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A phenomenological, kinematical model of the coronal magnetic fields in terms of thin flux tubes rising from the photosphere

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Abstract. A kinematical model is necessary for understanding the gross structure of the coronal magnetic field and its slow evolution in consistency with the small scale structure of the photospheric fields. Here we have developed a preliminary phenomenological model in terms of flux tubes of flux amounts $\approx 10^{17} - 10^{18.5}$ Mx rising across the inner corona in the form of arches and opening out in the outer corona. In contrast to Parker's estimate, this model is consistent with the observed spans of the chromospheric fibrils and x-ray arches. It is also consistent with the number of flux tubes present above the photosphere as estimated from the observed abundance of spicules.

Keywords. Solar corona; solar magnetic fields.

1. Introduction

The presence of magnetic structures renders the solar atmosphere extremely inhomogeneous. It may be that the essential physics of the coronal energy balance is not yet well understood because these magnetic inhomogeneities cannot be easily taken into account in the theoretical models of the solar atmosphere. In this context Piddington (1976) has pointed out the necessity of treating the 'non-magnetic', the 'magnetically open' and the 'magnetically closed' parts of the atmosphere separately. As is well known, the magnetic fields are predominantly 'closed' in the inner corona and almost wholly 'open' in the outer corona. This topological feature of the 'gross structure' of the coronal magnetic fields remains unchanged though the gross structure itself evolves 'slowly' on time scales of months and years. In order to maintain this feature, new fields must keep on emerging from the convection zone to replace the old fields which rise further, 'open out', migrate and finally leave the sun after some reconnections in the course of an 11 years magnetic cycle. Further, almost all the emerging fields must be in the form of flux tubes with flux amounts $\approx 10^{17}$—$10^{18.5}$ Mx, since the photospheric magnetic flux seems to be always concentrated in such flux tubes. Thus a kinematical model in terms of rising flux tubes of flux amounts $\approx 10^{17}$—$10^{18.5}$ Mx is needed to understand the 'slow' evolution of the gross structure and the maintenance of its overall topological appearance.

In §2 of this paper we develop a preliminary kinematical model using phenomenological approach with the following simplifications: (i) since we are interested in the slow evolution, all the 'transient' events (e.g. on time scales $\lesssim 1$ day) are completely ignored; (ii) the quantitative estimates are confined to only the orders of magnitude so that for this preliminary model we need not distinguish between the quiet regions and the non-transient conditions in the active regions; (iii) for the same reason, we have assumed symmetry around the axis of the solar rotation for estimates depending on the geometry.

In §3 we show that the model is consistent with (i) the observed spans of the 'closed' chromospheric and coronal structures and (ii) the number of flux tubes present above the photosphere as estimated from the observed abundance of spicules.

In §4 we discuss the limitations of the model.

2. The model

2.1. *Coronal fields as consisting of flux tubes of $\approx 10^{17}$—$10^{18\cdot 5}$ Mx*

The photospheric foot points of the coronal fields seem to be always concentrated in flux tubes of fluxes $\approx 10^{17}-10^{18\cdot 5}$ Mx (Stenflo 1976 and references therein). Therefore, most of the coronal fields must always consist of similar flux tubes. The presence of such flux tubes in the corona is strongly indicated by the coronal fine structures, (such as spicules, polar plumes, coronal rays, individual filaments in the arch filamentary systems, fine structures in prominences and the x-ray arches, etc.) whose thicknesses are compatible with the flux amounts $\approx 10^{17}-10^{18\cdot 5}$ Mx.

Theoretically the coronal fields computed with the 'current free' and 'force-free' assumptions agree fairly well with the observed shapes and sizes of coronal structures (e.g. Schatten *et al* 1969; Altschuler and Newkirk, 1969; Nakagawa *et al* 1973) on scales $> 10^5$ km. However, this agreement does not exclude the presence of electric currents or even non-force free configurations on smaller scales (e.g. Levine and Altschuler 1975) required theoretically for the presence of thin flux tubes as indicated by the aforementioned observations. (It fact it will be shown in §2·2 that on small scales, force free configuration is not essential for equilibrium).

