Observations of the Sun with high time and spatial resolution in UV and X-rays show that the emission from small isolated magnetic bipoles is intermittent and impulsive, while the steadier emission from larger bipoles appears as the sum of many individual impulses. We refer to the basic unit of impulsive energy release as a nanoflare. The observations suggest, then, that the active X-ray corona of the Sun is to be understood as a swarm of nanoflares.

This interpretation suggests that the X-ray corona is created by the dissipation at the many tangential discontinuities arising spontaneously in the bipolar fields of the active regions of the Sun as a consequence of random continuous motion of the footpoints of the field in the photospheric convection. The quantitative characteristics of the process are inferred from the observed coronal heat input.

Subject headings: hydromagnetics — Sun: corona — Sun: flares

1. INTRODUCTION

The X-ray corona of the Sun is composed of tenuous wisps of hot gas enclosed in strong \(10^5\) G bipolar magnetic fields. The high temperature \(2-3 \times 10^6\) K of the gas is maintained by a heat input of about \(10^7\) ergs cm\(^{-2}\) s\(^{-1}\) (Withbroe and Noyes 1977), most of which is lost by radiation as EUV and X-rays. It is observed that the surface brightness of the active X-ray corona is essentially independent of the dimensions of the confining bipole (Rosner, Tucker, and Vaiana 1978) from the normal active region with a scale of \(10^{10}\) cm down to the X-ray bright points at \(10^9\) cm, and in some cases even down to the small bipoles of \(2 \times 10^8\) cm at the limit of resolution of present observational instruments.

The heat source that causes the X-ray corona has proved elusive. There is a direct equation between magnetic field strength and heat input (Rosner, Tucker, and Vaiana 1978; Golub et al. 1980), and given a source of heat of about \(10^7\) ergs cm\(^{-2}\) s\(^{-1}\) the formation of the corona is straightforward: The heated gas expands upward from the top of the chromosphere at \(10^6\) cm s\(^{-1}\) and at higher levels where they expand against each other to fill the corona. Various ideas have been proposed to facilitate dissipation (cf. Hayyaerts and Priest 1983; Hollweg 1984, 1986, 1987; Kuperus, Ionson, and Spicer 1981; Ionson 1984; Lee and Roberts 1986; Davila 1987). The basic point is that in order to provide the necessary heat input without violating the observed upper limit of 25 km s\(^{-1}\) on the wave amplitudes (Cheng, Doschek, and Feldman 1979) the Alfvén wave must dissipate within about one period, which is reminiscent of the disintegration of a turbulent eddy (Hollweg 1984, 1986).

Alternatively it has been suggested (Parker 1979, 1983d, 1986c, 1988) that the X-ray corona is heated by dissipation at the many small current sheets forming in the bipolar magnetic regions as a consequence of the continuous shuffling and intermixing of the footpoints of the field in the photospheric convection. Insofar as the field is concentrated into separate individual magnetic fibrils at the photosphere, each individual fibril moves independently of its neighbors, producing tangential discontinuities (current sheets) between neighboring fibrils at higher levels where they expand against each other to fill the entire space (Glencross 1975, 1980; Parker 1981a, b; Sturrock and Uchida 1981). There is, however, a more basic effect, viz., a continuous mapping of the footpoints spontaneously produces tangential discontinuities (Sirovatsky 1971, 1981; Parker 1972, 1979, 1982, 1983a, b, c, d, 1986a, b, c, 1987a; Yu 1973; Tsinganos 1982; Tsinganos, Distler, and Rosner 1984; Moffatt 1985, 1986; Vainshtein and Parker 1986). The discontinuities appear in the initially continuous field at the boundaries between local regions of different winding patterns. The tangential discontinuities (current sheets) become increasingly severe with the continuing winding and interweaving, eventually producing intense magnetic dissipation in association with magnetic reconnection (Parker 1983d, 1986c).

Now, fundamental to any theoretical idea on the energy input to the corona is the mechanical work done on the magnetic field by the photospheric convection. Thus, far, observations have failed to detect either the expected wave motion or the expected shuffling and intermixing of the footpoints. The principal observational difficulty is the continuing inability to resolve the individual magnetic fibrils [with diameters of about

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200 km (0.2) at photospheric levels] which precludes a precise
determination of their motions.

The present writing is directed to observations of another
aspect of the corona, dealing directly with the heat input. To be
precise, X-ray and UV observations of the active corona and
transition region, employing high space and time resolution,
show a heat input composed of many localized impulsive
bursts of energy, which we refer to as nonoflares.

