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A Model of Solar X-ray Bright Points and Ephemeral Active Regions

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Abstract

Solar ephemeral active regions may provide a larger amount of emerging magnetic flux than the active regions themselves, and the origin and disposal of this flux pose problems. The related X-ray bright points are a major feature of coronal dynamics, and the two phenomena may entail a revision of our ideas of the activity cycle. A new large-scale subsurface magnetic field system has been suggested, but it is shown that such a system is neither plausible nor necessary. The emerging magnetic bipoles merely represent loops in pre-existing vertical flux tubes which are parts of active regions or the remnants of active regions. These loops result from the kink (or helical) instability in a twisted flux tube. Their observed properties are explained in terms of the flux-rope theory of solar fields. The model is extended to some dynamical effects in emerging loops. Further observations of ephemeral active regions may provide important tests between the traditional and flux-rope theories of solar magnetic fields.

1. Introduction

Solar ephemeral active regions (ER) are small short-lived centres of activity whose regular presence in large numbers was first established by Harvey and Martin (1973). Interest in ER was increased when it was found that X-ray bright points (XBP) are associated with small magnetic bipoles which would be identified as ER on magnetograms (Golub *et al.* 1974; Harvey *et al.* 1975). All XBP appear on the magnetograms as bipolar features, except for a few newly emerged or old and decayed XBP (Golub *et al.* 1977). The separation of the magnetic poles increases with age, showing that the flux is emerging, and this occurs at all latitudes and in both active and quiet regions.

The total magnetic flux in a typical XBP with lifetime ~ 8 h is 2×10^{19} Mx (Golub *et al.* 1977), or about $0\cdot2\%$ of the flux in an average active region. However, approximately 2000 XBP emerge per day in the lifetime range 2–48 h, and the number emerging with shorter lifetimes may be much greater. Accordingly, Golub *et al.* (1976) estimated that during the period of observations more magnetic flux emerged in XBP/ER than in active regions. They also estimated that the flux emerging in XBP at latitudes higher than the limits of the sunspot zones ($\approx \pm 30°$) exceeded that of all active regions. Golub *et al.* (1977) considered that these results are likely to necessitate revision of dynamo theories. If the XBP/ER fields are provided by additional dynamo action involving a new high-latitude system of submerged fields then drastic revision is indeed necessary. The alternative possibility is that ER represent localized perturbations in the already emerged fields of the solar cycle itself. In that case no new system of submerged fields is required and no major change in solar cycle theory. These two possibilities are now considered.

2. New Global Magnetic Field System

The origin of active regions and the solar cycle is thought to involve a weak poloidal field B_p to which is added a toroidal component as a result of differential rotation. Eventually the toroidal component becomes much stronger than B_p, and the complete field system B_0 is directed mainly east–west in one hemisphere and west–east in the other. The sheet of magnetic flux B_0 suffers localized eruptions to provide bipolar surface fields of mainly azimuthal orientation and 'Hale' polarities.

The ER also represent erupting flux loops, and at first sight one might envisage a similar origin involving a second system of submerged magnetic fields which develop as a result of a second gas velocity field. Golub *et al.* (1974) suggested that the second magnetic field system is provided by the supergranule motions acting on a much weaker subsurface field. This origin might explain the random orientation of the ER fields, their relatively small scale and their occurrence at all latitudes. However, the idea meets major difficulties as follows:

(i) Let us first consider the situation at high latitudes, where the ER problem is simplified by the absence of active regions and presumably of the B_0 fields. The basic requirement is now a weak magnetic field B_x, which serves the same purpose as B_p at lower latitudes and may perhaps be the high-latitude portion of B_p. In any case, B_x must permeate the supergranule cells, where it is amplified to provide stronger fields B_r, which then erupt as ER.

Such a model has been discussed earlier (Section 2A of Piddington 1978, hereafter referred to as Paper 1), where it is shown that the B_r field grows exponentially according to the equation

$$B_r \approx B_x \exp(t/\tau), \tag{1}$$

where t and τ are the elapsed time and the characteristic cell turnover period (≈ 1 day). At the end of a period τ, the cell motion ceases, and an entirely new pattern of shearing and amplification is imposed on the magnetic field system. After a few days an initially uniform field B_x is greatly amplified, but the new field B_r is in the form of tiny loops that are much smaller than the supergranule cell size. The ER fields could not possibly be produced by the amplification in supergranule cells of much weaker fields, since the result would be a completely tangled system.

