1-10-1995

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Recommended Citation

Moore RL, Larosa TN, Orwig LE. 1995. The wall of reconnection-driven magnetohydrodynamic turbulence in a large solar-flare. *Astrophys J* 438(2):985-96.

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THE WALL OF RECONNECTION-DRIVEN MAGNETOHYDRODYNAMIC TURBULENCE IN A LARGE SOLAR FLARE

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Received 1994 April 28; accepted 1994 July 15

ABSTRACT

LaRosa & Moore (1993) recently proposed that the bulk dissipation of magnetic field that is required for the electron energization in the explosive phase of solar flares occurs in a “fat current sheet,” a wall of cascading MHD turbulence sustained by highly disordered driven reconnection of opposing magnetic fields impacting at a turbulent boundary layer. In two-ribbon eruptive flares, this turbulent reconnection wall is supposed to develop at the usual reconnection site in the standard model for these flares; that is, the reconnection wall stands in the vertical magnetic rent made by the eruption of the sheared core of the preflare closed bipolar field. Here, we use the well-observed great two-ribbon eruptive flare of 1984 April 24/25 to assess the feasibility of both (1) the standard model for the overall three-dimensional form and action of the magnetic field and (2) the turbulent reconnection wall within it. The observed aspects of this flare that we use are (1) the preflare photospheric vector magnetic field; (2) the occurrence of a flare spray and the size, form, and spreading of the chromospheric flare ribbons; and (3) the rate of production of hard (≥ 25 keV) X-rays in the explosive phase of the flare. We find (1) that the morphology of this flare closely matched that of the standard model; (2) the preflare sheared core field had enough nonpotential magnetic energy to power the flare; (3) the model turbulent wall required to achieve the flare’s peak dissipative power easily fit within the overall span of the flaring magnetic field; (4) this wall was thick enough to have turbulent eddies large enough (diameters $\sim 10^8$ cm) to produce the $\sim 10^{26}$ ergs energy release fragments typically observed in the explosive phase of flares; (5) the aspect ratio (thickness/vertical extent) of the turbulent reconnection wall was in the 0.1–1 range expected by (Parker 1973). We therefore conclude that the viability of our version of the standard model (i.e., having the magnetic field dissipation occur in our turbulent reconnection wall) is well confirmed by this typical great two-ribbon eruptive flare.

Subject headings: acceleration of particles — MHD — Sun: flares — turbulence

1. INTRODUCTION

A solar flare is an explosion in the solar atmosphere, an outburst of bulk mass motion, plasma particle energization, and radiation. All flares occur in regions of closed magnetic field, straddling one or more polarity inversion lines in the photospheric magnetic flux (Svestka 1976; Machado et al. 1988). Flares show a strong preference for markedly nonpotential magnetic fields; that is, for fields that obviously contain stored magnetic energy because they are greatly deformed from their minimum-energy potential-field configurations (Hagyard, Moore, & Emslie 1984; Moore, Hagyard, & Davis 1987; Machado et al. 1988; Hagyard 1990). Moreover, the greatest flares occur in the largest agglomerations of the strongest highly nonpotential magnetic fields found on the Sun, those rooted in large impacted opposite-polarity sunspots exhibiting stark nonpotential deformity (Zirin & Liggett 1987; Zirin 1988). From these characteristics of the magnetic fields at flare sites, it is widely held that a flare is an explosive release of nonpotential magnetic energy from the preflare magnetic field (Svestka 1976; Sturrock 1980; Spicer, Mariska, & Boris 1985; Tandberg-Hanssen, & Emslie 1988). While there is little doubt that the flare energy comes from the magnetic field, the flare mechanism—the physical process (or sequence of processes)

that works the explosive conversion of magnetic energy into mass motion, hot plasma, and energetic particles—remains largely unsettled. In other words, this catastrophic conversion is the crux of the flare problem.

Flares often occur in complex magnetic field configurations made up of multiple impacted bipoles, each with its own polarity inversion. In these cases, the assembly of coronal loops and chromospheric ribbons in the flare has a correspondingly complex morphology (Machado et al. 1988). However, in some flares practically all of the energy release occurs within a magnetic field that bridges a single inversion line, so that the arrangement of loops and ribbons is simpler: a single arcade of coronal flare loops bridges the single inversion line and is rooted in a pair of flare ribbons that bracket this inversion line. This general class of single-bipole flares includes a subclass known as two-ribbon eruptive flares; the largest and most powerful flares usually are of this type (Zirin 1966, 1988; Svestka & Cliver 1992).

For two-ribbon eruptive flares, there is now a generally accepted picture for the overall three-dimensional magnetic field and its change during the flare. This standard picture is basically the one proposed by Hirayama (1974), which (with various modifications, refinements, and changes in emphasis)

has been adopted by many flare modelers (e.g., Kopp & Pneuman 1976; Heyvaerts, Priest, & Rust 1977; Moore & LaBonte 1980; Hagyard et al. 1984; Sturrock et al. 1984; Martins & Kuin 1989; Moore & Roumeliotis 1992; Forbes 1992). In this scheme, the flare energy release is driven by the eruption of a magnetic flux rope from the sheared core of a closed bipolar magnetic field (Moore 1988; Forbes 1992). By its eruption and expansion, the core flux rope works on the surrounding envelope field of the bipole, pushing up the top and stretching the legs of this field arcade. As the erupting flux rope vacates its preflare space in the core, the two stretched legs of the envelope cram together in this space and force reconnection at their interface. This driven reconnection does three things simultaneously: (1) it accelerates electrons and heats plasma to produce the hard and soft X-ray emissions of the flare; (2) it builds a growing arcade of coronal flare loops rooted in a pair of separating flare ribbons; and (3) it wraps the erupting flux rope in a growing cocoon of envelope field shorn of ties to the photosphere (continued expansion of the core rope and its unleashed cocoon field drives a coronal mass ejection out into the solar wind). All of these features of the standard picture are in good accord with the observed morphology and development of two-ribbon eruptive flares.