II. OBSERVATIONS

Consider first the observations of Lin et al. (1984) employing
an X-ray detector looking at the Sun from a position at the
orbit of Earth. They observe intermittent spikes of hard X-rays
(> 20 keV) with individual durations of 1-2 s. The larger
spikes represent individual energy emissions of 10^{27} ergs at the
Sun, but most of the emitted energy appears in the more
numerous smaller spikes down to the detection limit of about
10^{24} ergs per spike. One suspects that there may be many more
spikes below this instrumental cutoff. The total energy output
of the Sun in these hard spikes is about 10^{27} ergs s^{-1}, or
2 \times 10^{4} ergs cm^{-2} s^{-1}. At random intervals of the order
of 300 s there appear dense clusters of spikes, suggesting a micro-
flare with a duration of 5-100 s. The extraordinary feature is the
individual spike, indicating very small, very frequent
flaring. The small energy of each event suggests that the term
nanoflare is an appropriate appellation, which term we shall use
in the sequel to refer to any localized impulsive energy release
below the level of the conventional microflare (\geq 10^{27} ergs per
event). Evidently, then, the microflare is made up of a super-
position of many nanoflares. Indeed, we have suggested
(Parker 1987b) that flares of all sizes are made up of clusters
of nanoflares (see also the interesting parallel ideas proposed by
Sturrock et al. 1984).

To continue with the observations, Brueckner and Bartoe
(1983; Brueckner et al. 1986), observing in the EUV, discovered
intense "turbulent events" involving localized churning of the
gas at speeds of 10^5 km s^{-1}. The typical turbulent event
involves 10^{10} g of gas, with a kinetic energy of about 7 \times 10^{23}
ergs. The life of an individual event is typically 10^2 s. There are
about 10^3 new events each second over the entire Sun, so that
10^3 events are in progress at any time. The total energy adds
up to about 6 \times 10^{26} ergs s^{-1} or 10^4 ergs cm^{-2} s^{-1}, when
averaged over the surface of the Sun. The same EUV observations
also discovered intense pinpoint jets directed upward with velocities of 400 km s^{-1}, each jet with approximately
0.4 \times 10^{12} g of gas and a kinetic energy of 3 \times 10^{26} ergs. The
jets appear at a rate of about 20 s^{-1}, with an individual life of
50 s so that there are 10^3 jets present over the entire Sun at any
time. The total energy is then 6 \times 10^{20} ergs s^{-1}, or 10^5 ergs
= 8 \times 10^{24} ergs in 20 s. If a single nanoflares

be associated with the turbulent events and jets found by
Brueckner and Bartoe (1983). The essential point to be inferred
from the observations is that the heat input to the magnetic
bipole consists of many small transient bursts of energy.

Consider, then, the somewhat larger bipole with character-
istic dimensions of 10^{9} cm, associated with X-ray-bright
points and with ephemeral active regions. The essential point is
that these regions are made up of many small bright loops
which individually turn on and off to provide a continuing but
variable EUV and X-ray emission. The individual emitting
loops vary on time scales of the order of 400 s (Sheeley and
Occasional enhancements in the emission rise to the level of
microflares, so that the X-ray bright point seems to be a scaled
down version of the larger normal active region (Krieger,
Vaiana, and Van Speybroeck 1971; Golub et al. 1977; Moore
et al. 1977), Golub, Krieger, and Vaiana (1976a, b) and Habbal
and Withbroe (1981) found that the smaller X-ray-bright points are more numerous, more rapidly fluctuating, and
shorter lived than the larger X-ray-bright points. This fact,
together with the observed behavior of the smaller bipoles, is
to be understood as a direct result of the statistics of the nanoflares that occur at a rate (per unit area) that is not strongly
dependent on the dimensions of the local magnetic bipole. It is
just this condition which leads to the remarkable observational
fact, noted in the Introduction, that the surface brightness of the
X-ray corona depends only weakly, if at all, on the dimen-
sions of the associated magnetic bipole.

This condition extends, evidently, to the normal active
regions. Porter, Toomre, and Gebbie (1984), observing the
emission lines of Si iv and O iv from UV-bright points (with a
spatial resolution of 2 \times 10^{6} cm) in a normal active region,
found the impulsive brightening to be much the same as observed (Porter et al. 1987) in isolated small bipole of similar
dimensions. They found that the brightness varied typically by
20%-100% on characteristic time scales of 20-60 s. They remark that the continual flickering suggests heating by
random small-scale magnetic reconnection. They also provide
a convenient list of references to earlier papers reporting the ubiquitous bursts, scintillations, and flickerings associated with
solar active regions.

