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Momentum Balance in Eruptive Solar Flares: The Vertical Lorentz Force Acting on the Solar Atmosphere and the Solar Interior

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Abstract We compute the perturbed Lorentz force integrated over the outer solar atmosphere implied by changes in vector magnetograms during large, eruptive solar flares. This force should be balanced by an equal and opposite force acting on the solar photosphere and solar interior. We show that the approximate expression for the estimated force change, the "jerk" estimate given by Hudson, Fisher & Welsch (2008), should be a robust result if the observed magnetic field changes are small compared to the initial values, and assuming that the expression is integrated over the strong field portions of an active region. We show that magnetic eruptions should result in the magnetic field at the photosphere becoming more horizontal, and hence should result in a downward (inward) jerk acting on the photosphere and solar interior, as recently argued from an analysis of magnetogram data by Wang & Liu. We suggest that there should be an observational relationship between between the jerk amplitude computed from changes in the vector magnetograms, the outward momentum initially carried by the ejecta from the flare, and the amplitude of the helioseismic disturbance driven by the jerk. Finally, we compare the expected Lorentz force amplitude at the photosphere with simple estimates from flare-driven gasdynamic disturbances and from an estimate of the perturbed pressure from radiative backwarming of the photosphere in flaring conditions.

Keywords: Flares, Dynamics; Helicity, Magnetic; Magnetic fields, Corona

1. Introduction

Eruptive flares and CMEs result from a global reconfiguration of the magnetic field in the solar atmosphere. Recently, signatures of this magnetic field change have been detected in both vector and line-of-sight magnetograms, maps of the vector and line-of-sight component of the photospheric magnetic field, respectively. Is there a relationship between this measured field change and properties

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of the eruptive phenomenon? What is the relationship between forces acting on the outer solar atmosphere and those acting on the photosphere and below, in the solar convection zone?

We will attempt to address these questions by considering the action of the Lorentz force over large volumes in the solar atmosphere consistent with observed changes in the photospheric magnetic field. We will provide more context for the recent result of Hudson, Fisher, and Welsch (2008), who present an estimate for the inward force on the solar interior driven by changes observed in magnetograms, and provide additional interpretation of the recent observational results of Wang and Liu (2010), who find the force acting on the photosphere and interior is nearly always inward.

Finally, we will compare the downward impulse from changes in the Lorentz force with pressure impulses from heating by energetic particle release during flares, and with radiative backwarming during flares, to assess which physical mechanism produces the largest change in force density at the photosphere, and hence which might be most effective in driving helioseismic waves into the solar interior.

2. The Lorentz Force Acting on the Upper Solar Atmosphere

The Lorentz force per unit volume can be written as

$$\mathbf{f}_L = \nabla \cdot \mathbf{T} \tag{1}$$

where

$$T_{ij} = \frac{1}{8\pi}(2B_iB_j - B^2\delta_{ij}) \ , \tag{2}$$

and B_i and B_j represent Cartesian components of the magnetic field $\mathbf{B}$. The Lorentz force density in the vertical ($\hat{\mathbf{z}}$) direction is then given by

$$f_z = \frac{\partial}{\partial x}T_{xz} + \frac{\partial}{\partial y}T_{yz} + \frac{\partial}{\partial z}T_{zz} \tag{3}$$

or

$$f_z = \frac{1}{4\pi}\nabla \cdot [B_z\mathbf{B} - \frac{1}{2}(B_x^2 + B_y^2 + B_z^2)\hat{\mathbf{z}}] \ . \tag{4}$$

One can use Gauss' theorem to integrate the z-component of the Lorentz force over the volume that goes from $z = 0$ to $z = \infty$ (see Figure 1), and in the horizontal directions over the area of the vector magnetogram:

$$\int dV\, f_z = \frac{1}{4\pi}\int dA\, \hat{\mathbf{n}} \cdot [B_z\mathbf{B} - \frac{1}{2}(B_x^2 + B_y^2 + B_z^2)\hat{\mathbf{z}}]. \tag{5}$$

Assuming that all magnetic field components vanish sufficiently quickly as $z \to \infty$, that integrating over the top of the box makes a negligible contribution, and that the magnetogram extends far enough around the active region that