While it is generally thought that the reconnection somehow yields the plasma particle energization in two-ribbon eruptive flares, there is no well-accepted model for this process. The main difficulty is the electrons with energies ≥ 25 keV must be produced at a very large rate ($\sim 10^{36} \text{ s}^{-1}$) in order to provide the observed hard (≥ 25 keV) X-ray emission in the peak-power impulsive phase of large flares (e.g., Lin & Hudson 1976; Ramaty et al. 1980). This is the well-established electron bulk energization problem (Forman, Ramaty, & Zweibel 1986; Dennis 1988; Melrose 1992). Quasi-steady laminar-flow models of the reconnection in two-ribbon eruptive flares can plausibly process ambient electrons at a large enough rate, but practically none of these pass through the reconnection line, where there is a significant macroscopic electric field that could accelerate electrons there to high energies (Forbes 1992). The reconnection line is at the mutual vertex of two vertical outflow wedges, each formed by a pair of oblique "Petschek" shocks. Nearly all of the processed electrons flow in across these shocks well away from the reconnection line and then blow away in the outflow. There should be a strong termination shock at the bottom end of the downward outflow wedge. So, in these models, any bulk energization of the electrons is done by these shocks. The oblique shocks could heat the plasma to only a few keV at most (Whang 1992). The termination shock could energize the protons to a few tens of keV, but it is not clear that it would also energize the electrons to this extent (Cargill et al. 1994). Thus, whether laminar-flow reconnection models can provide the required bulk energization of the electrons remains an open question.

In this paper, we advocate another way of bulk energizing the electrons at the reconnection interface in two-ribbon eruptive flares, the way recently proposed by LaRosa & Moore (1993) and LaRosa, Moore, & Shore (1994). This new model for the reconnection region is a modification of the above laminar-flow model. As before, two opposing flows carrying opposing magnetic fields come in from the sides, forcing the fields to reconnect at their interface, and the reconnected fields drive out vertical exit flows that balance the inflow. Also as before, the flow is globally quasi-steady. The new departure is that, instead of being laminar, the interface region is extremely

disordered and turbulent. The inflowing field is taken to be packed with filamentary substructure instead of being uniform over the whole area of the interface. Consequently, because different strands of the opposing fields meet at different locations on the interface, the overall reconnection is neither steady nor well ordered to have a single reconnection line and set of Petschek shocks; instead, the reconnection proceeds randomly and piecemeal through many separate localized subbursts thickly scattered over the interface. In each of these reconnection fragments, the outflows are expected to be fully turbulent due to shear-flow instability (Chiueh & Zweibel 1987). If so, the ambient electrons can be bulk energized to ~ 25 keV by this cascading MHD turbulence via Fermi acceleration (LaRosa & Moore 1993; LaRosa et al. 1994).

Our purpose in this paper is to show that the standard model for two-ribbon eruptive flares, with the above turbulent model for the reconnection wall within it, is compatible with the observed morphology and power of the energy release in a typical large two-ribbon eruptive flare, the great flare of 1984 April 24/25. We first present the flare model in more detail, depicting the three-dimensional form and action of the magnetic field and the location of the reconnection wall within it, and bringing out features and parameters of the model that can be observationally checked or constrained. We then present observations of the form and spreading of the flare ribbons, the photospheric vector magnetic field, and the impulsive-phase hard X-ray burst in our flare. From these we estimate the configuration and strength of the magnetic field in the flare, the total rate of plasma energization in the impulsive phase, and the corresponding required overall dimensions of the model wall of turbulent reconnection. We find that (1) the observed flare had the morphology of the model, (2) the preflare core of sheared magnetic field along the inversion line had enough nonpotential energy to power the flare, (3) the model turbulent wall required to power the observed flare plasma energization fits comfortably within the observed spatial extent of the flare, and (4) the observational constraints on the model yield a thickness for the turbulent reconnection wall that agrees with the subsecond spikey texture of the impulsive-phase emissions from flares. Because the model accommodates all of these observational constraints, fitting them all together into one self-consistent picture, the model is compelling for this classic two-ribbon eruptive flare.

2. FLARE MODEL

2.1. Global Picture

The standard model for the progression of the global three-dimensional configuration of the magnetic field and plasma energization in two-ribbon eruptive flares is sketched in Figure 1. The preflare field is closed and bipolar, a space-filling arcade straddling the polarity inversion line. Near the inversion line, the field is greatly sheared so that it is directed nearly parallel to the inversion line. Such inversion-line channels of sheared field are common on the Sun; their roughly horizontal field often holds enough cool chromospheric material to be seen in chromospheric images as a long dark filament tracing the inversion line (e.g., Moore et al. 1991). The preflare model arcade field also mimics sheared-core arcade fields found on the Sun in that the degree of shear in the arcade field diminishes with distance from the core so that the core field is encased in an envelope of more nearly potential magnetic field that arches over the core at a large angle, more nearly perpen-

FIG. 1.—Standard model of the overall three-dimensional form and action of the magnetic field and its reconnection in two-ribbon eruptive flares (as depicted by Hagyard et al. 1984).

dicular than parallel to the inversion line (as in the upper left-hand panel of Fig. 1). If the core field were nearly potential, it would cross right over the inversion line as well. When the core field runs nearly orthogonal to the potential-field direction, as in the model, most of the magnetic energy in the core is nonpotential magnetic energy. Thus, the model preflare core field is well qualified to fuel a flare.

