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NANOFLARES AND THE SOLAR X-RAY CORONA[1]

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ABSTRACT

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

I. INTRODUCTION

The X-ray corona of the Sun is composed of tenuous wisps of hot gas enclosed in strong (10^2 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 2×10^8 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 with a pressure scale height of $1–1.5 \times 10^{10}$ cm; the density of the rising gas increases to about 10^{10} atoms cm^{-3}, at which point radiative losses balance the heat input. The gas pressure is then 6–9 dyn cm^{-2}, the speed of sound is $2–3 \times 10^7$ cm s^{-1}, the magnetic pressure (10^2 G) is typically 4×10^2 dyn, and the Alfvén speed is 2×10^8 cm s^{-1}. The magnetic field is essentially force-free.

The traditional view has been that the convection below the visible surface of the Sun produces sound waves, gravitational waves, and magnetohydrodynamic waves which propagate upward into the overlying atmosphere where they dissipate and deposit their energy as heat in the ambient gas (Bierman 1946, 1948; Alfvén 1947; Schwarzschild 1948; Parker 1958; Whitaker 1963). More recently it has become clear that all but Alfvén waves are dissipated and/or refracted before reaching the corona (Osterbrock 1961; Stein and Leibacher 1974; Sturrock and Uchida 1981; Priest 1982). Presumably, then, it is primarily Alfvén waves that reach the active X-ray corona. The problem is that Alfvén waves are disinclined to dissipate in the corona. Indeed, it is just that disinclination that allows them to penetrate the chromosphere and transition region to reach the corona. Various ideas have been proposed to facilitate dissipation (cf. Hayvaerts 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, 1983*d*, 1986*c*, 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 1981*a*, *b*; Sturrock and Uchida 1981). There is, however, a more basic effect, viz., a *continuous* mapping of the footpoints spontaneously produces tangential discontinuities (Syrovatsky 1971, 1981; Parker 1972, 1979, 1982, 1983*a*, *b*, *c*, *d*, 1986*a*, *b*, *c*, 1987*a*; Yu 1973; Tsinganos 1982; Tsinganos, Distler, and Rosner 1984; Moffatt 1985, 1986; Vainstein 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 1983*d*, 1986*c*).

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 *nanoflares*.

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 2×10^4 ergs cm^{-2} s^{-1}. At random intervals of the order of 300 s there appear dense clusters of spikes, suggesting a microflare 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 apellation, 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 superposition of many nanoflares. Indeed, we have suggested (Parker 1987*b*) 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 10^2 km s^{-1}. The typical turbulent event involves 10^{10} g of gas, with a kinetic energy of about 7×10^{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 10^5 events are in progress at any time. The total energy adds up to about 6×10^{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 0.4×10^{12} g of gas and a kinetic energy of 3×10^{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 6×10^{27} ergs s^{-1}, or 10^5 ergs cm^{-2} s^{-1} averaged over the surface of the Sun.

A recent paper by Porter *et al.* (1987) reports the discovery of localized brightenings throughout the magnetic network. The brightenings, observed most effectively in the lines of C IV, represent localized impulsive heating events (*nanoflares*) occurring in the small magnetic bipoles, with dimensions of $2\text{–}4 \times 10^8$ cm. A fraction of the brightenings last several minutes to an hour, but the most common events are short lived ($\sim 10^2$ s), occurring in the smaller bipoles. Some magnetic bipoles exhibit more frequent nanoflares than others, with perhaps 10% of the bipoles being continuously but variably bright. The larger and stronger the bipole, the more likely the rapid succession of nanoflares, producing continual brightening. Porter *et al.* suggest that these brightenings may perhaps 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 bipoles with characteristic 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 Golub 1979; Nolte, Solodyna, and Gerassimenko 1979). 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 (1976*a*, *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 dimensions 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 2×10^8 cm) in a normal active region, found the impulsive brightening to be much the same as observed (Porter *et al.* 1987) in isolated small bipoles 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 2×10^8 cm (4×10^{16} cm^2) 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 (4×10^{16} cm^2), it is possible to estimate the characteristic energy of that individual nanoflare. The total emission (at 10^7 ergs cm^{-2} s^{-1}) from the region is 4×10^{23} ergs s^{-1} or 8×10^{24} ergs in 20 s. If a single nanoflare contributes 20% of this, the nanoflare involves approximately 1.6×10^{24} ergs or 8×10^{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 $5^{-1/2}$, or about 44%. This is in rough agreement with the observed fluctuations of 20%–100% and with the 10^{24} 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 from 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, 1983*c*, *d*, 1986*c*). 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 (2–10×10^8 cm) regions of X-ray emission, requiring strong Alfvén waves with periods of 1–10 s if the wavelength is to be as small as the dimensions of the bipole. 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 1986*c*, 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 $v(l)$ with a characteristic scale l is proportional to $l^{1/3}$, while the characteristic life is $\tau = l/v(l) \propto l^{2/3}$. Hence $\frac{1}{2}\rho v(l)^2 \propto \tau(l)$, 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 bipole 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, 1981*a*, *b*, 1983*d*, 1986*c*, 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 1987*a*; 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 chracteristic velocity v 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 v 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 $|\Delta \boldsymbol{B}|$. Then when the strength $|\Delta \boldsymbol{B}|$ 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, 1984; 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); Vasyliunas (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 Chiueh 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 α (where $\nabla \cdot \boldsymbol{B} = \alpha \boldsymbol{B}$ for the force-free field $\boldsymbol{B}$) 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 α 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 1983*a*, *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 1987*b*). 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 $\langle v^2 \rangle^{1/2} \lesssim 25$ km s^{-1}, so that $\langle v^2 \rangle^{1/2}/V_A \approx 10^{-2}$. 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 10^7 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 1983*d*, 1986*c*, 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