The ER fields are ordered to a scale equal to that of the supergranule cells and have photospheric strengths of $\gtrsim 1500$ G ($= 0 \cdot 15$ T). To create these fields by supergranule motions would require an initial field strength $B_x \approx 500$ G and eruption after $t = \tau$. Such an initial field is highly improbable, and it is too powerful to be amplified by the cell motions. Even these simple considerations do not reveal the full range of difficulties because they ignore the fact that, of the total flux created by turbulence, half is driven upwards to erupt while half is driven downwards (see Fig. 3*b* of Paper 1) to be amplified and tangled further. Finally, there is the question of the granule motions which are stronger than the supergranule motions and will tangle to a smaller scale.

(ii) If the ER fields are parts of a large-scale submerged magnetic field system B_r then we must consider the relationship of B_r to the solar-cycle field B_0. The B_0 field is frozen into a sheet of plasma which is impervious to any external field, and so the B_r field and its plasma must be located either above or below the B_0 field; the two systems cannot interpenetrate. Now consider what follows the emergence of a large area of the B_0 field to form an active region which spreads to form two much larger regions of opposite predominant polarity. If the B_r field lies above the B_0 field then it will be ejected from the Sun over the whole area of B_0 emergence, extending to the outermost boundaries of the two large regions of opposite polarity. If the B_r field lies below the B_0 field then it will be confined there and prevented from emerging everywhere except between the inner boundaries of the two regions. In either case, no ER can form over large parts of the solar surface and, in particular, they are excluded from the interiors of the two spreading regions of opposite polarity. However, observations show (see Fig. 1 of Harvey *et al.* 1975) that ER are plentiful within these regions, and indeed Harvey *et al.* concluded that there was a marked tendency for ER to appear preferentially in regions of old predominantly unipolar flux. It is concluded that active regions and ER cannot erupt from different subsurface field systems, but that ER must also have their origin in the B_0 field system.

(iii) The total emerging flux in ER equals or exceeds that in active regions, and so the former should strongly influence or dominate large-scale surface and atmospheric magnetic structures. In fact, the reverse is true, both structures being determined almost entirely by active region flux. This result suggests that ER flux is dissipated more rapidly than active region flux (Harvey *et al.* 1975). An alternative explanation is that both fluxes have their origin in the same system of submerged fields (see next section).

If ER fields are scaled-down versions of active region fields then one might expect them to be dissipated in the same way by the spreading of the flux over larger areas. This is not the case, because ER fields simply vanish, sometimes within a few hours. Theory shows (Piddington 1975*a*, 1975*b*) that flux cannot be destroyed at such a rate, a surface field of dimensions $\gtrsim 100$ km taking years to dissipate by diffusion. The only way in which the ER fields could vanish within hours is by the hydromagnetic motion of the flux back into the Sun or out into space. In the following section a model is described which involves outward motion.

3. Loops in Vertical Flux Tubes

The vital clue to the origin of the XBP/ER magnetic fields is contained in the above conclusions that these fields erupt from the same magnetic system that provides the active region fields. However, while the latter erupt directly from the submerged toroidal field system B_0, the ER fields emerge predominantly in the regions of old mainly unipolar flux. These regions are densely populated by vertical flux tubes, and it is likely that the ER fields are created by hydromagnetic action from these vertical tubes as shown in Fig. 1. If a loop forms in the submerged part of a vertical flux tube as in Fig. 1*a*, its upward motion provides the new bipolar surface feature as illustrated in Fig. 1*b*.

The model presented in Fig. 1 explains a number of otherwise puzzling features of XBP/ER. It explains why the frequency of ER closely follows the solar cycle: ER are a minor part of that cycle. It explains the random orientation of the ER bipoles without having to invoke a new, improbable, submerged field system. It explains why ER vanish within hours and make no significant contribution to large-scale field systems: the bipole grows only as long as the upper half of the loop is emerging and ceases to exist when the whole loop has emerged (see caption to Fig. 1). Finally, the model explains the origin of a class of bipoles that are an order of magnitude smaller than those in the active regions.

