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SIGNATURES OF GLOBAL MODE ALFVÉN RESONANCE HEATING IN CORONAL LOOPS

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ABSTRACT

The *Yohkoh* Soft X-Ray Telescope (SXT) observations of active region coronal loops transient brightening is analyzed, and the scaling of the thermal energy release with loop lengths is found to be $E_{th} \sim L^{1.60\pm0.09}$. The numerically determined scaling of the global mode heating rate for the resonant absorption of Alfvén waves, $H \sim L$, is found to agree with the heating rate deduced from the observed thermal energy scaling, provided that the magnetic field scales as $B \sim L^{-0.70\pm0.05}$ and the waves are driven with a ω^{-1} spectrum. Previous analytical and numerical studies have shown that the heating due to resonant absorption of Alfvén waves is most efficient at the global mode frequency. In agreement with these studies, we suggest that coronal loop transient X-ray brightenings occur when a given length coronal loop is perturbed at its global mode frequency by random footpoint motions, which results in more efficient heating of the loop.

Subject headings: MHD — Sun: corona — Sun: magnetic fields — waves

1. INTRODUCTION

The Soft X-Ray Telescope (SXT) (Tsuneta et al. 1991) aboard the *Yohkoh* satellite reveals that active region loops exhibit many small flarelike brightenings with energies of 10^{25}–10^{29} ergs and durations of 2–10 minutes. The average occurrence rate ranges from about 3 minutes in a highly active region to about every 1 hr in a less active region (Shimizu et al. 1992, 1994; Shimizu 1995). Shimizu et al. (1994) investigated the morphology of 142 transient brightenings, and Shimizu (1995) investigated the energetics and the occurrence rate of more than 600 such events. In the present Letter, we suggest that transient brightenings occur as a result of resonant absorption of global mode Alfvén waves in coronal loops, excited by random footpoint motions of these loops. We reanalyze the *Yohkoh* SXT data obtained by Shimizu (1995) and find evidence in support of our claim.

The exact dissipation mechanism that heats the corona is still uncertain; however, resonant absorption of Alfvén waves appears to be one of the major candidates (Zirker 1993). The corona is highly structured and inhomogeneous, containing a large number of discrete magnetic loops, and there is some observational evidence of MHD waves propagating in coronal loops. Resonant absorption of Alfvén waves in coronal inhomogeneities was first suggested by Ionson (1978) as a nonthermal heating mechanism, and since then this mechanism has been extensively studied.

In the low-β compressible plasma, the resonant heating of a particular loop is most efficient at a frequency at which the loop couples resonantly to an external driver. Effectively, two resonance conditions are involved in the heating process: (1) the ideal Alfvén wave resonance condition $\omega = k_z v_A(x)$, where ω is the Alfvén wave frequency, k_z is the wavenumber parallel to the magnetic field, and $v_A(x)$ is the local Alfvén velocity; and (2) the resonant coupling of the driver to the coronal loop motions that correspond to the ideal "quasi mode" or "collective mode" (in which all parts of the loop oscillate at the same frequency, or collectively).

Poedts & Kerner (1991) showed that the "quasi mode" is the eigenmode of resistive MHD. Poedts, Goosens, & Kerner (1990a and references therein) used steady state calculations in resistive compressible linear MHD for determining the fractional absorption spectrum of one-dimensional cylindrical loops and investigated the effects of the global mode in this context. Poedts et al. (1990b) and Poedts & Kerner (1992) integrated in time and space the time-dependent resistive compressible linear MHD equations to determine the temporal evolution of resonant absorption in one-dimensional cylindrical loops. They determined the transient and the steady state phases of resonant absorption and investigated the influence of the global modes on the temporal evolution of resonant absorption. Hollweg (1990) considers an artificial antenna that drives surface waves on a "thick" interface and computes the heating rates and the corresponding resonant curves.

Steinolfson & Davila (1993) investigated the resonant absorption of Alfvén waves in the low-β approximation via solutions of the resistive time-dependent, linearized, compressible MHD equations. The authors have approximated the coronal loop by a slab with a density gradient perpendicular to the background magnetic field and along the direction corresponding to the loop radius. Thus, the loop acts as a resonance cavity for MHD waves. They have verified the importance of the global mode in the heating process for a broad range of loop densities. They have also investigated numerically the parametric dependence of the time to reach steady state and the resonant layer width on the Lundquist number and on the loop density. Comparison with more approximate analytical models showed generally a good agreement.