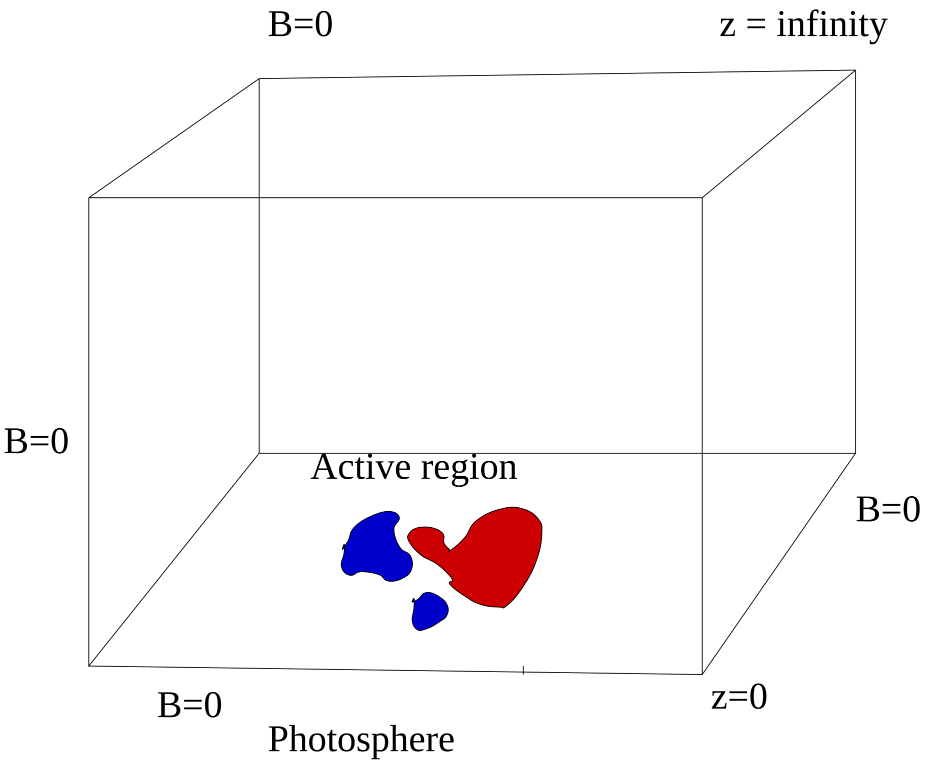

Figure 1. Schematic illustration of the volume in which the photospheric-to-coronal portions of a bipolar active region are imbedded. It is assumed that at the upper surface, the magnetic field is negligibly small, and that the side wall boundaries are sufficiently far away from the active region that they do not contribute to the Gauss' theorem surface integral. Note that at the photosphere, the surface normal vector $\hat{\mathbf{n}}$ points in the $-\hat{\mathbf{z}}$ direction. The red and blue colors represent the upward and downward vertical fluxes in the active region.

the horizontal components of $\mathbf{B}$ that pierce the sides of the Gaussian box are negligible, this results in

$$F_z \equiv \int dV\, f_z = -\frac{1}{8\pi}\int dA[B_z^2 - B_x^2 - B_y^2] \tag{6}$$

or

$$F_z = \frac{1}{8\pi}\int dA\,(B_x^2 + B_y^2 - B_z^2) \tag{7}$$

Here, the integration domain dA is the surface of the vector magnetogram, and B_x, B_y, and B_z are the field components in the magnetogram. The overall minus sign appearing in equation (6) occurs because the surface normal $\hat{\mathbf{n}}$ at the photosphere is in the $-\hat{\mathbf{z}}$ direction.

This expression has been used in the past to evaluate whether or not vector magnetograms are consistent with force-free configurations in the solar atmosphere (Low, 1985; Metcalf *et al.*, 1995).