However, in spite of its success in explaining the main features of XBP/ER, the loop model of Fig. 1 is not compatible with the traditional theory of solar activity and the dynamo theory of the solar cycle. A basic tenet of the traditional theory is that emerging magnetic fields are weak, in the sense that their energy density is less than the kinetic energy density of the convective motions (see e.g. Weiss 1977). After emerging, the magnetic flux is compressed in the boundary regions of the supergranule and granule cells to provide strong photospheric fields, as observed. Accordingly, submerged fields are generally weak, with strengths of order 100 G or less, although the pinching effect of the supergranulation motion may extend to depths of order 10^4 km. At greater depths the field lines flare out and merge with a 'general' mainly toroidal magnetic field. The dimensions of XBP/ER indicate that

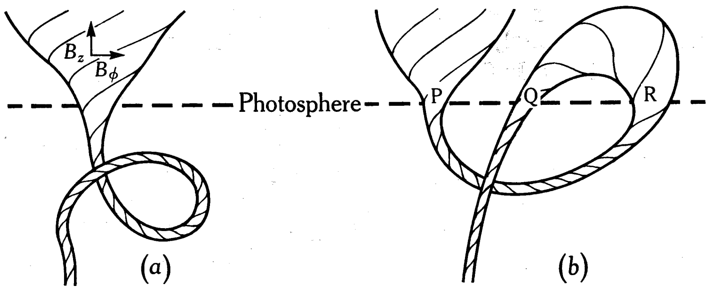

Fig. 1. Magnetic loop and bubble model for XBP/ER phenomena, showing the evolution of the structure:

(*a*) A long thin helically twisted flux tube is prone to the kink or helical instability, thus forming a loop.

(*b*) The loop is buoyant and rises through the photosphere. Its upper section provides a new bipolar magnetic region or ER. The magnetic arch QR provides an XBP.

The third, and final stage, of this evolving structure is not illustrated. The downward submerged magnetic loop PR rises through the solar surface and propagates away from the Sun. What remains is a single vertical flux tube emerging in the region marked Q.

the length of the flux tube of Fig. 1 must be of order 10^5 km, the field in the tube must have a strength of $\gtrsim 1500$ G and (see following subsection) the flux tube must be helically twisted. These characteristics make the model incompatible with the traditional theory of solar fields. On the other hand, the model of Fig. 1 is a simple extension of the flux-rope–fibre theory of solar magnetic fields and was, in fact, proposed earlier (see Fig. 2 of Piddington 1976*a*) as an explanation of ER.

(*a*) *Flux-rope Theory*

The flux-rope theory of solar magnetic fields (Paper 1 and references therein) is the antithesis of the traditional theory. Emerging fields are in the form of helically twisted flux ropes with field strengths of thousands of gauss and are impervious to convective motions. An average flux rope (see Fig. 1 of Paper 1) is made up of ~ 1000 flux fibres, each individually twisted. The series of events which precede the creation of the XBP/ER, and which support the validity of the flux-rope model are listed briefly as follows:

(i) The magnetic field of a new active region does not emerge in a steady stream (as would be expected from the traditional theory), but as individual flux bundles whose photospheric fields are already strong. These bipolar fields move apart to form bipolar regions, similar to ER, and a group of individual arch filaments. Successive groups of arch filaments rotate on the disc precisely as expected of the rope model given in Fig. 1 of Paper 1.

(ii) As the active region develops, pores form, and then sunspots form by the accretion of pores of like polarity, which may move past or between pores of opposite polarity (Vrabec 1974). This is definite proof that the magnetic fields of pores of one polarity are connected to one subsurface magnetic structure, while all fields of opposite polarity are anchored in another. The structures concerned are the two flux-rope sections from which smaller flux elements have 'frayed'.

(iii) A sunspot does not decay by the loss of a stream of flux, but by the motion of isolated flux bundles, seen as photospheric elements of 10^{18}–10^{20} Mx and termed moving magnetic features (MMF) by Harvey and Harvey (1973). The MMF move in pairs, transporting a total flux equal to several times that in the sunspot but a net flux equal to that in the sunspot. As Harvey and Harvey concluded (their Fig. 6), these results seem explicable only in terms of several bends in each flux tube leaving the sunspot, so that the flux tube traverses the photosphere in several places. I have suggested a modification of this model (see Fig. 3 of Piddington 1976*b*) by replacing the bends in the flux tube (opposed by magnetic forces) by loops caused by the kink instability. Thus MMF, which have fluxes in the ER range, are a particular form of ER.

