Tube Radii.
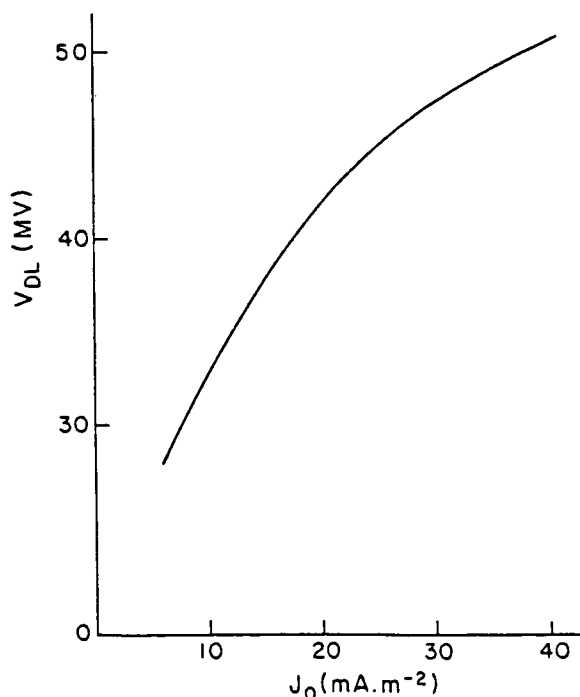


Figure 4: The Potential Difference Across the Double Layer as a Function of Current Density.

When the current density exceeds this value, the thermal particles cannot carry the current unless more electrons are scattered into the loss-cones. Since the mean free path is large, collisions will not do this. A plasma instability is required. The large self-inductance of the global electrical circuit prevents disruption of the current flow over short timescales; this factor provides the driving force for any instability leading to the scattering of more current carriers into the loss-cones. Such scattering implies the presence of a field-aligned electric field and a fall of the plasma density in the throat of the tube. The field-aligned potential difference accelerates enough electrons into the loss-cones for the current to be maintained. The density in the region of the electric field falls and the current becomes space charge limited. The curves shown in Figure (3) indicate the values of initial magnetic field strength (B) and current density (j) for tubes of various radii. Any conditions lying to the right of the appropriate curve satisfy the instability threshold criterion.

(iii) The Acceleration of Electrons

The value of the potential difference required to inject the extra electrons into the loss-cones may be calculated using Poisson's equation. The one-dimensional case is sufficient here. The relationship between the current density and potential drop across the layer is easily calculated using Poisson's equation in one dimension. The "cold plasma" approximation (Langmuir, 1929) gives the relation:

$$V_{DL} = \left( \frac{m \cdot j_o^2 (R/R_o)^4 \cdot d^4}{\varepsilon_o^2 \cdot e} \right)^{1/3} \qquad (9)$$

where d = Thickness of the layer,
e = electron charge,
m = electron mass,
$R_o$ = initial tube radius,
R = current throat radius,
$\varepsilon_o$ = permittivity of free space.

The thickness scale d, of the layer is a function of the geometry of the flux tube. It is of the order of the distance between the point where the instability criterion is met and the tube throat. In this calculation d is assumed to be 1 km. The electrons passing through the layer would be accelerated to an energy of Vdl eV. The potential drop across a layer of thickness 1 km, when the condition for the formation of the double layer is just satisfied, is shown in Figure (4). In this case electrons would be accelerated to energies of the order of 10 MeV. If the current density exceeds the threshold value, the potential difference will be larger.


(iv)  The Pulsations

The rate of energy dissipation by the double layer is given by the product of the total current through the double layer and the potential difference across it. A minimum condition for the stability of the double layer is that the rate of energy supply is not less than that value.

The dissipation of the energy of the magnetic field structure is equivalent to the dissipation of the torsional magnetic field component associated with the longitudinal current. The torsional magnetic field propagates to the double layer in the form of torsional (Alfvén) waves, where the magnetic field becomes unfrozen and the tube is free to untwist. It is very unlikely that the maximum torsional magnetic field strength associated with the Alfvén waves will exceed the longitudinal magnetic field strength in the tube, so the absolute maximum rate of energy supply to the double layer without disrupting the flux tube is therefore given roughly by:

$$W_{max} = u_a \cdot B_o^2 / 2\mu \qquad (10)$$

Provided that

$$W_{max} \geqslant \Pi \cdot R_T^2 \cdot j_T \cdot V_{DL} \qquad (11)$$

where $u_a$ = Alfvén speed
$R_T$ = Throat radius
$j_T$ = Throat current density

The stability of the layer will be a function of other criteria. However if the condition in Equation (11) is not satisfied, the layer will collapse as soon as the tube has untwisted in its vicinity so that Equation (11) is not longer satisfied. The layer will then collapse until the adjacent parts of the tube have once more become twisted enough for the layer to reform. The time taken for this would be of the order of an Alfvén transit time along the tube. For a tube carrying a current density of 40 mA per square meter and having a radius of 10,000 km, a double layer sustaining a potential difference of $10^7$ volts will dissipate energy at a rate of $10^{20}$ W. This value assumes that the double layer formation criterion has just been satisfied. For an Alfvén velocity of 2000 km/s and a tube radius 10,000 km – the maximum energy input rate would be about $10^{18}$ W. In this particular instance the layer would not be stable; it would be subject to a relaxation instability consisting of successive formation and collapse where the mean rate of energy supply is equal to the mean energy dissipation rate. The period of the instability is very small compared with the characteristic time-scales of the active region structures, so they would remain unaffected.

The pulsing double layer will produce pulses of electrons having MeV energies. These maintain the current and drive the X-ray and radio emission processes.

## (v)   The X-ray and Radio Emission

The production of X-rays is by free-free (bremsstrahlung) emission. Having small pitch angles, the electrons are potentially capable of penetrating to low levels in the solar atmosphere before being subject to mirroring. At these heights the beams are colli-sionally damped by the dense, thermal plasma, producing X-ray emission.

At meter wavelengths there are a variety of wave/particle inter-actions which can result in extraction of energy from the particle beam and the growth of plasma waves, which then contribute to radio emis-sion. However plasma waves are probably not important for microwave emission, because the high densities required would damp the waves. This would lead to the conversion of the beam energies into heat. Elec-tromagnetic radiation by the gyro-synchrotron mechanism would probably be more important at centimeter wavelengths. Electrons having small pitch angles are not subject to gyro-magnetic radiation losses, they must be scattered in pitch angle. There are beam/plasma instabilities which will achieve this. Once scattered the electrons will produce gyro-magnetic radiation.

## (vi)   The Radiated Flux

The spectrum of the radiation is difficult to estimate. At meter wavelengths the radiation will be a mix of plasma and gyro-synchrotron

emission; at microwave (centimeter) wavelengths, gyro-synchrotron emission will be predominant; the X-rays are produced by free-free damping of the high energy particles by the dense thermal plasma at lower heights above the photosphere. The total emission as a function of frequency is hard to calculate. If the emission is assumed to be uniformly distributed with frequency it is possible to estimate the flux density at the Earth. A double layer of dissipation $10^{20}$ W driving emission processes producing a uniform flux density over the wavelength range 1 A to infinity, the flux density at the Earth would be about 10 solar flux units. The pulsations observed by Gaizauskas and Tapping (1980) had a flux density of about 2 sfu at 2.8 cm wavelength.

## 3. Discussion

The high repetition rates of quasi-periodic pulsations imply small spatial sizes for the sources. Since pulsations have been observed which have a large instantaneous bandwidth, more than one emission mechanism is probably involved. This in turn suggests that the modulation mechanism is most likely to involve the supply of high energy electrons driving the various processes than the processes themselves. There are few acceleration mechanisms that are suspected to take place under solar conditions which can produce relativistic electrons from the thermal population in about a second.

The energetic electrons driving the gyro-synchrotron emission are damped primarily due to radiative energy losses. The damping time may be many seconds long, perhaps longer than the repetition period of the pulses. However the successive formation and collapse of the double layer in the flux tube would ensure that the tube contains torsional Alfvén waves. These will strongly modulate the gyro-synchrotron emission with the same period as the pulsing of the electron beam (Tapping, 1983). The pulsations at microwave and X-ray wavelengths would therefore occur at the same rate but not necessarily in synchronism. The pulse shapes would not necessarily be the same.

The pulsations observed during flares probably form just one way in which the energy release drives external phenomena. There is an abundance of available energy, accelerated electrons and evidence for magnetohydrodynamic disturbances. This is not the case for the pulsations observed in the absence of flares. In this latter case the fundamental problem is the electron acceleration process, and the way in which the slow evolution of the active region can, if the magnetic fields form the primary energy reservoir, lead to localized magnetic reconnection.

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