In the model, as in real active regions, throughout the preflare magnetic field that later directly participates in the flare energy release through reconnection, the field strength is great enough that the weight and pressure of the chromospheric and coronal plasma are negligible: the preflare magnetic field configuration is force free. In other words, the preflare field is in an equilibrium configuration throughout which magnetic pressure is balanced by magnetic tension (e.g., Cowling 1957). Globally, the magnetic pressure pushes against the solar surface (photosphere), urging the field in the bipole to expand outward; whereas, because the field lines are anchored in the surface, the magnetic tension pulls toward the surface, urging the field to contract downward. Throughout the preflare field these two opposing tendencies are in equilibrium. In the core of the bipole, because the field is sheared, the field has less curvature (is more nearly horizontal) than if it were potential. So, in the force-free configuration with sheared core field, the core field's magnetic pressure is less balanced by this field's own magnetic tension than in the no-shear potential case. The remainder of the confinement of the sheared core field is provided by the tension in the surrounding envelope field (Antiochos, Dahlburg, & Klimchuk 1994).

For a two-ribbon eruptive flare to occur in this model, it is assumed that the preflare configuration evolves appropriately for the core field to become eruptively unstable, and that the flare begins with the onset of the core eruption. The basic idea is that if the core field becomes both greatly sheared (so that it has little self-confinement) and thick enough (contains enough

magnetic flux), then the envelope field will no longer be able to confine the core field and the core field will erupt. The preflare field evolves to this unstable state through growth in the shear and flux in its core field; this can plausibly happen by various combinations of gradual cancellation of flux and shearing of the core field, all slowly driven by photospheric flows in the core channel (van Ballegoijen & Martens 1989; Moore & Roumeliotis 1992). As soon as the preflare configuration becomes unstable to core eruption, the core flux rope begins to erupt, and this allows the legs of the immediate envelope to impact together and begin reconnecting just below the rising core rope (as in the upper right-hand panel of Fig. 1). This driven reconnection further unleashes the envelope field that coats the core rope, which adds more magnetic flux to the detached core, which, in turn, reinforces the eruption and reconnection. In this way the eruption/reconnection becomes explosive.

The explosive phase usually lasts for no more than a few minutes, even in the largest flares. During this time, the flare ribbons rapidly grow to their full length along the inversion line and peak in their rate of spreading orthogonally to the inversion line, the soft X-ray emission (and hence the accumulation of the $T \sim 10^7$ K flare plasma that emits this radiation) undergoes its most rapid rise, and the hard X-ray emission (and hence the production of the energetic electrons that emit the hard X-rays and that apparently power the heating of the soft X-ray-emitting plasma) impulsively rises and peaks. Because of the impulsive hard X-ray emission and similarly impulsive microwave emission during the exposure phase, the explosive phase is also called the impulsive phase (e.g., Dodson-Prince & Bruzek 1977). The three-dimensional model for the magnetic field in the explosive phase of the flare is depicted in the lower left-hand panel of Figure 1. The overall topology of the field in the explosive phase is nearly the same as in the onset phase. In progressing from the onset phase to

the explosive phase, the field configuration has changed somewhat in that the core flux rope has risen up, the envelope over the core has been pushed up, and reconnection below the raised core rope has produced two topologically new features. One is the upward product of the reconnection: the helical cocoon field that wraps around the initial core rope. The other is the downward product of the reconnection: the arcade of newly connected loops that are filled with flare-heated plasma and whose feet stand in the flare ribbons. Both the cocoon field and the flare arcade loops receive injections of energized particles and hot plasma from the reconnection site as they are born. The particles and heat run along these field lines to their feet and heat the chromosphere there (the flare ribbons). Notice that in the explosive phase the overall bipolar field, though expanding, is still closed. At this stage the cocoon field as well as the flare arcade field feed the flare ribbons, the cocoon helix being rooted in the outer ends of the two ribbons, beyond the range of the flare arcade (as indicated in Fig. 1). Also at this stage, the field being added to the growing flare arcade, though less sheared than the preflare core field, retains some obvious shear.

In the explosive phase of the model flare, the rope of detached core field has erupted up, taking the form of a rising helical arch oriented along the inversion line and transiently having a height of the order of the separation of its two feet. This is in agreement with the observed transient form of erupting core-tracing filaments in the flare impulsive phase (Kahler et al. 1988). As this growing helical flux rope erupts on up into the outer corona, on its way to escaping into the solar wind, the flare enters its late phase or decay phase (sketched in the lower right-hand panel of Fig. 1). By this time, much of the preflare envelope field has already reconnected in the wake of the core eruption, so that the field loops in the newly forming outer edge of the flare arcade are nearly orthogonal to the inversion line (have no obvious shear), arch well above the height of the preflare sheared core field, and are rooted at the leading edges of the two flare ribbons, which are now well separated from the inversion line. The rates of reconnection, flare arcade growth, and ribbon spreading are much slower, and the hard X-ray emission is much weaker than in the explosive phase. In the late phase, it is appropriate to consider the unreconnected envelope field to be open rather than closed. The flare ribbons are now fed by only one topological set of flare loops rather than two. This set is formed entirely by the downward product of the reconnection that recloses the open remnants of the envelope field.