2.2. *Dense packing of the flux tubes in the inner corona as required by the lateral balance*

Excepting the local and transient phenomena like active prominences, flares, coronal transients, etc., and the related events, the corona is almost in static equilibrium upto heliocentric distances $\approx 2\ R_\odot$ where the solar wind acceleration becomes comparable to other terms in the momentum equation. Hence, upto these distances the coronal flux tubes must be normally in lateral balance with the non-magnetic plasma surrounding them. The lateral balance requires that

$$B_{\rm rms}^2 \Big/ 8\pi = p_{\rm out} - p_{\rm in} \tag{1}$$

where $B_{\rm rms}$ is the average root mean square field intensity inside the flux tubes, and $p_{\rm in}$ and $p_{\rm out}$ are respectively the plasma pressure inside and outside the flux tubes.

To see how this balance is maintained at various heights z above the photosphere, we must know the average height dependence of the axial field B_a in a typical flux tube. However, the field intensity at a given height will vary from one location on the sun to another. Additional uncertainty comes from the fact that different methods have to be used to measure the field at different heights. However, in the absence of better data, we disregard the difference between the variation of the $B_a(z)$ over 'quiet' regions and that over 'active' regions in nontransient condition to obtain crude but reasonable limits on the variation of $B_a(z)$ as represented by the curves in figure 1.

In table 1 we compare the corresponding magnetic pressure with the plasma pressure p_{emp} from an empirical model of the average corona (Athay 1976). We find that upto heights $\sim 10^5-10^6$ km, we have

$$B_a^2 / 8\pi \gg p_{\text{emp}}. \tag{2}$$

This implies

$$B_{\text{rms}}^2 / 8\pi \gg p_{\text{emp}}, \tag{3}$$

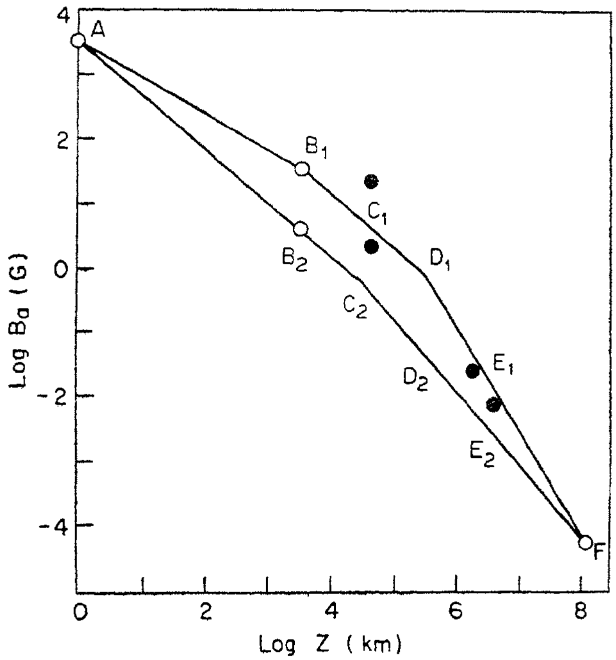

Figure 1. Curves $AB_1C_1D_1E_1F$ and $AB_2C_2D_2E_2F$ represent limits on the variation of the average axial field intensity B_a in a typical flux tube as a function of the height z above the photosphere (cf. §2.2). The point A follows from the photospheric data (Stenflo 1976). The point F represents the interplanetary fields measured near 1 A.U. The point B_1 represents the upper limit on the chromospheric field intensity obtained by assuming that the chromospheric fibrils (which are presumably at heights $10^{3.5}$ km: Foukal 1971) are flux tubes of fluxes $10^{19.5}$ Mx. The point B_2 represents a likely lower limit on the chromospheric field intensity as indicated by some preliminary observations (Tsap 1971).