The purpose of the present writing is to emphasize that,
collectively, the observations suggest that what we see as the
X-ray corona is simply the superposition of a very large
number of nanoflares. That is to say, a statistical distribution
of nanoflares ranging downward in individual energy from
about 10^{27} ergs makes up the phenomenon that we call the
X-ray corona. The average nanoflare probably has an energy
of 10^{24} ergs or less, whereas the largest nanoflares, approaching
10^{27} ergs, produce the isolated turbulent events and high
velocity jets observed by Brueckner and Bartoe (1983) and
cause the hard X-ray bursts observed by Lin et al. (1984). The
active X-ray corona is to be understood on this basis.

A crude estimate of the characteristic nanoflare can be made
from the fluctuations reported by Porter, Toomre, and Gebbie
(1984). They find that a region with dimensions of 2 \times 10^{8} cm
\left(4 \times 10^{16} cm^{2}\right) fluctuates by 20%-100% on characteristic
times of 20-60 s. If we attribute the shortest time scale of 20 s
to the individual nanoflare, producing a 20% fluctuation in the
total brightness of the region \left(4 \times 10^{16} cm^{2}\right), it is possible to
estimate the characteristic energy of that individual nanoflare.
The total emission \left(10^{27} ergs cm^{-2} s^{-1}\right) from the region is
4 \times 10^{12} ergs s^{-1} or 8 \times 10^{24} ergs in 20 s. If a single nanoflares

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contributes 20% of this, the nanoflares involve approximately 1.6 x 10^{14} ergs or 8 x 10^{22} ergs s. There are, on this basis, about five nanoflares in progress in the region at any given time, suggesting fluctuations in brightness by a typical fraction 5^{-1/3}, or about 44%. This is in rough agreement with the observed fluctuations of 20%-100% and with the 10^{14} ergs per nanoflare, deduced from observations of the local flickering of a normal region of the active X-ray corona.

III. IMPLICATIONS

If observations indicate that the X-ray corona is primarily a collection of nanoflares, then it would appear that the corona is created by a large number of small-scale magnetic reconnections. Porter, Toomre, and Gebbie (1984) made this suggestion based on their observation of the small-scale flickering of the UV emission from the transition region. We suggested the idea based on a critical review of the theoretical possibilities (Parker 1979, 1983c, d, 1986c). In particular, the traditional view that the X-ray corona is heated by the dissipation of waves propagating up from the photosphere runs into grave difficulty in accounting for the brightness of the very small (2-10 x 10^8 cm) regions of X-ray emission, requiring strong Alfven waves with periods of 1-10 s if the wavelength is to be as small as the dimensions of the bipolar. For if the wavelength is significantly longer, then the passage of the wave represents only a slow quasi-static deformation of the magnetic field (see discussion in Parker 1986c, 1988), producing little or no heating. Strong waves at such short periods would be a revelation in themselves. They could not be understood as a turbulent cascade from either granule motions (with characteristic time \( \tau \approx 300 \) s) or from observed oscillations with periods of 10\(^2\) s. For the Kolmogorov spectrum predicts that the velocity \( \nu(t) \) with a characteristic scale \( l \) is proportional to \( t^{1/3} \), while the characteristic life is \( \tau = l/\nu(t) \propto t^{2/3} \). Hence \( \frac{2}{3} \rho \nu(t)^3 \propto t(l) \), and such short-period waves would have kinetic energy density smaller in direct proportional to their periods, i.e., smaller by a factor of 10-50 than the waves with 10\(^2\) s period. The waves at 10\(^2\) s may perhaps carry sufficient energy (\( \sim 10^7 \) ergs cm\(^{-2}\)), but the waves at 2-10 s would be entirely inadequate.

If, on the other hand, we accept the idea that the footpoints of the bipolar fields are subject to random shuffling and mixing, then there are tangential discontinuities produced in the bipolar fields. The number of discontinuities (current sheets) and the individual amplitudes of each discontinuity increase with the passage of time (see discussion in § IV). Eventually a point is reached where rapid reconnection of the magnetic field across the individual discontinuities destroys them as fast as they are created by the motions of the footpoints. Hence, we expect the bipolar fields above the surface of the Sun to be filled with small-scale reconnection events, i.e., filled with nanoflares. We suggested some years ago (Glencross 1975, 1980; Parker 1979, 1981a, b, 1983d, 1986c, 1988) that this is the principal cause of the active X-ray corona. This theoretical picture seems to be substantiated now by the accumulating observations cited above.