Recently, Ofman, Davila, & Steinolfson (1995, hereafter

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ODS95) investigated the scaling of the global mode heating rate on the wavenumbers. They find that the global mode heating rate H scales as $H \sim k_z^{-1}$ for small k_z and $k_y \sim O(1)$, where k_y is the perpendicular wavenumber. They have also found the dependence of the heating rate on k_y. Their results indicate that when loops of various sizes in an active region are excited by a broadband spectrum of perturbation, certain loops will be heated more effectively. Wright & Rickard (1995) found global modes in an inhomogeneous MHD cavity, driven by random boundary motions in the linear regime. Extending the calculations to the nonlinear regime indicates that nonlinear effects may increase the effective dissipation (Ofman, Davila, & Steinolfson 1994; Ofman & Davila 1995b). Nonlinear studies of resonant absorption indicate that global modes can be excited by a broad-frequency band driver and may explain transient brightenings of coronal loops (Ofman & Davila 1995b).

In a recent Letter, Klimchuk & Porter (1995, hereafter KP) presented scaling of heating rates with loop lengths in 47 quasi-steady solar coronal loops (see also Porter & Klimchuk 1995). They have found that the loop pressure is inversely correlated with length, such that $P \propto L^{\alpha}$, with the most probable value of $\alpha = -0.96$ and a 90% confidence interval of $-1.82 \leq \alpha \leq -0.22$. Based on this result and the quasi-steady nature of the loops, they have used the relation between the volumetric heating rate, pressure, and temperature (e.g., Rosner, Tucker, & Vaiana 1978, hereafter RTV) to determine the power-law index in the relation between the volumetric heating rate and the loop length. In order to compare their results to the predictions of existing coronal heating models (e.g., Parker 1983; ODS95), they have assumed that the magnetic field strength in these loops scales as $B \propto L^{\delta}$. They have found that the value of δ depends on the particular model used to calculate the coronal heating. Golub et al. (1980) found that the average pressure in active regions of various sizes relates to an average magnetic field as $\langle p \rangle \sim \langle B \rangle^{1.6}$. In the above studies, the results are obtained from (or dominated by) the quasi-steady loops, and the RTV scaling is used to relate the observations to particular models.

In the present Letter, we reanalyze about 400 transient loop brightenings observed by the *Yohkoh* SXT (Shimizu 1995) using an approach similar to KP's. However, the loops that undergo transient brightening are not in a quasi steady state—they are dominated by the heat input. Consequently, RTV scaling does not apply in this case. Therefore, it is not surprising that we find a different scaling of the volumetric heating rate with loop length. We find that, subject to the assumptions, global mode heating appears to be consistent with the *Yohkoh* SXT observations of active region loop transient brightenings. We suggest that X-ray transient brightenings of coronal loops are signatures of a global mode resonant heating mechanism by Alfvén waves, which we believe is the mechanism of coronal heating. Below we present evidence in favor of this hypothesis.

2. THEORETICAL SCALING OF GLOBAL MODE ALFVÉN RESONANCE HEATING

Ofman, Davila, & Steinolfson (1995) solved the time-dependent, linearized, compressible MHD equations in the low-β approximation, to model a coronal loop with a perpendicular density gradient and a uniform background magnetic field. In the present section, we discuss the scaling of the heating rate with k_z calculated with the model in ODS95. However, one must remember that the scalings in ODS95 were obtained with the linearized MHD equations. Nonlinear effects might affect the details of these scalings (see Ofman & Davila 1995a).

The dependence of the normalized heating rate on k_z was presented in Figure 6 of ODS95. They found that $H \sim k_z^{-1}$ for small k_z, in agreement with the analytical scaling (Kappraff & Tataronis 1977). The longest wavelength of a standing Alfvén wave in the loop is determined by the loop length; thus, $k_z = 2\pi a/L$, where a is the half-width of the loop. The period averaged values of H were calculated at the global mode frequency for each wavenumber at the steady state. When other parameters are fixed, the global mode frequency is proportional to k_z (see Fig. 8 in ODS95). We extended the calculation range of ODS95 to longer perturbation wavelengths and found that when $k_z^{-1} \gg 1$, the heating rate is inversely proportional to k_z, in even better agreement with Kappraff & Tataronis (1977). When $k_z^{-1} < 10$, the heating rate decreases more slowly with the wavelength.