The segments $B_1C_1D_1E_1$ and $B_2C_2D_2E_2$ are smooth limiting curves drawn using Newkirk's (1971) data for quiescent prominences and polar regions which is represented by filled circles. From Newkirk's figure, the data from transient phenomena like bursts is strictly omitted.

Table 1. Estimates of B_a, $B_a^2/8\pi$ and p_{emp} at various heights z above the photosphere. The two values for B_a and $B_a^2/8\pi$ correspond to the two limits in figure 1.

z (km)	B_a (G)		$B_a^2/8\pi$ (dyne cm^{-2})		P_{emp} (dyne cm^{-2})
	upper	lower	upper	lower	
10^3	63	10	$1\cdot6\times10^2$	4	3
2×10^3	50	5·6	10^2	1·2	0·1
10^4	18	1·6	$1\cdot2\times10^1$	10^{-1}	10^{-2}
10^5	2	0·16	$1\cdot6\times10^{-1}$	10^{-3}	$10^{-2.5}$
$10^{5.5}$	0·63	0·04	2×10^{-2}	6×10^{-5}	$10^{-3.5}$
10^6	0·1	0·001	4×10^{-4}	4×10^{-8}	$10^{-4.5}$

since, being an algebraic average, B_a will be $\lesssim B_{rms}$. Now since the observations leading to the empirical model do not resolve the magnetic and the non-magnetic parts of the solar atmosphere, we may write

$$p_{emp} = \alpha\, p_{in} + (1-\alpha)\, p_{out}, \tag{4}$$

where $\alpha(z)$ is the fraction of the coronal space (around the height z) occupied by the magnetic flux tubes. From (1) and (4) we have

$$p_{in} = p_{emp} - (1-\alpha)\, B^2_{rms}\Big/8\pi. \tag{5}$$

Since p_{in} must be > 0, we must have

$$(1-\alpha) < p_{emp}\Big/\left(B^2_{rms}\Big/8\pi\right).$$

It follows from (3) that for the heights $z \approx 2\times10^3$ km to $z \approx 10^5$—$10^{5.5}$ km, $(1-\alpha) \ll 1$ i.e. α must be very close to unity.

This means that at any instant *nearly whole of the inner corona must be full of magnetic flux tubes.* Thus on small length scales (i.e. comparable to the thickness of the flux tubes) equilibrium is possible *without insisting on a force free magnetic configuration.*

2.2.1. *The instantaneous gross structure*: The eclipse photographs (e.g. figures IV 15 and IV 16 in Athay 1976) and the computed models of the large scale coronal fields (e.g. Altschuler *et al* 1977) show a transition from predominantly 'closed' arches in heights $\lesssim 10^5$ km to 'open' structures in heights $\gtrsim 10^6$ km. In some places (e.g. in coronal holes) the transition may occur at heights $\ll 10^5$ km and in high latitudes there are hardly any 'closed' structures. The topological distribution of the flux tubes in the model must correspond to such a gross structure. This will be shown to be plausible in § 2·6 and 2·7.

2.3. *The emergence and growth of individual flux tubes through successive equilibria*

The equilibrium discussed need not be perfectly static. The long term variability of the corona and the reversal of the large scale field every ≈ 11 years or so demand that the flux tubes in the corona must keep on moving out and must be continually replaced by new flux tubes emerging above the photosphere.

The emergence of the magnetic flux takes place in active regions (including the ephemeral ones). The first signs of activity are always in the form of photospheric and chromospheric faculae, whose sizes correspond to flux values $\approx 10^{17}$—$10^{18.5}$ Mx. This suggests that the magnetic flux may indeed be emerging in the form of flux tubes of such flux values.

Observations show that the emerging flux tubes first form primary arches of spans comparable to the sizes of supergranules and that the supergranular flows are able to hold the foot points in approximate equilibria (Harvey and Martin 1973; Frazier 1972).

Larger arches must be formed by merging of the smaller arches either due to reconnections (Babcock 1961) or due to the emergence of intermediate subphotospheric segments of the flux tubes (e.g. Gokhale 1975).