The reconnection region is not shown in any detail in Figure 1. In the onset and impulsive-phase panels, the reconnection is merely implied in the perspective drawings and is only indicated by the cross in the end views. In Figure 2 the explosive-phase model field configuration is sketched in more detail, especially for the immediate magnetic-field environment of the reconnection region. The wall of turbulent reconnection is sandwiched between the two legs of the envelope field. Only a single strand or field line of the erupted core flux rope is shown; this core field and its helical cocoon field have their feet in the two more remote segments of the flare ribbons. Likewise, the sketch shows only a single loop of the flare arcade that is rooted all along the two less remote segments of the flare ribbons. In the same vein, the sketch shows only two representative strands of the immediate envelope field on the sides of the reconnection wall, one on the front side and one on the back side. In the explosive phase, because the core flux rope

EXPLOSIVE PHASE

FIG. 2.—Location and magnetic field environment of our turbulent reconnection wall (here labeled the turbulent dissipation region) within the model global field configuration for two-ribbon eruptive flares in their explosive phase.

has only erupted to a height of the order of the overall length of the flare and because the preflare envelope field immediately coating the core rope is also rather highly sheared, the envelope fields on the front and back of the reconnection wall are not vertical; their horizontal component is comparable to their vertical component (as in Fig. 2). Consequently, the flare arcade made by the reconnection in the explosive phase is markedly sheared; its field loops are far from orthogonal to the inversion line. In Figure 2, the two field strands shown merging into the front and back of the turbulent reconnection wall are about to reconnect. The downward product of this reconnection will be a new loop added to the sheared arcade below the reconnection wall; the upward product will be a new strand added to the helical erupting core field above. The sketch in Figure 2 also emphasizes that because the reconnection is between two sets of closed field loops, in the explosive phase there are actually four flare ribbons, two conjugate pairs rather than just one pair; the outer pair linked by the erupting core helix and the inner pair linked by the newborn sheared arcade. Finally, notice that if the two field strands shown on the sides of the reconnection wall in Figure 2 represent elementary filamentary substructures (flux tubes) in the envelope field, then the reconnection wall is large enough for tens of these elementary flux tubes to press simultaneously into each side of this wall. These two opposing and crossed sets of flux tubes will meet and reconnect nearly simultaneously at their hundreds of crossing points within the reconnection wall. This makes the reconnection wall highly disordered and turbulent on scales of the elementary flux tube diameters and smaller (LaRosa & Moore 1993).

2.2. Turbulent Reconnection Wall: Steady-Flow Model

In this section, we apply the constraints of mass and energy conservation to the turbulent reconnection region in our overall flare model to quantitatively link this central feature of the model to observable aspects of a flare. For this we need a model for the reconnection region that is simplified enough to be tractable while retaining the gross size, shape, and physical function of the actual reconnection region. The model that we adopt is depicted in Figure 3. This model is defined by the following conditions that are plausibly roughly valid for the actual reconnection region in the explosive phase of two-ribbon eruptive flares.

FIG. 3.—Schematic representation of our steady-flow model for the turbulent reconnection wall. *Upper left*: perspective view; *upper right*: top view; *lower left*: end view; *lower right*: side view. The inflows and outflows are indicated by the fat arrows; the magnetic fields carried in these flows are represented by the thin arrows. Only the vertical component of the inflowing field is seen in the end view, and only the horizontal component of this field is seen in the top view. In the perspective view, the orientation of the wall and the direction of the magnetic field on the front and back sides correspond to those in Fig. 2.

1. The model reconnection region has the orientation and bulk form of a vertical wall, that is, a rectangular parallelepiped oriented as in Figures 2 and 3.

2. Magnetized plasma flows in through the sides of the wall and out through the top and bottom; there is negligible flow through the ends.

3. Although the flow is strongly fluctuating and turbulent on scales much smaller than the overall wall, on average scales comparable to the length of the wall, the flow across a face of the wall is roughly uniform in speed, density, and magnetic field. The overall flow is quasi-steady: at each instant the rate of mass and energy outflow through the top and bottom of the wall practically equals the rate of mass and energy inflow through the sides.

4. There is negligible compression or expansion of the flow within the model reconnection wall; the plasma density is constant throughout the model.

5. The two inflowing magnetic fields on the opposite sides of the wall are perpendicular to the inflow, have identical horizontal components, and have equal but opposite vertical components.

6. As the magnetic field rides the flow through the interior of the reconnection wall, the vertical components of the two merging fields are consumed by being converted into bulk-flow kinetic energy and random-velocity particle energy via reconnection and turbulent cascade as proposed by LaRosa & Moore (1993), but the horizontal component of the merging fields is preserved. Consequently, the residual field exiting in the outflow at the top and bottom of the reconnection wall is

horizontal and identical to the horizontal component of the inflowing field.

7. The outflowing plasma is accelerated to its exit speed by slingshot action of the reconnected field within the reconnection wall. The slingshot action comes from the unleashed tension in the vertical component of the reconnected field. On this basis, in this model we take the speed of the exiting flow to be of the order of the Alfvén speed given by the vertical component of the magnetic field in the flow entering the sides.