Now, let B_x, B_y, and B_z depend on time as well as on magnetogram position, and evaluate the time rate of change of the integrated Lorentz force:

$$\frac{\partial F_z}{\partial t} = \frac{1}{4\pi} \int dA \left(B_x \frac{\partial B_x}{\partial t} + B_y \frac{\partial B_y}{\partial t} - B_z \frac{\partial B_z}{\partial t} \right) . \tag{8}$$

Letting $\delta B_x = \partial B_x / \partial t \; \delta t$ (similarly for y and z terms), and assuming that the magnetic field changes observed in a vector magnetogram occur over the time period δt, then gives an expression like the un-numbered equation in Hudson, Fisher, and Welsch (2008), but with the opposite sign:

$$\delta F_z = \frac{1}{4\pi} \int dA \left(B_x \delta B_x + B_y \delta B_y - B_z \delta B_z \right) . \tag{9}$$

Here, δF_z is the change in the volume integrated Lorentz force acting on the outer solar atmosphere. This expansion over time δt assumes $\delta B_x / B_x$, $\delta B_y / B_y$, and $\delta B_z / B_z$ are small. Wang and Liu (2010) find that δt for significant field changes is a few minutes.

To get the sign of the force estimated in Hudson, Fisher, and Welsch (2008), one must invoke Newton's third law: Since the net Lorentz force from the photosphere out to infinity is given by equation (8), and assuming that this force is unbalanced by any other force within the above Gaussian volume, then the force acting from the photosphere downward must be equal and opposite, *i.e.*

$$\frac{\partial}{\partial t} F_{z,\; inward} = \frac{1}{4\pi} \int dA \left(-B_x \frac{\partial B_x}{\partial t} - B_y \frac{\partial B_y}{\partial t} + B_z \frac{\partial B_z}{\partial t} \right) . \tag{10}$$

The assumption that the change in the upward (outward) Lorentz force of the volume is not balanced by any other forces within the volume needs further discussion. First, from energetic considerations, the magnetic field is believed to be the source of energy for eruptive flares and coronal mass ejections: Forbes (2000) has argued that no other known source of energy can provide the observed kinetic energy of outward motion observed in coronal mass ejections, and there simply is no other viable source for the thermal and radiated energy known to be released in solar flares. Second, apart from the Lorentz force, the only other significant forces known to be operating on the solar atmosphere are gas pressure gradients and gravity. To evaluate the change in the pressure gradient forces, one can perform the same Gaussian integral of the vertical component of the pressure gradient force. The net change in the outward force is just the difference between the gas pressure change at the top of the Gaussian volume from that at the bottom. If the plasma β in the solar atmosphere is low, as is generally the case in active regions, it is hard to believe that this will be significant compared to the change of the Lorentz force. Nevertheless, in §3, we will briefly consider perturbations to the gas pressure at the photosphere and estimate their effectiveness. In the case of the gravitational force, unless the plasma has moved a huge distance ($\sim R_{Sun}$) away from the Sun on the time-scale of the observed field change, the gravitational force acting on the given mass of the plasma within the gaussian volume must be approximately the same, and hence the change in the gravitational force should be small.

Using the same assumptions as above to find δB_x, δB_y and δB_z then results in an equation with the same sign and form as that in Hudson, Fisher, and Welsch (2008) except that it is integrated over the vector magnetogram area:

$$\delta F_{z,inward} = \frac{1}{4\pi} \int dA \left(-B_x \ \delta B_x - B_y \delta B_y + B_z \delta B_z \right) . \tag{11}$$

In essence, this expression uses a first-order approximation, namely that the changes in the magnetic field components when integrated over the timescale of the observed field change, are small compared to their initial values.

In summary, if the expression in Hudson, Fisher, and Welsch (2008) is integrated over the strong field portions of the flaring active region, such that surface terms on the vertical side walls make no significant contributions to the Gaussian integral, and that the amplitude of the field changes is small compared to the initial field values, then the Hudson, Fisher, and Welsch (2008) result should be robust and accurate. Most likely, the area integral could be further restricted to the regions where the *change* in the strong fields is significant, since it is only the change in the force that we are considering. Hudson, Fisher, and Welsch (2008) find downward surface densities of the Lorentz force of $\sim 2.5 \times 10^3$ dyne cm^{-2} for the case they investigated.