2.4. *The slow rate of ascent of flux tube arches*

A rising arch is acted upon by the buoyancy force which overcomes the combined effect of magnetic tension and gravity. It is easy to verify that if the net acceleration f, given by

$$f = f_{\text{buoy}} - f_{\text{mag}} - f_{\text{g}},$$

were comparable to any of the terms on the right hand side of this equation (viz. the accelerations due to the three forces indicated by the suffixes), then the tops of the arches would reach speeds $\approx 10^7$—10^8 cm s^{-1} by the time they reach heights $\approx 10^5$ km above the photosphere. Since a major part of the corona upto these heights is full of flux tube arches, such speeds would imply either (i) an outward mass flux far exceeding the observed solar wind mass flux (viz. by two to three orders of magnitude), or (ii) a permanent presence of downward flows with similar speeds all over the corona, which is not observed.

Thus f must be $\ll f_{\text{buoy}}$, f_{mag} and f_{g}. In this sense the flux tube arches must rise on the average so slowly that they may be considered to be in a 'quasi-equilibrium', at all stages except during the transient events such as 'merging' or 'opening out' (cf. §2.6.)

2.5 *The magnetic flux transport*

The reversal of the large scale field every eleven years or so implies a transport of magnetic flux away from the sun at an average rate

$$\dot{\Phi}_{\text{obs}} \approx 10^{14.5} \text{ Mx s}^{-1}$$

If the corona in the central latitudes is full of flux tube arches upto an average height z_0, then the average rate of flux transport in the model will be

$$\dot{\Phi}_{\text{model}} \approx 2\pi (R_\odot + z_0)\, B_a(z_0)\, v(z_0)$$

where $v(z_0)$ is the average velocity of rise near z_0. It follows that for $\dot{\Phi}_{\rm model}$ to be $\approx \dot{\Phi}_{\rm obs}$, one must have

$$v(z_0) \approx \dot{\Phi}_{\rm obs} [2\pi (R_\odot + z_0) B_a(z_0)]^{-1}.$$

From the values of $B_a(z_0)$ in figure 1, we note

$$v(z_0) \approx 3 \times 10^2 - 4 \times 10^3 \text{ cm s}^{-1} \text{ if } z_0 \approx 10^5 \text{ km},$$

$$v(z_0) \approx 2 \times 10^3 - 1{\cdot}5 \times 10^4 \text{ cm s}^{-1} \text{ if } z_0 \approx 10^{5\cdot5} \text{ km}.$$

These estimates, though only illustrative, are well within the upper limits imposed by the solar wind mass flux, suggesting that it may be possible to account for the magnetic flux transport in the solar cycle in terms of the ascent of flux tubes in the model.

In fact, since the estimates of $v(z_0)$ are substantially below the velocities corresponding to the average solar wind mass flux, the solar wind must be substantially weaker in the closed field regions than in the open field regions. It may be indeed so (cf. Withbroe and Noyes 1977).

2.6. *The 'opening-out' of the ascending arches*

The lateral balance of a flux tube discussed in §2.2 implies a transverse gradient of the plasma pressure with a scale length of variation comparable to the thickness of the flux tube. The surrounding large scale field may be treated as force free. Although differing in several details, this configuration is essentially similar to that considered by Giachetti *et al* (1977) which develops a kink instability when the relative thickness ϵ (defined as $\pi \times$ mean thickness $\div$ length) of a flux tube becomes less than a critical value $\lesssim 0{\cdot}3$.

As will follow from the equilibrium shapes calculated in §3, the 'relative thickness' $\epsilon(z)$ of a flux tube arch goes on decreasing with increasing height of its top and $\epsilon(z) < 0{\cdot}3$ when $z \approx 10^5$ km (cf. §3). Thus it seems plausible that as a flux tube arch rises through successive quasi-equilibria, it may 'open out' by developing a kink instability when its top reaches heights $z_0 \approx 10^5$—$10^{5\cdot5}$ km. This plausible conclusion agrees with the initial frequencies of type III bursts (see appendix). It would also account for the transition from the predominantly 'closed' to the wholly 'open' configurations in the instantaneous appearance of the gross structure described in §2.2.1.