(iv) An active region decays by the spreading of innumerable mainly vertical flux tubes into large areas of one dominant polarity. The characteristics of these unipolar magnetic regions are explained by a tree-like structure (see Fig. 7 of Paper 1) whose trunk is a flux-rope section and whose hierarchy of branches comprises flux strands and smaller flux fibres. The polarity of the surface fields is that of the flux rope, except where small ER have formed as in Fig. 1*b*. Only such a rigid foundation can explain why the small photospheric features endure in spite of the violent rotary motions of the granules. The same explanation extends to spicules and other plasma structures which would rotate violently in the absence of a rigid magnetic foundation (see Fig. 4*a* of Piddington 1976*a*).

This brief summary seems to provide conclusive evidence for the flux-rope–fibre structure of solar fields, and to provide a basis for the XBP/ER model given in Fig. 1.

(*b*) *Flux Fibres and XBP/ER*

An essential feature of the model of Fig. 1 is that the flux tube is helically twisted over a length $\gtrsim 10^5$ km. Such a twist is required to ensure both the stability of the tube against the flute or interchange instability and its instability to the kink or helical deformation.

The events (i)–(iv) listed in the preceding subsection provide evidence of twists in the small flux tubes involved, because the isolation and stability against fragmentation require this feature. Further evidence of twists in numerous structures ranging in size from sunspots to fibrils has been reviewed in Paper 1 (Section 4*c*). Additional evidence is provided by high resolution observations of prominences (Engvold 1976) which show plasma structures as small as $\lesssim 400$ km. These 'threads' probably represent magnetic structures, and their isolation is likely to be caused by individual twists. Evidence of large-scale twists in coronal active regions is provided by the X-ray observations of Krieger *et al.* (1976) and the radio observations of Stewart and Vorpahl (1977).

All of the above helical twists are in atmospheric magnetic fields, while here we are concerned with submerged fields. However, the only plausible origin of atmospheric twists is their generation in the submerged fields themselves because: (1) twists are evident even in the emerging fields, as shown by the arch filament systems; (2) atmospheric gas motions would not be powerful enough to twist fields of strength $\gtrsim 1500$ G; (3) a hierarchy of appropriate vortex motions of the photospheric gas is not observed and is extremely unlikely. I conclude that the hierarchy of twists must be introduced while the flux rope is being fabricated below the convection zone.

We now have a reasonable observational basis for the model given in Fig. 1 and for its supporting structure at greater depths (given in Fig. 7 of Paper 1). The kink or helical instability then sets in when the free length L of the twisted flux fibre is given by (Hasegawa 1975)

$$L > 2\pi r\, B_z/B_\phi\,, \tag{2}$$

where r is the fibre radius, and B_z and B_ϕ are the axial and azimuthal components of its field. This equation suggests that the degree of twisting required to provide a loop is very small. In an ephemeral active region the flux of each polarity is typically 10^{19} Mx. If the field B_z in a submerged fibre is, say, 3000 G then the radius is $r \approx 300$ km. For a free length of 5×10^4 km we have $B_\phi \approx 100$ G, or only 3% of B_z.

4. Rising Magnetic Bubbles

The magnetic fields in the loops of Fig. 1*b* are buoyant and so they tend to continue rising, lifting the submerged loop (PR in Fig. 1*b*) out of the Sun. The rate of rise will be roughly equal to the observed rate of growth of the bipole QR, which is about $2\cdot2\ \mathrm{km\,s^{-1}}$ (Golub *et al.* 1977). A typical loop diameter is 2×10^4 km, so that the time to reach maximum dimensions is 4500 s or $1\cdot3$ h. The lower half of the loop then emerges, and the bright point fades and dies after a lifetime of $2\cdot6$ h. Thus the model relates (in a very simple manner) the growth rate, size and lifetime of a typical X-ray bright point.

It is of interest to compare our result with the lifetime of a miniature active region, which is the only AR (active region) model consistent with the dynamo theory of solar magnetic fields. According to this theory the lifetime of erupted flux is given by (Stix 1974)

$$T \approx l^2\eta^{-1}\,, \tag{3}$$

where l is the characteristic dimension and η the appropriate diffusivity. There is disagreement about the value of η, which may lie between the molecular diffusivity ($\approx 10^5\ \mathrm{cm^2\,s^{-1}}$) and a hypothetical 'turbulent diffusivity' ($\approx 10^{12}\ \mathrm{cm^2\,s^{-1}}$). There is no proof of the concept of turbulent diffusivity and there are strong arguments against it (Piddington 1975*b*). However, it is an essential part of dynamo theory and so we suppose that $\eta = 10^{12}\ \mathrm{cm^2\,s^{-1}}$, in which case $T \approx 10^6$ s. Small ER have lifetimes of ~ 2 h or $<10^4$ s, so that even if we allow turbulent diffusion the dynamo theory of ER fails.