Wang and Liu (2010) find that $\delta F_{z,inward}$ is generally downward for nearly all of the cases they have investigated, where the magnetic field is observed to change in the sense that its orientation becomes more horizontal. Our Newton's third law argument then implies that a force of the same magnitude, but in the upward direction, acts to push the upper atmosphere outward during the course of the flare. Thus a change in the orientation of the photospheric field from the vertical toward the horizontal directions implies both an outward force on the solar atmosphere, and an inward impulse toward the solar interior. We therefore anticipate a direct relationship between the increased Lorentz force acting on the solar atmosphere (computed with equation 8) and the outward momentum from the eruptive flare or CME ejecta. We also anticipate that the equal and opposite downward jerk will drive a helioseismic disturbance into the solar interior whose initial impulse should be related to the temporal and spatial properties of the jerk.

3. Other Disturbances in the Force

We argue above that assuming that the plasma β in the flaring active region is small implies that changes to gas pressure gradients during a flare are most likely unimportant compared to changes in the Lorentz force. Nevertheless, the flare-induced gas pressure change from energy deposited in the flare atmosphere has been considered in the past to be a viable candidate for the agent that excites flare-associated helioseismic disturbances (Kosovichev and Zharkova, 1998). Another suggested mechanism is heating near the solar photosphere driven by radiative backwarming of strong flaring emission occurring higher up in the solar atmosphere (Donea *et al.*, 2006; Lindsey and Donea, 2008). We briefly consider each of these possibilities in the following sections.

3.1. Pressure Changes Driven by Flare Gasdynamic Processes

During the impulsive phase of flares, emission in the hard X-ray and γ-ray energy range is typically emitted from small, rapidly moving kernels in the chromosphere of the flaring active region (*e.g.* Gan, Li, and Miroshnichenko, 2008). This emission is generally assumed to be the signature of energy release in the form of a large flux of energetic electrons. Energetic electrons in the 10-100 KeV range that impinge on the solar atmosphere will emit nonthermal bremsstrahlung radiation from Coulomb collisions with the ambient ions in the atmosphere, and will also rapidly lose energy via Coulomb collisions with ambient electrons, resulting in strong atmospheric heating (Brown, 1972). This results, in turn, in a very large gas pressure increase in the upper chromosphere, due to rapid chromospheric evaporation. Kosovichev and Zharkova (1998) proposed that this large pressure increase is the agent responsible for flare-driven helioseismic waves into the solar interior that have been observed.

Can this large pressure increase in the flare chromosphere result in a sufficiently large pressure change at the photosphere to be significant compared to the observed changes in the Lorentz force?

To address this question, we consider the flare-driven pressure increase from two different approaches: (1) the dynamics of a flare-driven "chromospheric condensation", and (2) a solution to an acoustic impulse problem in a one-dimensional, gravitationally stratified model of the preflare chromosphere.

Chromospheric condensations are the dense, downward-moving plugs of plasma that form behind a downward-moving shock-wave or pressure disturbance driven by impulsive phase chromospheric evaporation in flares. A simple analytic model of the dynamic evolution of chromospheric condensations was developed by Fisher (1989). The model was found to do a good job of describing the results of more detailed numerical gasdynamic simulations. The model predicts the maximum column depth that the chromospheric condensation can penetrate into the solar atmosphere, in terms of the flare-induced pressure P_2 driven by electron-beam heating of the solar atmosphere. The maximum column depth of propagation, N_{max}, is given approximately by

$$N_{max} = \frac{P_2}{\bar{m}g} \ , \qquad (12)$$

where $\bar{m} \simeq 1.4m_p$ is the mean mass per proton in the solar atmosphere, and $g = 2.74 \times 10^4$ cm s^{-2} is the value of surface gravity. Numerical gasdynamic simulations of flare heating with large fluxes of non-thermal electrons ($\sim 10^{11}$ erg s^{-1} cm^{-2}) result in maximum pressures in the chromosphere of $100-1000$ dyne cm^{-2}. This results in values of N_{max} that are no larger than $\sim 10^{22}$ cm^{-2}. The column depth of the solar photosphere, on the other hand is $\sim 10^{24}$ cm^{-2}. Thus, using the chromospheric condensation model, flare-driven pressure disturbances can only propagate down to about 1% of the column depth of the photosphere, and thus do not seem to be a viable competitor to the Lorentz force change at phospheric depths.