8. In addition to much of the vertical-component magnetic energy going into the bulk kinetic energy of the exiting plasma, much of the vertical-component magnetic energy also goes into the random-velocity energy of the electrons in this plasma. The electrons are energized by Fermi acceleration in the cascading MHD turbulence in the outflows from the many localized transient reconnection sites thickly scattered throughout the reconnection wall as proposed by LaRosa et al. (1994). For our model reconnection wall, we assume equipartition of the vertical-component magnetic energy, half going to bulk kinetic energy and half to particle energy. So, in the exiting flow the particle energy density and the bulk kinetic energy density are equal and each is of the order of one-half the energy density of the vertical component of the magnetic field in the flow entering the sides. (For our application of the model [§ 3], the results are not very sensitive to the equipartition condition; it need hold only to order of magnitude.)

9. The loss of energy from the model reconnection wall is strongly dominated by the convective losses; losses by radiation and conduction are negligible. The turbulence within the reconnection wall prevents the energized electrons from escaping (LaRosa et al. 1994). For our model reconnection wall, as the flow exits the top and bottom, the turbulence abruptly dies out, releasing the energized electrons to stream along the field lines to the chromosphere, where they produce thick-target hard X-ray emission and heat the flare ribbons.

10. In the sequence of reconnected field lines that exits the top or bottom of the reconnection wall, each successive field line is rooted progressively farther from the polarity inversion line; its two feet are at the leading edges of a conjugate pair of flare ribbons. In other words, the sequence of reconnection ordered by the global arrangement of the magnetic field and its inflow to the reconnection wall results in the spreading of the flare ribbons.

We now proceed to the linkage of our model reconnection wall to certain observable aspects of two-ribbon eruptive flares. First, there is the direct connection of the electron energy in the outflow to the vertical component of the magnetic field in the inflow. Because we assume (following LaRosa et al. 1994) that the MHD turbulent cascade Fermi-accelerates the electrons but not the protons, in the outflow the electrons carry practically all of the random-velocity particle energy while the protons carry practically all of the bulk-flow kinetic energy. In our model, the inflowing vertical-component magnetic energy is entirely converted and equipartitioned into these two components of the outflow energy. This condition, together with the condition of constant density, yields

$$\frac{B_{\text{vert}}^2}{8\pi} = 2n_e \mathcal{E}_e, \quad (1)$$

where B_{vert} is the strength of the vertical component of the inflowing magnetic field, n_e is the electron density of the plasma in the reconnection wall, and $\mathcal{E}_e$ is the electron mean particle

energy in the outflow. As equation (1) states, in our model the particle energy $\mathcal{E}_e$ of the bulk-energized electrons is determined entirely by B_{vert} and n_e . If we have "observed" values for n_e and $\mathcal{E}_e$ for the bulk-energized electrons in the reconnection region in a flare, then equation (1) gives the value of B_{vert} required by our model reconnection region.

There is also a direct connection between the speed of the flow entering the sides of the reconnection wall and the speed at which the leading edge of a flare ribbon moves away from the polarity inversion line. In our model, the leading edges of the flare ribbons at any given instant closely coincide with the locus of the feet of all the field lines that are being swept through the sides of the reconnection wall at that instant. Consequently, during any time interval in the flare, the magnetic flux crossed by the leading edge of a flare ribbon equals the magnetic flux swept in through each side of the reconnection wall. The global configuration of the magnetic field in the explosive phase of our model flare (as sketched in Figs. 1 and 2) indicates that a flux tube being swept into the reconnection wall has a cross-section area that is larger at the reconnection wall than at the photosphere. As appears plausible from Figures 1 and 2, we assume that these flux tubes spread with height significantly in the direction orthogonal to the reconnection wall but negligibly in the direction along the wall. That is, we assume that the horizontal length of the reconnection wall is practically equal to the length of each of the four flare ribbons in Figure 2. The identity of the magnetic flux swept into each side of the reconnection wall with the magnetic flux crossed by the leading edge of a flare ribbon then gives

$$v_{\text{in}} = \frac{B_{\text{phot}}}{B_{\text{vert}}} v_{\text{ribbon}}, \quad (2)$$

where v_{in} is the speed of the inflow, v_{ribbon} is the speed of the leading edge of a flare ribbon, and B_{phot} is the strength of the vertical component of the magnetic field at the leading edge of the flare ribbon. Equation (2) states that in our model the ribbon front speed v_{ribbon} is directly proportional to the speed v_{in} of the inflow entering the reconnection wall, the factor of proportionality being $B_{\text{vert}}/B_{\text{phot}}$. If we have "observed" values of v_{ribbon} , B_{phot} , and B_{vert} , equation 2 gives the value of v_{in} required by our model.

Once we obtain empirical estimates of B_{vert} and v_{in} from equations (1) and (2), we can estimate the vertical extent of the reconnection wall from the total rate of magnetic energy consumption $\dot{E}$ within the wall. The rate of inflow of consumable magnetic energy through the two sides of the reconnection wall is $2lhv_{\text{in}}B_{\text{vert}}^2/8\pi$, where l and h are the length and vertical extent of the wall. Equating the rate of inflow and rate of consumption of the vertical-component magnetic energy, we have

$$lh = \frac{4\pi\dot{E}}{v_{\text{in}}B_{\text{vert}}^2}. \quad (3)$$

Equation (3) expresses that for our model reconnection region the total rate of magnetic energy release is proportional to the side area lh , the inflow speed v_{in} , and the density of releasable magnetic energy $B_{\text{vert}}^2/8\pi$. If we have "observed" values of $\dot{E}$, v_{in} , B_{vert} , and l , equation (3) gives the value of h required by the model.