The heating rate is normalized by $B_0^2 v_A/8\pi$, where B_0 is the magnitude of the background magnetic field, $v_A = B_0(4\pi\rho_0)^{-1/2}$ is the Alfvén velocity, and ρ_0 is the density at the center of the loop. The wavelength is given in units of a typical loop half-width a. Obviously, the values of B_0, ρ_0, and a may vary for different loops. Thus, the heating rate in physical units $\hat{H}$ scales as

$$\hat{H} \sim B_0^3 \rho_0^{-1/2} k_z^{-1}. \tag{1}$$

In the above equation, we have assumed a uniform perturbation spectrum that drives the loops. If we assume that the driving spectrum is a power law, i.e., $P(\omega) = \omega^{-q}$, and use $\omega = k_z v_A$, we get

$$\hat{H} \sim B_0^{3-q} \rho_0^{(q-1)/2} k_z^{-q-1}. \tag{2}$$

For $q = 1$, consistent with Kolmogorov turbulence, we get

$$\hat{H} \sim B_0^2 k_z^{-2}. \tag{3}$$

It is reasonable to assume that the magnetic field magnitude scaling on loop length has the following form:

$$B_0 \sim L^{\delta}. \tag{4}$$

If $\delta > -1$ in the above equation, then it is evident from equation (3) that the heating rate increases with loop length, since the longest wavelength of a standing Alfvén wave inside the loop is determined by the loop length (for a fixed loop width). The dependence of the loop length on the magnetic field strength is unknown; however, it is reasonable to assume that B decreases with L from the general consideration that the magnetic field strength decreases far away from the Sun. In the next section, we present the observed dependence of the thermal energy content of transient brightenings on the loop length.

The global mode heating rate reaches its maximal value at $t = \tau_{ss}$, where τ_{ss} is the heating time that depends on the geometry of the loop (i.e., L), density, and the dissipation coefficients in the loop (e.g., Kappraff & Tataronis 1977; Poedts & Kerner 1992; Steinolfson & Davila 1993). The heating time for typical loop parameters is several hundred seconds (Steinolfson & Davila 1993) and is of the same order of magnitude as the duration of a typical transient brightening Δt_b; thus, $H = H(t)$ varies during the brightening. However, for

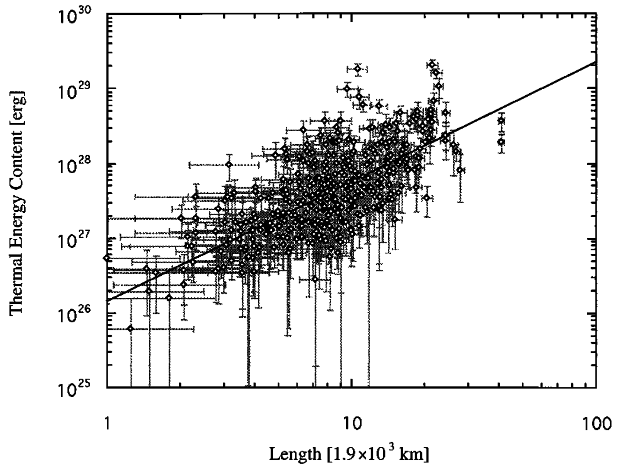

FIG. 1.—Thermal energy content of the loops that undergo transient brightenings, observed by the *Yohkoh* SXT (Shimizu 1995). The nonparametric best fit to the data yields $E_{\rm th} \sim L^{1.60\pm0.09}$.

simplicity, we will consider time-independent H, and the total thermal energy deposited in the loop during brightening is taken to be proportional to $H\Delta t_b$.