Other features of rising magnetic bubbles are as follows:

(i) When a section of a twisted flux fibre such as QR of Fig. 1*b* emerges into the atmosphere it expands. The result is that B_z decreases as r^{-2} while B_ϕ decreases only as r^{-1}, so that the amount of twist increases. Thus if B_z falls from 3000 to 30 G in the corona, B_ϕ falls from 100 (see previous section) to 10 G and the twist increases by a factor 10. However, this is only the beginning of the increase because, as Jockers (1978) has shown, more twist propagates upwards from the unexpanded submerged flux fibre. As a result we might expect B_ϕ/B_z to increase from 1/30 to near unity.

The above result is important in two ways, both related to the formation of current sheets between adjacent parrallel flux fibres. These have parallel B_z components, but antiparallel B_ϕ components which provide a current sheet. In the corona the current sheet is strong and reconnection may be rapid, thus accounting for the (5–10) % of bright points which become small flares (Golub *et al.* 1974). In the convection zone we have $B_\phi/B_z \approx 1/30$ and so the field lines of adjacent flux fibres are tilted from one another by only $\sim 4°$. Reconnection here is likely to be very slow and may be almost entirely suppressed in a rope interior, where flux fibres are closely packed and Petschek-type plasma flow is inhibited. Thus we have the important result that, while twists are strong and observable in the atmosphere, they are too weak in the convection zone to destroy the flux rope.

(ii) In most or all references to XBP/ER these features are referred to as bipolar magnetic features, while the model of Fig. 1*b* has three photospheric flux concentrations. This difference may provide a test of the model against the traditional model of emerging flux. In Fig. 2, I reproduce the magnetogram of Harvey *et al.* (1975). The small circles were drawn by Harvey *et al.* to mark ER as bipoles comprising a white (positive) and black (negative) element. In many, if not most of the marked cases a *tripole* is evident within the circle, or with a third pole just outside. I have marked a dozen of the circles by a short bar to indicate the best examples of tripoles, but others are marginal. It should also be noted that a third flux concentration may be present but not visible. The longitudinal field component is alone recorded, and if a flux concentration has a tilted field (such as Q of Fig. 1*b*) then it provides a correspondingly weak signal. Thus further application of the tripole test appears to be desirable, preferably in even quieter regions than those studied by Harvey *et al.* (1975) or Golub *et al.* (1977).

(iii) The question of the heating of the gas within XBP, and a possible relationship to solar atmospheric heating, may warrant some study. For many years the most popularly held source of solar atmospheric heating has been acoustic waves, and these may well be the main source of heat in the lower chromosphere which is almost entirely free of magnetic flux (see Fig. 2 of Piddington 1976*c*). However, this region must be regarded as a separate component of the atmosphere, isolated from the upper chromosphere and corona by the magnetic field which pervades the latter. When acoustic waves impinge on the magnetic regions, including XBP, they transform to fast MHD waves which are refracted away from the interior regions of strong fields. It is unlikely therefore that acoustic or fast MHD waves could account for the small (≈ 3000 km) bright cores of XBP, where the heating appears to be most concentrated.