Because the chromospheric condensation model's assumptions begin to break down during the last stages of its evolution, we also consider the downward propagation of flare-driven pressure disturbances using an entirely different approach:

The assumption that the disturbance can be represented by an acoustic wave. The acoustic wave assumption is extremely dubious in the upper chromosphere, where the chromospheric condensation approach works well, but it has the advantage of being a much better description as the disturbance moves deeper into the atmosphere. It also has the advantage of being a non-dissipative hydrodynamic solution, so that the amplitude of the downward moving wave represents an upper limit to the actual case, where radiative and viscous processes will dissipate energy in the wave.

Assuming that the pre-flare chromosphere can be represented by an isothermal, gravitationally stratified atmosphere at temperature T_{ch} with pressure scale height $\Lambda_P = C_s^2/(\gamma g)$, where C_s is the adiabatic sound speed, the equation for the perturbed vertical velocity is found to be

$$\frac{\partial^2 v}{\partial t^2} - C_s^2 \left(\frac{1}{\Lambda_P}\frac{\partial v}{\partial s} + \frac{\partial^2 v}{\partial s^2}\right) = 0 \ . \tag{13}$$

Here, s measures vertical distance in the downward direction, measured from the initial position of the flare chromosphere. We assume that at the top of the flare chromosphere, the result of the flare heating is a sudden downward depression, with a displacement Δs occurring over a very short time. We then want to follow this displacement, using the above acoustic wave equation, as it propagates downward. At $s = 0$, we therefore assume the time evolution of the velocity v is given by

$$v(s = 0, t) = \Delta s \delta(t) \ , \tag{14}$$

where $\delta(t)$ is the Dirac delta function. By performing a Laplace transform of equation (13) with this assumed time behavior at $s = 0$, we find

$$\begin{aligned} v(s,t) &= \Delta s \ \exp\left(-\frac{s}{2\Lambda_P}\right) \\ &\times \left[\delta(t - \frac{s}{C_s}) - \frac{s}{2\Lambda_P\sqrt{t^2 - \frac{s^2}{C_s^2}}} J_1\left(\omega_a\sqrt{t^2 - \frac{s^2}{C_s^2}}\right) H(t - \frac{s}{C_s})\right] \ , \end{aligned} \tag{15}$$

where J_1 is a Bessel function, H is the Heaviside function, and ω_a is the acoustic cutoff frequency ($\omega_a = C_s/(2\Lambda_P)$). The important point is that the velocity amplitude is attenuated exponentially as it propagates downward, with an envelope function that goes as $\exp(-s/(2\Lambda_P))$. The perturbed pressure will scale in roughly the same way as the velocity. Therefore, we can estimate the decrease in amplitude of the perturbed pressure by using the estimated pressure at the top of the flare chromosphere and this attenuation function. The result, for flare induced gas pressures of $100 - 1000$ dyne cm^{-2}, and assuming a propagation distance of 1000 km and preflare chromospheric temperatures of 6000K, is photospheric gas pressure changes of at most $10 - 100$ dyne cm^{-2}. This is at least an order of magnitude smaller than the Lorentz force change estimated by Hudson, Fisher, and Welsch (2008). Most likely, given the neglect of many effects that will only decrease the perturbed pressure, the flare-induced gas pressure change will be even smaller. We conclude that electron heating of the flare chromosphere is very unlikely to result in force perturbations at the photosphere that can compete with changes to the Lorentz force.

3.2. Pressure Changes Driven by Radiative Backwarming

Observations of the spatial and temporal variation of optical continuum (white light) emission and hard X-ray emission during solar flares show an intimate temporal, spatial, and energetic relationship between the presence of energetic electrons in the flare chromosphere and white light emission from the solar photosphere (Hudson *et al.*, 1992; Metcalf *et al.*, 2003; Chen and Ding, 2005; Watanabe *et al.*, 2010). One mechanism that might explain this connection is radiative backwarming of the continuum-emitting layers by UV and EUV line and bound-free emission that is excited by energetic electrons penetrating into the flare chromosphere, at some distance above the photosphere. Since the radiative cooling time of the flare chromosphere immediately below the regions undergoing chromospheric evaporation is so short (Fisher, Canfield, and McClymont, 1985), the temporal variation of UV and EUV line emission from plasma within the $10^4 - 10^5$K temperature range will closely track heating by energetic electrons, detected as hard X-ray emission emitted from footpoints in the flare chromosphere. The backwarming scenario is illustrated schematically in Figure 2.