$$\tan \theta(t) \approx vt/L \tag{1}$$

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

$$B_\perp \approx Bvt/L\ . \tag{2}$$

The tension in the flux bundle trailing out behind the moving footpoint opposes the onward 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

$$\begin{aligned} W &\approx vB_\perp B/4\pi \\ &= (B^2/4\pi)v^2 t/L \text{ ergs m}^{-2}\text{ s}^{-1}\ . \end{aligned} \tag{3}$$

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 $W = 10^7$ 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 $L = 10^{10}$ 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^{-1}. At that point in time $B_\perp \approx \frac{1}{4}B$ and $\theta \approx 14°$, so that the individual flux bundle is only moderately inclined to the mean field direction. Evidently, then, when θ reaches some such value as 14°, 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 10^7 ergs cm^{-2} s^{-1} (Parker 1983*d*).

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 θ reaches 14°, then $B_\perp$ and W would increase still further. Eventually, at some larger θ 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 *inversely* with the effectiveness of the dissipation.

Note that the characteristic strength $|\Delta \boldsymbol{B}|$ 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 θ. With the values of v and B assumed for purposes of the present discussion it follows that $|\Delta \boldsymbol{B}| \approx 25$ G. Other choices of v and B give other values for t 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 Schwarzschild 1961), so that the length $l = v\tau$ 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 $\Delta L \approx L/n = l \cot \theta = lL/vt = 10^3$ km along the bundle. We expect approximately one tangential discontinuity to be associated with each such random step (cf. Parker 1987*a*).

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 to a first approximation most of the random steps of mutual winding of two locally defined flux bundles are individually confined to the characteristic length ΔL. Then the energy $\mathscr{E}$ in the magnetic deformation associated with each random winding is of the order of $B_\perp{}^2/8\pi$ multiplied by the volume $V \approx l^2 \Delta L$ associated with each winding. With the numbers estimated above ($l = 250$ km, $\Delta L = 10^3$ km, $B_\perp = 25$ G) the result is

$$\begin{aligned} \mathscr{E} &= l^2 \Delta L B_\perp{}^2/8\pi \\ &\approx 6 \times 10^{24} \text{ ergs} \end{aligned}$$

in order of magnitude. The quantity $\mathscr{E}$ represents an estimate of the free energy of the individual deformation. The typical nanoflare produced by the associated tangential discontinuity has an energy below the value of $\mathscr{E}$. As noted in the earlier sections, the most common nanoflares are at the level of about 10^{24} 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 1987*b*) or from the reconnection of flux bundles that are larger than assumed in the calculation of $\mathscr{E}$. 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 l, ΔL, and $\mathscr{E}$ apply to smaller active regions, with $L < 10^5$ km. The only change is in the time t required to reach the steady state. Thus, for instance, in an X-ray bright point, with the characteristic field length $L = 10^4$ km, we find $t = 5 \times 10^3$ s (1.4 hr). The individual footpoints undergo 10 random steps in this time, rather than 10^2, but the same length $\Delta L = 10^3$ 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 hope 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.

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