It appears, then, that the X-ray corona of the Sun, and hence X-ray coronas of similar solitary, late-type, main-sequence stars, are primarily a consequence of the tangential discontinuities formed spontaneously in the surface magnetic fields by the shuffling of the footpoints of the field in the photospheric convection. The spontaneous formation of tangential discontinuities is a peculiar consequence of the static equilibrium properties of the magnetic field embedded in an infinitely conducting fluid. The discontinuities arise when the field is subjected to continuous but complex deformation, so that the magnetic lines of force are wound and wrapped about each other in complicated patterns (see discussion and references in Parker 1987a; Moffatt 1987; Low and Wolfson 1988). Each discontinuity causes the local magnetic energy to degrade through the dynamical nonequilibrium and consequent rapid reconnection of the field across the discontinuity.

IV. DISCUSSION

It is unfortunate that the motions of the magnetic fibrils are not presently available from observation, since it is the jiggling and wandering of those fibrils that provides most of the energy input to the X-ray corona. We shall assume, for the sake of discussion, that, in keeping with the granule motions of 1-2 km s\(^{-1}\), the footpoints of the magnetic field are shuffled about at random with a characteristic velocity \( \nu \) of the order of 0.5 km s\(^{-1}\) and with a correlation length \( l \) comparable to a granule radius. Hopefully, within the next decade a proper observational determination of \( \nu \) and \( l \) will become available.

On the theoretical side, we should be aware that a quantitative calculation of the rate of dissipation at a specified tangential discontinuity is not forthcoming, because of the complex nonlinear dynamical character of the reconnection. However, using present observations as a guide, it is possible to infer some of the main features of the process.

To begin, then, experience (both in the laboratory and in theoretical numerical simulations) indicates that the strength of the individual tangential discontinuity, or current sheet, increases from zero with the passage of time with only a very slow reconnection occurring, presumably proportional to the discontinuity \( \Delta B \). Then when the strength \( \Delta B \) of the discontinuity exceeds some threshold, there is a runaway dynamical instability leading to an explosive reconnection phase, producing both hydromagnetic and plasma "turbulence," which further enhances the reconnection. The rapid reconnection phase is not unlike the individual large-scale burst of disruptive magnetohydrodynamical activity observed in magnetically confined, current-carrying plasmas in the laboratory apparently initiated by the onset of an internal instability of the plasma and field (cf. Rosenbluth, Dagazian, and Rutherford 1973; Kadomtsev 1975, 1974; Waddell et al. 1976; Finn and Kaw 1977; Montgomery 1982; Lichtenberg 1984; Dahlburg et al. 1986) and leading to reconnection between the inner and external fields. The reader is referred to such works as Taylor (1974, 1975, 1976, 1986); Vasylinas (1975); Van Hoven (1976, 1979, 1981); Tajima, Brunel, and Sakai (1982); Spicer (1977, 1982); Biskamp (1982, 1984, 1986); Van Hoven, Tachi, and Steinolfson (1984); Steinolfson and Van Hoven (1984); Matthaeus and Lamkin (1985, 1986); Lee and Fu (1986); Tajima and Sakai (1986); Priest and Forbes (1986); Dahlberg et al. (1986); and Chiu and Zweibel (1987) for a presentation of some of the more salient theoretical facets of the reconnection phenomenon. Dixon, Browning, and Priest (1988) conjecture that the rapid reconnection may cut off only when the field has been reduced to a form with uniform torsion \( \zeta \) (where \( \mathbf{v} \cdot \mathbf{B} = \zeta \mathbf{B} \) for the force-free field \( \mathbf{B} \)) throughout the region in accordance with Taylor's hypothesis (Taylor 1974, 1975, 1976, 1986). It is not entirely clear how to apply this idea to a field that has been wound and interwoven at random so that the overall mean value of \( \zeta \) is close to zero.
The possibility that hydromagnetic waves play an essential role should not be overlooked, triggering the explosive phase of the reconnection in the manner illustrated by the recent calculations of Sakai, Tajima, and Brunel (1974; Sakai and Washimi 1982; Tajima, Brunel, and Sakai 1982; Sakai 1983a, b) and Matthaeus and Lamkin (1985, 1986). The disturbance produced by the explosive reconnection at one locality may trigger explosive reconnection in surrounding regions. Such effects occur in the more violent reconnection that produces a flare (Vorpahl 1976; Parker 1987b). On the other hand, the low upper limit placed by observation on the unresolved wave noise (Beckers 1976, 1978; Beckers and Schneeburger 1977; Bruner 1978, 1979; Cheng, Doschek and Feldman 1979) is \( <v^2>^{1/2} \leq 25 \text{ km s}^{-1} \), so that \( <v^2>^{1/2}/v_x \approx 10^{-2} \). It is not obvious that this background noise would have an interesting effect. However, the build up of a large-amplitude resonance oscillation is at least a theoretical possibility (cf. Davila 1987), although it requires that the resonant flux surface be closed on itself to form a tube of some sort if it is to avoid having edges, where the waves may leak away, and it is not obvious that there are extended flux surfaces in a field whose lines of force are subject to interweaving.