Finally, if we have empirical values of B_{vert} , v_{in} , and h from equations (1), (2), and (3), then we can estimate the thickness of the reconnection wall. By conservation of energy and the con-

dition of equipartition between bulk kinetic energy and electron random-velocity energy in the outflow, we have $B_{\text{vert}}^2/8\pi = n_e m_p v_{\text{out}}^2$, or $v_{\text{out}}^2 = (V_A)_{\text{vert}}^2/2$, where m_p is the proton mass, v_{out} is the speed of the exiting flow, and $(V_A)_{\text{vert}} = B_{\text{vert}}/(4\pi m_p n_e)^{1/2}$ is the Alfvén speed given by the vertical component of the inflowing magnetic field. By conservation of mass in our constant-density steady flow, we have $v_{\text{out}}d = v_{\text{in}}h$, or

$$\frac{d}{h} = \frac{v_{\text{in}}}{v_{\text{out}}} = \frac{\sqrt{2}v_{\text{in}}}{(V_A)_{\text{vert}}}, \quad (4)$$

where d is the wall thickness. Equation (4) states that in our model the thickness and vertical extent of the reconnection region are in the same proportion as the inflow and outflow velocities. If we have empirical values for v_{in} , $(V_A)_{\text{vert}}$, and h , equation (4) gives the value of d required by our model.

3. THE GREAT FLARE OF 1984 APRIL 24/25

3.1. Observations

3.1.1. Spatial Development in H α

The energetically largest flares release a total energy of order 10^{32} ergs (Bruzek 1967; Svestka 1976). These great flares usually occur in exceptionally large δ -configuration sunspots (Zirin 1988). A δ sunspot is two (or more) opposite-polarity sunspots so close together that their penumbrae overlap; the polarity inversion line runs between the opposite-polarity umbrae in a narrow penumbral channel. Those δ sunspots that produce great flares are highly nonpotential; the magnetic field all along the inversion-line penumbral channel is greatly sheared. Each 11 yr sunspot cycle produces only of order 10 δ sunspots that are large enough and nonpotential enough to produce great flares (Zirin & Liggett 1987). One of the best observed great flares of the last solar cycle (cycle 21) was the two-ribbon eruptive flare of 1984 April 24/25. This was a typical great flare in that it was eruptive (produced a flare spray) and was seated in a large δ sunspot. The spatial development of this flare in H α was well observed by the USAF SOON station at Holloman Air Force Base in New Mexico. The sequence of high-resolution red-wing H α filtergrams from this observatory has a cadence of 1–2 minutes beginning early in the explosive phase. A selection of four of these filtergrams is shown in Figure 4.

The heliographic location of the flare was S11,E45. The large panel of Figure 4 shows that the flaring δ sunspot was on the leading (western) end of a large sunspot group (NOAA 4474). This filtergram was taken about 15 minutes after the end of the explosive phase of the flare. It shows that by this time the two flare ribbons were well separated and that some loops of the flare-heated arcade linking them had cooled to chromospheric temperatures and had dense enough plasma to become bright in H α . Another obvious feature seen in this filtergram is the long twisted striated dark structure that is rooted southwest of the flare and splays out to the southeast. The base of this feature first became visible in these red-wing filtergrams about 5 minutes after the end of the explosive phase; over the next 10 minutes the body gradually filled in from bottom up to attain its maximum extent, that seen in Figure 4. The form of this dark feature and its development in the red wings of H α is typical of the back-draining remnants of flare sprays, which are the dark chromospheric filaments that are flung out with the core field in eruptive flares (Tandberg-Hanssen, Martin, & Hansen 1980). Hence, we take the occurrence of this dark fila-

FIG. 4.—Morphology of the great flare of 1984 April 24/25, as observed in red-wing $H\alpha$ filtergrams (from USAF SOON station, Holloman Air Force Base). The three small panels (at 23:59:32, 00:00:32, and 00:01:32 UT) show the δ -sunspot site of the flare and the explosive-phase development of the flare ribbons. The large panel at (01:16:32 UT) shows the ribbons well separated, the presence of postflare loops, and the remnant of a flare spray in the gradual phase of the flare. East is up, and north is to the right. In the middle small panel, the north-south span of the ribbons is about 100,000 km.

mentary flare-spray feature in this flare to be evidence that this flare was indeed an eruptive flare.

The three small panels of Figure 4 are from the three filtergrams taken during the explosive phase. The explosive phase was just beginning in the top panel, was near its peak in the middle panel (1 minute later), and was near its end in the bottom panel (another minute later). In the top panel, the flare ribbons had not yet grown enough to cover much of the δ sunspot. At this stage, the portions of the flare ribbons inside the δ sunspot lay in or closely along the inversion-line penumbral channel. The middle and bottom panels show that over the next 2 minutes the flare ribbons grew greatly in area, expanding both along and away from the inversion line. Figure 4 also shows that throughout the explosive phase each of the two opposite-polarity ribbons had two segments: a relatively straight inner segment that extended into or through the middle of the δ sunspot and a more curled or irregular outer segment that lay mainly outside of the δ sunspot. Such a four-ribbon signature is typical in the early phases of large flares (Zirin 1988). This four-ribbon arrangement is in agreement with our flare model in the explosive phase, as sketched in Figure 2. In this interpretation, the inner pair of ribbon segments is fed by the downward product of the reconnection, the newly formed flare arcade, while the outer pair is fed by the upward product of the reconnection, the newly formed helical cocoon field added to the erupting core field.