Estimates of the continuum opacity and atmospheric density near the solar photosphere indicate that the layer responsible for most of the optical continuum emission is about 1 continuum photon mean-free path thick, or roughly 70 km. Thus all the energy from the impinging backwarming radiation will be reprocessed into optical continuum emission within a thin layer near the solar photosphere.

Does the absorption of this radiation within this thin layer result in a significant downward force, via a pressure perturbation? This mechanism has been suggested by Donea *et al.* (2006) and Lindsey and Donea (2008) as a potential source for "sunquake" acoustic emission seen during a few solar flares. Here, we ask whether this mechanism can be as effective in creating a force perturbation as that from the Lorentz force change described earlier.

The simplest estimate of the pressure change, which will be an overestimate, is to assume that the backheated photospheric plasma is frozen in place during the heating process, and that its temperature will rise to a level where the black-body radiated energy flux equals the combined output of the preflare solar radiative flux plus the incoming flare energy flux due to backwarming.

What is the flux of energy from backwarming available to heat the photosphere? In order to compute the backwarming flux, we must estimate the fraction of the non-thermal electron energy flux that is balanced by chromospheric UV/EUV emission, and the fraction of this radiated energy that impinges on the nearby solar photosphere. Assuming that we can collect all of these effects into a single "dilution factor" for backwarming, $f_{\rm back}$, results in this estimate of the elevated photospheric temperature T:

$$\sigma T^4 = \sigma T_{eff}^4 + f_{\rm back} F_{flare} \ , \qquad (16)$$

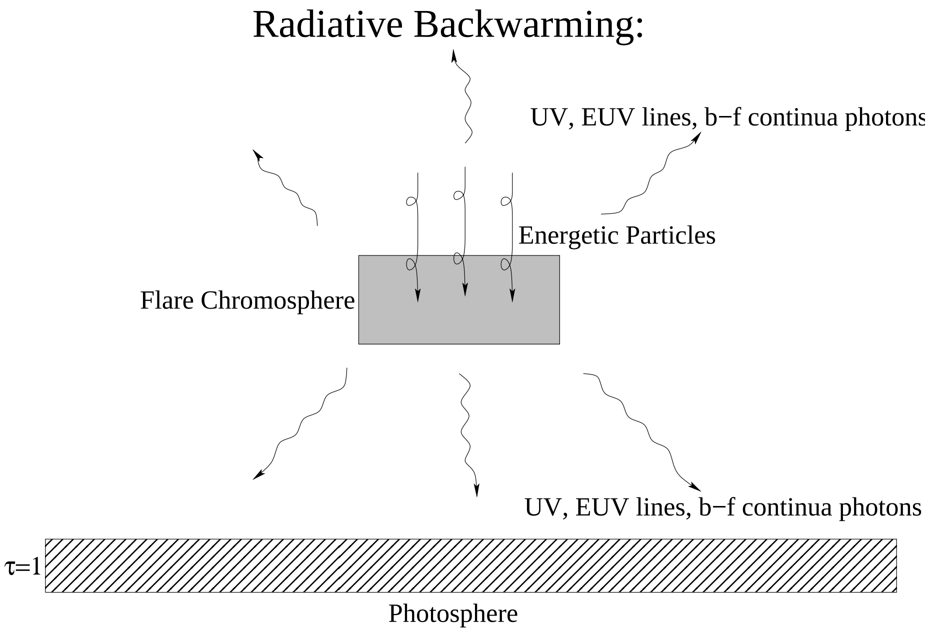

Figure 2. Schematic illustration of radiative backwarming in a solar flare. Energetic electrons are stopped collisionally in the upper flare chromosphere, raising the temperature of the plasma there. The increased energy input is balanced by an increased radiative output in the form of EUV and UV line radiation, and the emission of b-f continua from excited ions. This radiation is emitted in all directions, but a signficant fraction of it is re-absorbed in optically thick layers near the solar photosphere. These layers respond with an increase of temperature and pressure, with an amplitude that will depend sensitively on the energy flux, area coverage, and timing of the impinging radiation.