2.7 *The open fields*

2.7.1. *In the outer corona*: From the observations at 1 A.U. it seems that the space at these distances is continuously filled by magnetic fields which presumably consist of open field lines. The flux of these fields is $\approx 10^{23}$ Mx (Piddington 1976). This means that at height $z = 1{\cdot}5\ R_\odot$, the field intensity should be $\lesssim 0{\cdot}12$ G if the space is continuously filled by magnetic fields, or should be $> 0{\cdot}12$ G if there are substantially extensive non-magnetic regions. From figure 1, it seems unlikely that the real value of B_a at $z = 10^6$ km exceeds $0{\cdot}12$ G. Therefore, it seems that after opening out in the 'critical heights' $\leqslant 10^6$ km, the flux tubes expand as much so to *fill continuously the space in heights* $\gtrsim 1{\cdot}5\ R_\odot$.

2.7.2. *In the inner corona—at high latitudes and coronal holes*: The migration of open fields from low latitudes to high latitudes might account for the predominantly open configuration of the field at high latitudes. On the other hand, in some regions the rate of supply of flux tube arches from the photosphere may become too slow to compensate for the loss of arches which open out. In such places the fields will remain predominantly open leading to enhanced outward transport of mass and energy resulting in a decrease of density and temperature. The cooler and rarer environment might lead to the 'opening' of newly arrived arches at abnormally lower heights. Such a region would, therefore, resemble a coronal hole.

2.8 *Summary of the model*

Coronal magnetic fields consist of flux tubes of flux amounts $\approx 10^{17}$—$10^{18{\cdot}5}$ Mx filling almost all the space in the inner corona. The fields are maintained by flux tubes rising from the photosphere which first form arches of lengths comparable to the dimensions of supergranules. The arches keep on rising often merging to form successively larger arches that continue to rise further. The average rate of rise is so slow that the arches may be considered to be rising in 'quasi-equilibrium' at each stage. Yet this rate would be adequate to account for the amount of poloidal magnetic flux transported away from the sun over an eleven year cycle. The rising arches 'open out' when their tops reach some 'critical heights' which are ordinarily $\approx 10^5$ km but which may vary from $\approx 10^4$ to 10^6 km. One possible reason may be that at such heights the flux tubes become too thin compared to their lengths and so become vulnerable to the kink instability. Open fields in high latitudes may be provided by migration of fields opened elsewhere and the open field configuration in coronal holes may result from a reduction in the supply of arches from the photosphere.

3. Two more observational verifications

From the values of B_a in figure 1 we estimate the dimensions w of the cross-sections of typical flux tubes with fluxes $\approx 10^{17}$—$10^{18{\cdot}5}$ Mx as a function of height z (table 2). We note that at all heights z, w is much smaller than h_{mag}, the scale height of magnetic field variation. Thus we can treat the flux tubes as 'thin'. Using this fact, we now draw two important inferences from the model and show that they agree with observations.

3.1 *Foot point separation of a flux tube in equilibrium*

In his model for the x-ray bright points, Parker (1975) has shown that if a 'thin' flux tube is in a state of equilibrium with its surroundings, it will assume a shape given by

$$y(z) = \pm \int_z^{z_1} d\,\zeta\,[\tau^2(\zeta)/\tau^2(z_1) - 1]^{-1/2} \tag{6}$$

where y and z are respectively the horizontal and the vertical coordinates of a point in

Table 2. Values of $w(z)$, $h_{mag}(z)$, $D(z)$, $L(z)$ and $\epsilon(z)$ at various heights z. The two values corresponding to each parameter are respectively those calculated from the upper and lower curves of figure 1. In estimating $w(z)$, we have assumed that the upper curve corresponds to flux tubes of $\approx 10^{18.5}$ Mx and the lower one corresponds to those of $\approx 10^{17}$ Mx.