As we indicated in § 2 (eq. [2]), v_{ribbon} , the speed at which the leading edge of a flare ribbon spreads away from the polarity inversion line, is one of the direct empirical constraints on our flare model. To quantify this speed and its evolution in our flare, we measured the distance (orthogonal to the inversion line) between the leading edges of the two inner flare ribbons where they overlapped along the inversion line in the middle of the δ sunspot. This distance was measured on the first 14 red-wing $H\alpha$ filtergrams of the sequence taken during the flare; the upper small panel of Figure 4 is from the first filtergram of this sequence. This separation distance (calibrated from full-disk filtergrams and corrected for projection so that it is the horizontal separation on the solar surface) is plotted against time in Figure 5. This plot verifies that the explosive phase ended about the time of the lower panel in Figure 4. As Figure 5 shows, the ribbon-front separation speed was about 100 km s^{-1} before that time, abruptly dropped to about 20 km s^{-1} right after that time, and slowed to about 10 km s^{-1} about 10 minutes later. Figure 4 shows that the two ribbons in the middle of the δ sunspot roughly equal each other in thickness during the explosive phase. So the speed of one ribbon front is roughly half the speed of separation of the two fronts, and from Figure 5 we see that in the explosive phase v_{ribbon} was about 50 km s^{-1} .

Another empirical input for quantifying our flare model (through eq. [3]) is the length l of the dissipation wall. In our

FIG. 5.—History of the separation S between the fronts of the inner pair of flare ribbons. The speed of separation dS/dt can be gauged from the slopes of the straight lines. In the explosive phase of ribbon expansion (the interval between the two vertical dashed lines), the speed of each of the two ribbon fronts $[(dS/dt)/2]$ was about 50 km s^{-1} .

model, during the explosive phase, the dissipation wall should be about as long as each of the four flare ribbons if the field configuration is roughly as sketched in Figure 2. At the peak of the explosive phase in our flare the two inner ribbons were each about 40,000 km long (measured from the filtergram of the middle small panel in Fig. 4). Thus, from the $H\alpha$ images we infer that the dissipation wall was about 40,000 km long during the peak of the explosive phase.

3.1.2. Magnetic Field

The photospheric magnetic field throughout sunspot region 4474 was observed with the MSFC vector magnetograph about 2 hr before the great flare (Moore et al. 1987; Hagyard, Venkatakrishnan, & Smith 1990). The middle panel of Figure 6 shows the observed vector magnetic field in and around the main sunspots. The right-hand panel of Figure 6 is the same field of view in a red-wing $H\alpha$ filtergram taken (by Big Bear Solar Observatory) about 5 minutes after the end of the explosive phase. Comparison of the middle and right-hand panels locates the polarity inversion line relative to the sunspots. The comparison confirms that the cluster of sunspots at the leading end of the group comprised a δ sunspot, and the flare ribbons bracketed the polarity inversion line that ran through this δ sunspot. The comparison also shows that there was another very large δ sunspot at the trailing end of the group.

The left-hand panel of Figure 6 is the potential-field vector magnetogram computed from the line-of-sight component of

FIG. 6.—Sheared photospheric magnetic field along the polarity inversion line through the site of the great flare of 1984 April 24/25. *Middle panel*: MSFC vector magnetogram taken at 22:11 UT, less than 2 hr before flare onset. The contours map the line-of-sight component of the field; solid (dashed) contours are for positive (negative) polarity; contour levels: 10, 100, 500, 1000, 1500, 2000, and 2500 G. The distributed dashes map the strength and direction of the transverse component; dash length is proportional to the transverse field strength, the longest dashes marking 2000 G. *Right panel*: same field of view from a Big Bear Solar Observatory red-wing $H\alpha$ filtergram taken at 00:00:07 UT, early in the gradual phase of the flare. *Left panel*: potential transverse field vectors computed from the observed line-of-sight magnetic field.

the observed magnetic field. It is seen that at most places on the inversion line the potential field is nearly orthogonal to the inversion line, especially within the two δ sunspots and in the interior of the group where the inversion line runs diagonally southeast-northwest. Comparison of the observed and potential vector magnetograms shows that (1) the field along the interior diagonal interval of the inversion line was nearly potential, (2) the field along the inversion line in the trailing δ sunspot was greatly sheared only about half-way through this δ sunspot (the southeastern half) and was nearly potential the rest of the way, and (3) in contrast, the leading δ sunspot—the flare site—had a thick channel of strong shear all the way through it along its inversion line. So, the vector magnetogram shows that leading δ sunspot apparently had the classic pre-flare field configuration of the standard model for eruptive two-ribbon flares: a bipole with a strongly sheared core field all along its inversion line (as in Fig. 1).

As we pointed out in § 2.2 (eq. [2]), another direct empirical constraint on our flare model is B_{phot} , the strength of the vertical component of the magnetic field at the leading edges of the flare ribbons. From comparison of the vector magnetogram in Figure 6 with the explosive-phase flare ribbons in Figure 4, we find that B_{phot} along the leading edges of the inner pair of flare ribbons at the peak of the explosive phase ranged from as low as a few hundred gauss outside of the δ sunspot to as high as 2500 G in the umbras. So, the average B_{phot} along these ribbon edges was of the order of 1000 G.