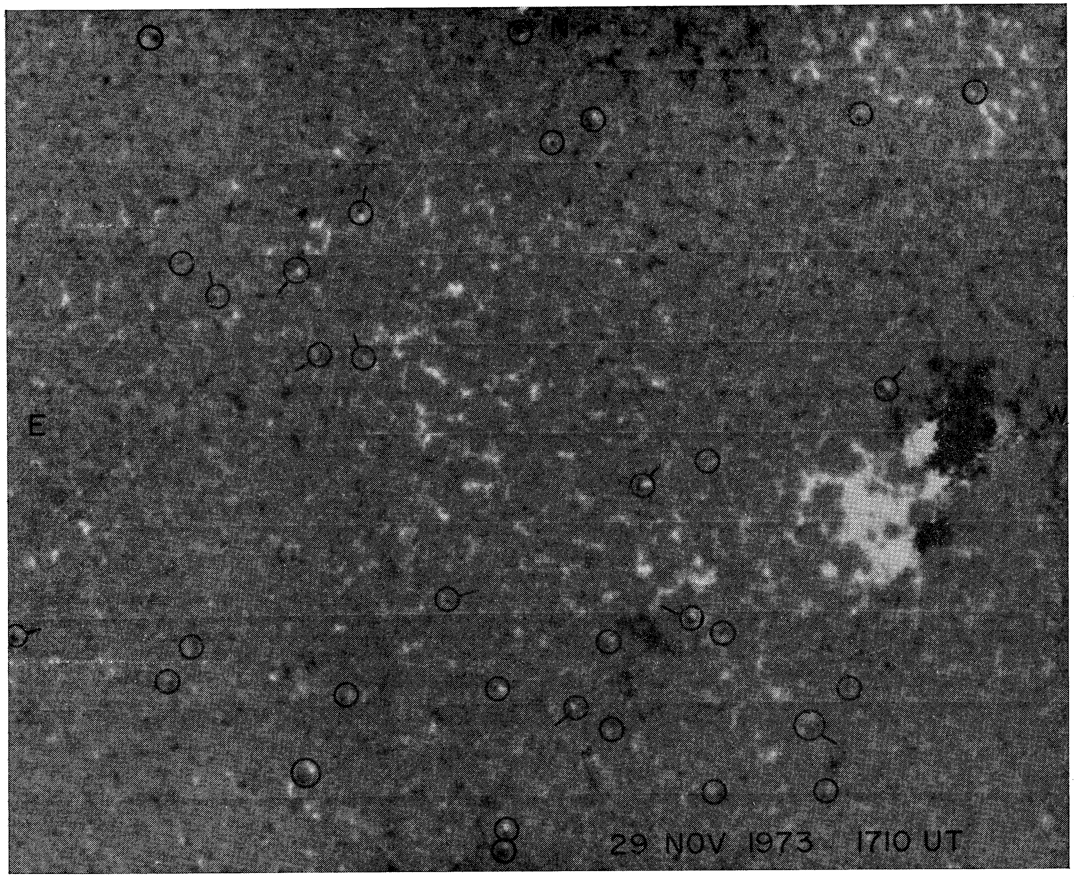

Fig. 2. Magnetogram showing the longitudinal component of the field as bright or dark depending on the polarity of the field. The area is 1000″ × 1200″ arc centred on the solar disc, and the circles were drawn by Harvey *et al.* (1975) to mark ephemeral regions. I have added short bars to a dozen circles to denote magnetic tripoles; other ER appear as less clearly defined tripoles. (Photograph reproduced by courtesy of K. L. Harvey).

I have argued previously (see e.g. Piddington 1976*c*) that most of the solar atmosphere is heated by Alfvén waves, and these may be a major source of heating within XBP. Such waves will be generated near regions Q and R of Fig. 1*b* by impact of granules on the flux tube. It has been shown (Piddington 1976*c*) that the resulting energy flux could be enough to heat the solar atmosphere. A few per cent of this flux, dissipated deep within the coronal loop, is sufficient to provide the X-ray emissions.

However, the flux-rope model of XBP suggests a second source of heat: that generated in current sheets. It has been shown in Paper 1 that flux fibres have typically a flux of $\sim 3\times 10^{18}$ Mx, while XBP have fluxes of 10^{19} Mx and sometimes more. Thus some XBP must contain three or more flux fibres, between which current sheets will develop as the amount of twist increases by upward transfer of B_ϕ. As shown below, the total magnetic energy carried upwards in magnetic bubbles is enough to heat the whole atmosphere. The smaller amount of energy in the twists would be enough to heat XBP and perhaps provide the coronal heat. A similar heat source in 'braided' flux ropes has been proposed by Glencross (1975).

(iv) The rising magnetic bubble of Fig. 1 represents the transfer of a considerable amount of magnetic energy and also plasma into the solar atmosphere. A typical loop with flux of 10^{19} Mx, diameter 2×10^4 km and (photospheric) field strength 1500 G has a magnetic energy of $\sim 4\times 10^{30}$ erg (4×10^{23} J), equal to that of a moderate flare. Several thousand XBP appear each day on the Sun, representing a total magnetic energy input of $\sim 2\times 10^6\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, which is about the energy needed to heat the solar atmosphere. As the magnetic bubble rises and expands it will promote turbulence which will cause heating and perhaps contribute appreciably to the overall heat balance of the atmosphere. The rising bubble will also carry plasma in its lower section (the loop PR of Fig. 1*b*) and this may contribute to the atmospheric velocity field. For example, plasma sometimes flows downwards continuously in prominences and so there must be an equivalent upward flow.

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