Consider then, what can be deduced from the observed facts, that the energy release through the reconnection and nanoflaring is of the order of \( 10^3 \) ergs cm\(^{-2}\) s\(^{-1}\) in bipolar fields of \( 10^2 \) G subject to continuous deformation by the motion \( v \) of the footpoints.

**V. INFERENCES**

The general nature of the energetics associated with the mutual winding and wrapping of the magnetic lines of force is readily deduced, given the scale \( l \) and the velocity \( v \) of the motions of the footpoints at the photosphere (cf. Parker 1983d, 1986c, 1988). To provide the simplest model, suppose that the field is initially uniform and perpendicular (vertical) to the photosphere (\( z = 0 \)) extending a distance \( L \) straight up to a plane \( (z = L) \) in which the footpoints are fixed. Then consider a given elemental flux bundle, whose footpoint at the photosphere moves about with a random velocity \( v \). The flux bundle connects the moving footpoint at \( z = 0 \) with the fixed footpoint at \( z = L \) as the moving footpoint loops in and out around the footpoints of the neighboring vertical flux bundles. The bundle has a more or less, uniform deviation \( \theta(t) \) to the vertical, where

\[
\tan \theta(t) \approx vt/L
\]

at least for \( \theta(t) < 1 \). If the vertical component of the field is \( B \), the transverse (horizontal) component \( B_\perp \) is \( B \tan \theta(t) \), so that

\[
B_\perp \approx Bvt/L.
\]

The tension in the flux bundle trailing out behind the moving footpoint opposes the outward random march of the footpoint with a stress \( B_\perp B/4\pi \) so that the footpoint does work on the field at a rate

\[
W \approx \nu B_\perp B/4\pi = (B^2/4\pi)\nu^2 t/L \text{ ergs m}^{-2} \text{ s}^{-1}.
\]

The power input, then, increases linearly with time, as the field is progressively extended transversely by the motion of the footpoint.

From observation (Withbroe and Noyes 1977) we have \( W = 10^3 \) ergs cm\(^{-2}\) s\(^{-1}\) for the time-averaged power input. With the values \( B = 10^2 \) G and \( v = 0.5 \) km s\(^{-1}\), and with \( L = 10^3 \) cm appropriate for a coronal loop in a normal active region, it follows that \( W \) increases to the necessary level in a time \( t = 5 \times 10^4 \) s. At that point in time \( B_\perp \approx \frac{1}{2}B \) and \( \theta \approx 14^\circ \), so that the individual flux bundle is only moderately inclined to the mean field direction. Evidently, then, when \( \theta \) reaches some such value as \( 14^\circ \), the dissipation (presumably rapid reconnection across the spontaneous tangential discontinuities) destroys \( B_\perp \) as rapidly as it is produced by the motion \( v \) of the footpoints. A steady state is reached and \( B_\perp \) grows no further, so that \( W \) remains at about \( 10^3 \) ergs cm\(^{-2}\) s\(^{-1}\) (Parker 1983d).

It is important to note that if the dissipation were less effective, so that \( B_\perp \) is not destroyed as rapidly as it is produced when \( \theta \) reaches \( 14^\circ \), then \( B_\perp \) and \( W \) would increase still further. Eventually, at some larger \( \theta \) the reconnection must get going to produce a statistically steady state. The result would be a substantially larger heat input. We have the interesting situation, then, that the heat input varies \textit{inversely} with the effectiveness of the dissipation.