Flux in a tube (Mx)	z (km)	$w(z)$ (km)	$h_{mag}(z)$ (km)	$D(z)$ (km)	$L(z)$ (km)	$\epsilon(z)$
	$10^{3.5}$	3200	5800	5600	14000	0·71
$10^{18.5}$	10^{4}	4200	14000	18400	37000	0·33
	$10^{5.0}$	12500	110000	147000	320000	0·13
	$10^{3.5}$	1600	4100	4400	11000	0·50
10^{17}	10^{4}	2500	12000	24400	35000	0·25
	$10^{5.0}$	8400	90000	416000	350000	0·07

the plane of the flux tube with respect to the midpoint of the projection of the flux tube, $\tau(\zeta)$ is the magnetic tension in the flux tube at $z=\zeta$, and z_1 is the value of z at the top of the flux tube. (It is of course assumed that the flux tube is in a vertical plane through the foot points). From this he concluded that for a coronal flux tube in equilibrium, the foot points must be separated by a distance not more than a few scale heights at the photosphere (i.e. *not more than* $\approx 10^3$ km or so). In evaluating the integral (6), Parker assumed that at all heights z, the temperature, T_1 inside the flux tube is approximately same as the temperature T_0 outside the flux tube. In view of the extreme reduction of the thermal conductivity normal to the field lines, and also in view of the conspicuous differences in the observed intensities of the emission inside and outside the coronal structures, *there seems to be no reason* to assume $T_1=T_0$. A better way of carrrying out the integration in (6) without assuming $T_1=T_0$ is as follows:
We have

$$\tau(\zeta) = B_a^2(\zeta)\, A(\zeta)/8\pi,$$

where $A(\zeta)$ is the area of cross-section of the flux tube which must be such that

$$B_a(\zeta)\, A(\zeta) = \text{const.}$$

Using the last two equations, together with (6) we can write the distance between the foot points of an arch as

$$D(z_1) = 2y(0) = 2\int_0^{z_1} d\zeta\, [B_a^2(\zeta)/B_a^2(z_1) - 1]^{-1/2},$$

and the length $L(z_1)$ as

$$L(z_1) = 2\int_0^{z_1} d\zeta\, [1 - B_a^2(z_1)/B_a^2(\zeta)]^{-1/2}.$$

We have evaluated $D(z_1)$ and $L(z_1)$ using the values of $B_a(z)$ from the curves in figure 1. The integration was carried out graphically since the approximations employed would not allow better methods to yield more accurate estimates. The results are given in table 2.

In contrast to Parker's (1975) result, our results are *in agreement* with: (i) the observed lengths and heights of H_α-fibrils [$D(z_1) \approx$ 5000–15000 km for $z_1 \approx 10^{3\cdot5}$ -10^4 km (Foukal 1971; Athay 1976)] and (ii) the foot point separations of x-ray arches [$D(z_1) \approx 1{\cdot}5 \times 10^5$—$3 \times 10^5$ km; cf. Van Speybroeck *et al* 1970].

3.2. *The number of flux tubes required to fill the inner corona and a part of the outer corona*

The more or less horizontal 'top' portion of a flux tube reaching a height z will have a volume

$$V_{\rm top} = 2 \int_{z-w(z)}^{z} d\zeta w^2(\zeta)\,(ds/d\zeta)$$

$$= 2 \int_{z-w(z)}^{z} d\zeta w^2(\zeta)\,[1-B_a^2(z)/B_a^2(\zeta)]^{-1/2}, \tag{7}$$

where $ds^2 = dy^2 + d\zeta^2$. Since the flux tubes are thin, we may approximate $B_a(\zeta)$ by:

$$B_a(\zeta) \approx B_a(z) - (z-\zeta)\, dB_a/dz$$

$$\approx B_a(z)\,[1+(z-\zeta)/h_{\rm mag}(z)], \tag{8}$$

where $h_{\rm mag}(z)$ is the scale height of variation of $B_a(z)$. Similarly from the constancy of the axial magnetic flux we have