where T_{eff} is the non-flare photospheric effective temperature, and F_{flare} is the energy flux in non-thermal electrons inferred from hard X-ray observations. To estimate $f_{\rm back}$, we first assume that half of the nonthermal electron energy flux is diverted into chromospheric evaporation (the dynamic evolution described in §3.1, for example, is driven by pressure increases from chromospheric evaporation) and/or other energy channels. Second, we estimate the geometrical dilution of a UV/EUV emitting flare kernel with roughly 1000 km horizontal extent, based on estimated flare kernel sizes of roughly 1 arc-second^2, located in the flare chromosphere roughly 1000 km above the photosphere (see schematic drawing in Figure 2) and find a subtended solid angle of just less than 1 steradian, while the energizing radiation is assumed to be emitted isotropically over 4π steradians. Combining these two assumptions, we estimate $f_{\rm back} \simeq 0.034$. Then, using canonical nonthermal electron energy flux levels of $F_{flare} \sim 10^{11}$ erg cm^{-2} s^{-1}, results in a backwarming induced pressure enhancement of ~ 1000 dyne cm^{-2}, assuming a pre-flare photospheric pressure of 7.6×10^4 dyne cm^{-2} (see model S of Christensen-Dalsgaard *et al.*, 1996).

This is probably an overestimate, however, since it assumes the temperature changes instantaneously (ignoring the time-lag due to the finite heat capacity of the photospheric plasma), and it assumes the photospheric plasma is frozen in place and does not respond dynamically to the increased heating (the plasma should expand in response to the enhanced heating on a sound-crossing time – for a 70 km thick photospheric layer, with $C_s \sim 8$ km s^{-1}, this is ∼10s). This treatment also ignores the possibility of multi-step radiative reprocessing, in which the backwarming radiation that reaches the photosphere comes not from the primary source in the flare chromosphere, but from secondary backheating sources, where the UV line emission is first converted via backwarming to other radiation mechanisms (*e.g.* H b-f continuum emission), before finally reaching the photosphere. Each step of the multi-step reprocessing will result in at least another factor of two in dilution.

In summary, our simple calculation results in an estimated pressure enhancement that is roughly half of the effective downward pressure resulting from the Lorentz force perturbation from Hudson, Fisher, and Welsch (2008). Individual backheating driven photospheric pressure enhancements could be significantly higher or lower than what we find here, but for the reasons described above, there certainly is no compelling case that they must always be higher. Further, the backheating area coverage factor, assumed to be roughly equal to the observed areas of enhanced white-light emission, is probably much smaller than the photospheric area over which significant magnetic field changes occur, resulting in an area integrated force which is probably not as great as that due to the Lorentz force.

4. Conclusions

We show that the expression for the vertical Lorentz force in Hudson, Fisher, and Welsch (2008) should be robust and accurate, if integrated over the strong field regions of a vector magnetogram, and if the change to the observed magnetic field components is small compared to the initial field component values. We argue that the force computed from equation (10) arises from an equal and opposite upward force that corresponds to the Lorentz force driving the outward motion of the flare and CME ejecta. We speculate that the expression for the perturbed Lorentz force in Hudson, Fisher, and Welsch (2008), integrated over area, will be well correlated with observed measurements of the outward momentum per unit area of flare ejecta, as well as the helioseismic signature driven by compensating downward jerk.

We also estimate force perturbations in the photosphere due to changes in gas pressure driven by flare-driven chromospheric evaporation and from radiative backwarming of the photosphere. We find the Lorentz force clearly dominates gas pressure changes driven by chromospheric evaporation, and very likely dominates gas pressure changes driven by radiative backwarming. Since the primary source for energy release in eruptive solar flares is believed to be the solar magnetic field in strong-field, low β active regions, it makes sense that changes in the magnetic field itself will have a more direct and larger impact than changes due to secondary processes, such as the production of energetic particles, gasdynamic motions, and enhanced radiative output.

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References

Brown, J.C.: 1972, The Directivity and Polarisation of Thick Target X-Ray Bremsstrahlung from Solar Flares. *Solar Phys.* **26**, 441 – 459. doi:10.1007/BF00165286.

Chen, Q.R., Ding, M.D.: 2005, On the Relationship between the Continuum Enhancement and Hard X-Ray Emission in a White-Light Flare. *Astrophys. J.* **618**, 537 – 542. doi:10.1086/425856.