Note that the characteristic strength \( |\Delta B| \) of the individual tangential discontinuities is of the same order as \( B_\perp \), i.e., the discontinuity in the field direction is of the order of \( \theta \). With the values of \( v \) and \( B \) assumed for purposes of the present discussion it follows that \( |\Delta B| \approx 25 \) G. Other choices of \( v \) and \( B \) give other values for \( v \) and \( B_\perp \), of course, and we cannot be sure of the precise value of \( v \) until there is direct observations of the motions of the magnetic fibrils.

To continue, then, note that with \( v = 0.5 \) km s\(^{-1}\) for a period of \( t = 5 \times 10^4 \) s the footpoint of a given flux bundle has traversed a wandering pathlength \( vt = 2.5 \times 10^4 \) km, equivalent to the diameter of a supergranule. It is not unreasonable to associate each random step of the footpoint with the life \( \tau = 500 \) s of the adjacent granules (Bahng and Schwarzchild 1961), so that the length \( l = vt \) of each random step is 250 km, and the total pathlength \( vt \) involves \( n = t/\tau = 10^2 \) random steps.

The wrapping of the individual flux bundle around its neighbors along the length \( L \) of the flux bundle follows the same random looping as experienced by the wandering footpoint, of course. Hence we expect each elemental flux bundle to undergo \( n = 10^2 \) random steps between and around its neighbors along the length \( L \). Each random step extends for a distance \( \Delta L \approx L/n = L \cot \theta = 1L/vt = 10^3 \) km along the bundle. We expect approximately one tangential discontinuity to be associated with each such random step (cf. Parker 1987a).

To obtain an estimate of the energy associated with each discontinuity, assume that the flux bundles are all actively winding and braiding about each other so that at a first approximation most of the random steps of mutual winding of two locally defined flux bundles are individually confined to the characteristic length \( \Delta L \). Then the energy \( \mathcal{E} \) in the magnetic deformation associated with each random winding is of the order of \( B_\perp^2/8\pi \) multiplied by the volume \( V \approx L^3 \Delta L \) associated with each winding. With the numbers estimated above (\( l = 250 \) km, \( \Delta L = 10^3 \) km, \( B_\perp = 25 \) G) the result is

\[
\mathcal{E} = L^3 \Delta L B_\perp^2/8\pi \\
\approx 6 \times 10^{24} \text{ ergs}
\]

in order of magnitude. The quantity \( \mathcal{E} \) represents an estimate of the free energy of the individual deformation. The typical
nofflare produced by the associated tangential discontinuity has an energy below the value of \( \delta \). As noted in the earlier sections, the most common nanoflares are at the level of about 10^{24} \text{ ergs} (which is also close to the instrumental cutoff). Hence improved instruments may one day suggest a smaller average energy per nanoflare. Larger nanoflares are less common and are expected either from the simultaneous (presumably cooperative) reconnection at several neighboring discontinuities (Parker 1987b) or from the reconnection of flux bundles that are larger than assumed in the calculation of \( \delta \).

Smaller nanoflares, below the instrumental threshold of present observations, are expected and may be understood as small reconnection events which quench before consuming more than a small fraction of the available free energy. And of course there is a whole distribution of sizes of discontinuities. The present calculations are limited to what we might call the “characteristic” discontinuity.

Finally, it should be noted that the same estimates of \( I, \Delta L \), and \( \delta \) apply to smaller active regions, with \( L < 10^3 \text{ km} \). The only change is in the \( t_r \) required to reach the steady state. Thus, in an X-ray bright point, with the characteristic field length \( L = 10^4 \text{ km} \), we find \( t_r = 5 \times 10^5 \text{ s} \) (1.4 hr). The individual footpoints undergo 10 random steps in this time, rather than \( 10^2 \), but the same length \( \Delta L = 10^3 \text{ km} \) is obtained. It follows, then, that the character of the individual nanoflares is expected to be pretty much independent of the scale \( L \) of the magnetic field, on the basis of the present elementary analysis. It is to be hoped that the future will bring improved high-resolution, high-speed, low-threshold observations (in the EUV and X-rays) of the individual nanoflares in X-ray coronal regions. Such observations, together with observations of the motions of the magnetic fibrils, are essential in establishing any firm theory for the cause of the phenomenon that we call the active X-ray corona.

REFERENCES


NANOFLARES AND SOLAR X-RAY CORONA


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