$$w^2(\zeta) \approx w^2(z)\,[1-(z-\zeta)/h_{\rm mag}(z)] \tag{9}$$

Substituting from (8) and (9) in (7), we get

$$V_{\rm top}(z) \approx 2^{1/2} w^2(z) \int_{z}^{z-w(z)} d\zeta\,[(z-\zeta)/h_{\rm mag}(z)]^{-1/2} \cdot [1-(z-\zeta)/h_{\rm mag}(z)]$$

$$\approx 2^{3/2}\,[w(z)]^{5/2} \cdot [h_{\rm mag}(z)]^{1/2}, \tag{10}$$

where an additional term $\approx [w(z)]^{7/2} \cdot [h_{\rm mag}(z)]^{-1/2}$ has been neglected since $w(z) \ll h_{\rm mag}(z)$. If the coronal space in the height range $\approx z_1$ to $\approx z_2$ above the latitude zone $\approx$ 45°S–45°N is to be filled simply by such more or less horizontal 'top portions' of flux tubes in quasi-equilibrium, the number of flux tubes required will be

$$N(z_1, z_2) \approx (1/2) \int_{z_1}^{z_2} dz \cdot 4\pi R^2(z)/V_{\rm top}(z),$$

where $R(z) = R_\odot + z$.

Using the limits on the values of $w(z)$ and $h_{\rm mag}(z)$ from tables 1 and 2 employing the graphical method of integration for the same reasons as in §3.1, we estimate:

$$N(\approx 10^{3\cdot0}\text{ km}, \approx 10^{4\cdot0}\text{ km}) \approx 2{\cdot}6 \times 10^5 - 1{\cdot}9 \times 10^6.$$

$$N(\approx 10^{4\cdot 0}\ \text{km}, \approx 10^{5\cdot 0}\ \text{km}) \approx 3\cdot 8 \times 10^5 - 1\cdot 5 \times 10^6.$$

$$N(\approx 10^{5\cdot 0}\ \text{km}, \approx 10^{5\cdot 5}\ \text{km}) \approx 3\cdot 2 \times 10^4 - 8\cdot 6 \times 10^4.$$

$$N(\approx 10^{5\cdot 5}\ \text{km}, \approx 10^{6\cdot 3}\ \text{km}) \approx 1\cdot 0 \times 10^4 - 1\cdot 0 \times 10^5.$$

At each height a fraction of volume will be occupied also by 'non-horizontal' parts of those flux tubes (both 'open' and 'closed') which reach the larger heights. If, for a simple crude estimate we assume this fraction to be small, then the number of flux tubes required to fill the 'inner' corona in the central latitudes in our model (of §2) will be, (for illustration) $\approx 6\cdot 4 \times 10^5 - 3\cdot 5 \times 10^6$.

Since the magnetic flux of the 'open' flux tubes (which fill the corona at and above heights $\gtrsim 1\cdot 5\ R_\odot$) is $\approx 10^{23}$ Mx, the number of all the '*open*' flux-tubes, including those in latitudes $> 45°$, in the model will be $\approx 3 \times 10^4$–10^6 depending upon what value in the range $\approx 10^{17}$–$10^{18\cdot 5}$ Mx represents the *average* flux per flux tube.

The estimate $N(\approx 10^{5\cdot 5}\ \text{km}, \approx 10^{6\cdot 3}\ \text{km})$ shows that the number of 'closed' flux tubes, (if any) *partially* filling the volume in the height range $\approx 10^{5\cdot 5} - \approx 10^{6\cdot 3}$ km will be $\lesssim 10^5$.

Thus in the model of §2 the total number of flux tubes N_{model} required to account for all the flux tubes above the photosphere will be $\approx 6\cdot 5 \times 10^5 - 4\cdot 5 \times 10^6$.