3. OBSERVED SCALING OF THE THERMAL ENERGY WITH LOOP LENGTH

Recently, Shimizu (1995) measured the parameters of more than 600 active region loops that were subject to transient brightening. In his detailed study, Shimizu examined the possibility that transient brightenings make a significant contribution to coronal heating. Typically, the following physical conditions were measured: temperature $T = (4-8) \times 10^6$ K, emission measure $\Lambda = 10^{44.5}$–$10^{47.5}$ cm^{-3}; electron density $n = (2–20) \times 10^9$ cm^{-3}; gas presure P = 5–20 dyn cm^{-2}, loop length $L = (5-40) \times 10^3$ km; loop width $2a = (2-7) \times 10^3$ km, and duration Δt = 2–7 minutes. The energy involved in the observed transient brightening was estimated to range from 10^{25} to 10^{29} ergs. Shimizu found a power-law dependence of the occurrence rate of the events on the peak intensity.

The thermal energy content of the hot plasma in a coronal loop is given by

$$E_{\rm th} = 3N_e k_{\rm B} T V, \tag{5}$$

where N_e is the electron density, T is the temperature, V is the volume of the loop, and $k_{\rm B}$ is Boltzmann's constant. The errors in determining the loop length are assumed to be 1 CCD pixel of the SXT, or about 1.9×10^3 km, since the projection effects are small in the relatively short loops (typically, $L = 10^4$ km). In Figure 1 we show the thermal energy content in about 400 loops versus the length of these loops. The power-law dependence of the thermal energy on the loop length is clearly evident. Using a nonparametric statistical analysis (KP; Porter & Klimchuk 1995, and references therein), we find that $E_{\rm th} \sim L^{1.60\pm0.09}$ with a 90% confidence interval of (1.47, 1.74) for the exponent. The error bars on the power-law index correspond to a 68.26% confidence interval, which becomes $\pm 1\ \sigma$ interval for the normal distribution. It is interesting to note that the least-squares fit of the energy power law based on Gaussian statistics yields virtually identical results.

A power-law fit to the subset of the data that includes only long loops ($L > 1.9 \times 10^4$ km) yields $E_{\rm th} \sim L^i$, where $i = 2.10^{+0.26}_{-0.36}$. However, the exponent might be higher due to the selection effect at $L = 1.9 \times 10^4$ km. We also found that the the maximal X-ray intensity (with subtracted background intensity) detected by the *Yohkoh* SXT is highly correlated with $E_{\rm th}$ (with $r = 0.93$, where r is the correlation coefficient).

The average width of the 441 loops in the data set is 2.32 CCD pixels. Since the measurement error is assumed to be 1 CCD pixel, it is not possible to infer the scaling of the loop width with L with a reasonable degree of confidence; i.e., using the nonparametric statistical analysis, we find that the probability that these variables are uncorrelated is 79%.

Assuming that the width of the loops is not correlated with the loop length, the thermal energy per unit volume scales as $\varepsilon_{\rm th} \propto E_{\rm th}/L$. As discussed in the previous section, we take the thermal energy content to be proportional to the time-integrated volumetric heating rate, i.e., $\varepsilon_{\rm th} \propto \langle Q \rangle \Delta t_b$. The duration of the brightening is weakly correlated with the loop length. Thus, the volumetric heating rate scaling with L becomes

$$\langle Q \rangle \sim L^{0.60\pm0.09}, \tag{6}$$

with a 90% confidence interval of (0.47, 0.74) for the power-law index.

In order to compare the observed thermal energy scaling to the scaling of the heating rate in our model, we need to assume a form for the driving spectrum. A uniform spectrum may be used as a zero-order approximation. However, as in KP, we suggest the ω^{-1} spectrum as a better initial estimate. In addition, we need to estimate the dependence of the magnetic field strength inside the loop, B_0 on L. Using equation (3) and assuming $B_0 \sim L^{-0.5}$, we get

$$\hat{H} \sim L, \tag{7}$$

which is in agreement with observations. We have performed a nonlinear three-dimensional simulation of global mode heating by randomly driven Alfvén waves (Ofman & Davila 1995b) for several values of L and found that the time-averaged heating rate scaling with L agrees with equation (7). Thus, in order to better match the observed power law for $\langle Q \rangle$, we need to assume that $B_0 \sim L^{-0.70\pm0.05}$, or assume a different power law for the driving spectrum.