Christensen-Dalsgaard, J., Dappen, W., Ajukov, S.V., Anderson, E.R., Antia, H.M., Basu, S., Baturin, V.A., Berthomieu, G., Chaboyer, B., Chitre, S.M., Cox, A.N., Demarque, P., Donatowicz, J., Dziembowski, W.A., Gabriel, M., Gough, D.O., Guenther, D.B., Guzik, J.A., Harvey, J.W., Hill, F., Houdek, G., Iglesias, C.A., Kosovichev, A.G., Leibacher, J.W., Morel, P., Proffitt, C.R., Provost, J., Reiter, J., Rhodes, E.J. Jr., Rogers, F.J., Roxburgh, I.W., Thompson, M.J., Ulrich, R.K.: 1996, The Current State of Solar Modeling. *Science* **272**, 1286 – 1292. doi:10.1126/science.272.5266.1286.

Donea, A., Besliu-Ionescu, D., Cally, P.S., Lindsey, C., Zharkova, V.V.: 2006, Seismic Emission from A M9.5-Class Solar Flare. *Solar Phys.* **239**, 113 – 135. doi:10.1007/s11207-006-0108-3.

Fisher, G.H.: 1989, Dynamics of flare-driven chromospheric condensations. *Astrophys. J.* **346**, 1019 – 1029. doi:10.1086/168084.

Fisher, G.H., Canfield, R.C., McClymont, A.N.: 1985, Flare Loop Radiative Hydrodynamics - Part Seven - Dynamics of the Thick Target Heated Chromosphere. *Astrophys. J.* **289**, 434. doi:10.1086/162903.

Forbes, T.G.: 2000, A review on the genesis of coronal mass ejections. *JGR* **105**, 23153 – 23166.

Gan, W.Q., Li, Y.P., Miroshnichenko, L.I.: 2008, On the motions of RHESSI flare footpoints. *Advances in Space Research* **41**, 908 – 913. doi:10.1016/j.asr.2007.05.001.

Hudson, H.S., Fisher, G.H., Welsch, B.T.: 2008, Flare Energy and Magnetic Field Variations. In: R. Howe, R. W. Komm, K. S. Balasubramaniam, & G. J. D. Petrie (ed.) *Subsurface and Atmospheric Influences on Solar Activity*, *Astronomical Society of the Pacific Conference Series* **383**, 221.

Hudson, H.S., Acton, L.W., Hirayama, T., Uchida, Y.: 1992, White-light flares observed by YOHKOH. *Pub. Astron. Soc. Japan* **44**, L77 – L81.

Kosovichev, A.G., Zharkova, V.V.: 1998, X-ray flare sparks quake inside Sun. *Nature* **393**, 317 – 318. doi:10.1038/30629.

Lindsey, C., Donea, A.: 2008, Mechanics of Seismic Emission from Solar Flares. *Solar Phys.* **251**, 627 – 639. doi:10.1007/s11207-008-9140-9.

Low, B.C.: 1985, Modeling solar magnetic structures. In: M. J. Hagyard (ed.) *Measurements of Solar Vector Magnetic Fields*, 49 – 65.

Metcalf, T.R., Jiao, L., McClymont, A.N., Canfield, R.C., Uitenbroek, H.: 1995, Is the solar chromospheric magnetic field force-free? *ApJ* **439**, 474 – 481.

Metcalf, T.R., Alexander, D., Hudson, H.S., Longcope, D.W.: 2003, TRACE and Yohkoh Observations of a White-Light Flare. *Astrophys. J.* **595**, 483 – 492. doi:10.1086/377217.

Wang, H., Liu, C.: 2010, Observational Evidence of Back Reaction on the Solar Surface Associated with Coronal Magnetic Restructuring in Solar Eruptions. *Astrophys. J. Lett.* **716**, L195 – L199. doi:10.1088/2041-8205/716/2/L195.

Watanabe, K., Krucker, S., Hudson, H., Shimizu, T., Masuda, S., Ichimoto, K.: 2010, G-band and Hard X-ray Emissions of the 2006 December 14 Flare Observed by Hinode/SOT and Rhessi. *Astrophys. J.* **715**, 651 – 655. doi:10.1088/0004-637X/715/1/651.