This may be compared to $N_{\text{obs}} \approx 3 \times 10^6$, which is the number of flux tubes normally present above the photosphere as estimated from the observed abundance of spicules, viz. $\approx 2\cdot 8 \times 10^6$ (cf. Beckers 1968). [Here we have assumed that most of the flux tubes are in the closed form with *two* foot points, but that on the average only half the number of foot points are associated with spicules at any instant.]

These estimates of N_{model} and N_{obs} are so crude that in spite of their differences they may be considered to be agreeing.

4. Summary and discussion

In §2 we have constructed a model for the gross magnetic structure of the corona and its mean evolution in terms of flux tubes of fluxes $\approx 10^{17} - 10^{18\cdot 5}$ Mx rising in the form of 'arches' across the inner corona in the central latitudes and opening out in the outer corona. In §3 we have obtained a corollary which agrees with the observed foot point separations of the magnetic arches at different heights. The number of flux tubes above the photosphere as suggested by the abundance of spicules may be adequate to account for the number of flux tubes required by the model.

In the model presented in this paper, some important questions have been side-tracked.

One is about the internal structure of the flux tubes and its stability. The internal structure may not be required for comparison with magnetic observations till the latter achieve the necessary spatial resolution. However, the internal structures will have to be either known or assumed for estimating the rates of energy transport and energy dissipation while using the present magnetic model for constructing the thermodynamical model.

We have also not taken into account the 'reconnections' in the coronal magnetic fields (e.g. Pneuman 1974). Such reconnections will be facilitated by the presence of thin flux tubes as in our present model, and also by the sun's differential rotation. The reconnections may involve reorientation of the 'closed' as well as the 'open' flux tubes on global scales and may introduce effective 'jumps' in the migration of the open flux tubes (Hansen and Hansen 1977). These processes will have to be taken into account for studying the evolution of the coronal magnetic fields in a more detailed way than in the present model.

However, it is hoped that the present model will serve as a first step towards a composite model of the solar atmosphere which takes into account the separate natures of the thermodynamical structure and the energy balance in its 'magnetically open', 'magnetically closed' and 'non-magnetic' components. Separate models for the three types of regions have already started appearing in the literature (e.g. Stenflo 1974; Landini and Fossi 1975; Giovanelli 1975).

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Appendix

Heights of 'flux tube opening' as indicated by Type III radio bursts

Because of their association with the release of relativistic electrons to the interplanetary space, Type III radio bursts give an indirect indication of heights at which the flux tube arches 'open out'. Here we interpret the data from table I (p. 602) and figure 23 (p. 105) of Kaplan and Tsytovich (1973) in a way slightly different from theirs.

The secondary peak at ≈ 200 MHz and the similarity of distributions in the ranges ≈ 200–400 and ≈ 100–200 MHz (cf. figure 23 of Kaplan and Tsytovich) indicate that a substantial fraction among the bursts in the 200–400 MHz range may be 'second-harmonic' of frequencies in the range 100–200 MHz. Thus a majority of Type III bursts have first harmonic initial frequencies in the range ≈ 100–200 MHz corresponding to the electron plasma frequencies $\approx 6\times10^{8}$—$1{\cdot}2\times10^{9}$ s^{-1}. In an average model these densities correspond to heights $\approx 10^{5}$—4×10^{5} km. In active regions these may correspond to greater heights.

Bursts with initial frequencies as first harmonics in the range $\approx$ 200–400 MHz will be relatively rare and those with 'first harmonic' initial frequencies in the range $\approx$ 400–600 MHz will be still rarer. These two frequency ranges correspond to flux tubes 'opening out' in height ranges $\approx 6\times10^{4}$–10^{5} and $\approx 10^{4}$–6×10^{4} km respectively.

On the other hand the minimum frequencies reached by the U-bursts indicate that during the process of opening out, the arches may occasionally remain 'closed' upto heights $\gtrsim 10^{5\cdot5}$ km.

Summing up, we conclude the following: Typically the flux tube arches open out on reaching heights $\approx 10^{5}$ km above the photosphere. Sometimes they may