The exact form of the driving spectrum or the amount of power available in Alfvén waves to heat the corona is presently unknown. However, the recently launched *Solar Heliospheric Observatory* (*SOHO*) carries several instruments that may help to determine the driving spectrum of the Alfvén waves. From the present analysis, we can combine equations (2) and (6) to place a constraint on the Alfvén wave spectrum power-law index, i.e.,

$$q = \frac{m + \alpha/2 - 3\delta - 1}{1 + \alpha/2 - \delta}, \tag{8}$$

where m is the power-law index in equation (6), α is the power-law index for the density scaling with L, δ is the magnetic field power-law index, and $1 + \alpha/2 - \delta \neq 0$. The above relation may be used to test the validity of the assumptions in the present study against the power-law indices obtained independently from observations.

It is interesting to note that KP obtained $\delta = -2$ for the wave heating model and $\delta = -0.5$ for Parker's (1983) heating model. Repeating KP's analysis with our data set, we get $\delta > 0$ for Parker's heating model. The disagreement between KP's results and our value of $\delta = -0.70 \pm 0.05$ for wave heating may be attributed to their use of quasi-steady loops to find the relation between the loop heating rate and length. In such loops, the radiative and conductive losses are of the same magnitude as the heat input. The resulting scaling of the loop pressure on the loop length is different from the scaling predicted by the wave heating term alone. Coronal loops that undergo transient brightenings might better agree with the scaling obtained from the global mode heating theory, since the heating term is dominant in such loops.

4. CONCLUSIONS

Earlier analytical and numerical studies have shown that the heating due to resonant absorption of Alfvén waves is most efficient at the global mode frequency, which depends essentially on the loop length and the Alfvén velocity in the loop. Ofman, Davila, & Steinolfson (1995) related numerically the global mode resonant heating of coronal loops to the wavelengths of the Alfvén waves in the loops. Ofman, Davila, & Steinolfson (1995) and Ofman & Davila (1995a, b) extended these studies into the nonlinear regime. In particular, Ofman & Davila (1995b) have shown that global modes may be excited in randomly driven coronal loops and can lead to transient brightening of the loops.

Observations with the SXT on the *Yohkoh* satellite (Shimizu 1995) indicate a relation between the transient brightening thermal energy content and the dimensions of the coronal loops. Morphological studies of transient X-ray brightenings of active region loops by Shimizu et al. (1994) indicated that more than half of the brightenings occur in multiple loop structures. The multiple loops appear to have similar lengths and to converge into the same photospheric footpoints. This observation is consistent with the global mode resonance heating, determined by the loop length and a random driving spectrum. If equal length loops are driven by random motions of their common footpoints, then our model would predict simultaneous transient brightening in these loops (see Ofman & Davila 1995b).

It is evident from observations that 5×10^3 km $\leq L \leq 4 \times 10^4$ km for loop transient brightening. Obviously, the lower bound of L is determined by the resolution of the SXT. However, the upper bound of L must depend on the available driving spectrum and the magnetic field topology of active regions (i.e., the available range of magnetic loop lengths). In an active region where many loops of various sizes are present, the heating will be most effective at any given time in a number of distinct loops that match the Alfvén wave global mode resonance condition. In order to determine which loops will be heated the most (or the scaling of the heating rate with loop length), one needs to know the spectrum of the driving Alfvén waves in addition to the density and the magnetic field. The exact nature of the driver that heats the corona is unknown, and the magnitude of B in the corona is poorly known at present.

We reanalyzed the *Yohkoh* SXT data of coronal loop transient brightening (Shimizu 1995) and found that the scaling of the thermal energy release of loop brightenings with loop lengths is in agreement with the numerically determined scaling of the global mode heating rate with loop length. However, it is evident that many assumptions are required in our simple model. In the present study, we find that the heating rate scaling agrees with observations provided that $P(\omega) \sim \omega^{-1}$ spectrum and $B \sim L^{-0.70\pm0.05}$, in addition to other simplifying assumptions, discussed above.

In agreement with linear (ODS95) and nonlinear simulations (Ofman, et al. 1994; Ofman & Davila 1995a, b), we suggest that coronal loop transient brightenings occur when a given coronal loop is perturbed at its global mode frequency, contained in a random driving spectrum, which results in more efficient heating of a particular loop. The temporal variations in the random driver amplitude at any given location, the evaporation of the hot plasma into the coronal loops, and thermal losses may lead to changes in the global mode response of the loop and variations in its X-ray brightness.

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