3.1.3. Hard X-Ray Emission

The hard X-ray burst from our flare was observed by the *Solar Maximum Mission* (SMM) Hard X-Ray Burst Spectrometer (HXRBS). This instrument had 15 energy channels that covered the photon energy range 24–400 keV. In Figure 7 we have plotted the HXRBS observations (gathered into four multichannel energy bands) from about 8 minutes before to about 20 minutes after the explosive phase of our flare. It is seen that the hard X-ray burst first began about 23:52 UT, and that its impulsive phase started about 23:59 UT and peaked 1–2 minutes later. The time interval bounded by the vertical dashed lines (23:59:32–00:01:32) is the same as that in Figure 5, the time interval spanned by the three small panels in Figure

FIG. 7.—The hard X-ray burst from the great flare of 1984 April 24/25, as observed by the Hard X-Ray Burst Spectrometer of the *Solar Maximum Mission*. As in most flares, this burst rose and peaked impulsively in intensity and spectral hardness in step with the explosive expansion of the H α ribbons (during the interval between the two vertical dashed lines).

4. Thus, Figure 7 confirms that this flare's impulsive/explosive phase did indeed peak in this 2 minute time interval.

During the time spanned in Figure 7, our flare behaved as a typical impulsive flare (or Class B flare in the hard X-ray flare classification of Tanaka 1987 and Dennis 1988). As can be seen from the vertical separation of the profiles for the four energy bands in Figure 7, the hard X-ray emission underwent the characteristic soft-hard-soft evolution, peaking in spectral hardness in the peak of the explosive phase. Hard X-ray images from *SMM* and from *Hinotori* have shown that in impulsive flares hard X-ray emission from the feet of the flare loops is most prominent during the explosive phase; during the more gradual phase following the impulsive peak (the phase beginning around 00:02 UT in our flare [Fig. 7]) the hard X-ray emission at the soft end of the spectrum (~ 25 keV) typically becomes more concentrated in a source between the flare ribbons, presumably the tops of the flare loops (Tanaka 1987; Dennis 1988). Therefore, it appears that the thick-target model for the production of the hard X-rays may be roughly valid during the explosive phase, but that after that it may greatly overestimate the electron production rate because then much of the emission may be coming from an essentially thermal source ($\sim 10^8$ K loop tops) rather than from a thick-target nonthermal source (loop feet).

To estimate the total rate of energy expenditure in the flare for the energization of the electrons for the hard X-ray emission, we fitted the HXRBS hard X-ray spectrum with a single power law with low-energy cutoff at 25 keV, and used the thick-target assumption to compute in the usual way (e.g., Tandberg-Hanssen & Emslie 1988) the power P_{thick} in energized electrons required to produce a spectrum of the observed amplitude and slope. The result is plotted in Figure 8. As remarked above, this estimate of the electron power is plausibly accurate to order of magnitude during the explosive phase

FIG. 8.—The power in the ≥ 25 keV electrons required to produce the hard X-ray burst of Fig. 7. This power was calculated by fitting a single power law to the hard X-ray fluxes observed in 15 energy channels (covering the range 24–400 keV) and by taking the thick-target model for deriving the spectrum of source electrons from this hard X-ray spectrum. The two vertical dashed lines bracket the explosive phase as in Figs. 5 and 7.

but may be a strong overestimate at later times. So we will use this estimate only for the explosive phase. In our model, the total rate of magnetic energy consumption $\dot{E}$ is assumed to be twice the power for the production of the $\gtrsim 25$ keV electrons. So, $\dot{E} \sim 2P_{\text{thick}}$ in the explosive phase. Thus, from the observed hard X-ray emission we have (from Fig. 8) that $\dot{E} \sim 10^{29}$ ergs s^{-1} in the peak of the explosive phase of our flare. The thick-target peak power for the electrons that emit the hard X-rays is typically of order 10^{29} ergs s^{-1} in great flares (Lin & Hudson 1976; Ramaty et al. 1980).

3.2. Feasibility of the Model

The imaged observations presented above—the vector magnetogram and the H α filtergrams—fit the basic morphology, motion, and sequence of the standard model for two-ribbon eruptive flares sketched in Figures 1 and 2. The vector magnetogram shows that the preflare magnetic field had an overall bipolar configuration with a channel of strong shear along its polarity inversion line. The H α filtergrams show clear evidence that a flare spray was produced; this indicates that this flare was an eruptive flare in which a chromospheric filament was entrained in the sheared core field that erupted and expanded, exploding open the bipole and becoming a coronal mass ejection. In the explosive phase, the rapidly growing flare ribbons had a four-part, two-pair arrangement. As the flare evolved beyond the explosive phase, the ribbons grew no larger, slowed but continued to spread away from the inversion line, and evolved into a single pair, well separated from the inversion line and linked by postflare loops visible in H α emission. Having established the good morphological, qualitative agreement of the model with this flare, we now proceed to consider the quantitative feasibility of the model in terms of the observed field strength, ribbon length, ribbon speed, and dissipative power in the explosive phase of the flare.

3.2.1. Energy Supply

Fundamental to the model is the idea that the entire flare event, comprised of both the coronal mass ejection and the magnetic energy release and dissipation in the reconnection wall, is driven by the eruptive expansion of the sheared core field (Moore 1988). That is, all of the flare energy is supposed to come from the nonpotential magnetic energy that is in the core field before it erupts. Thus, for the model to be feasible for our flare, the preflare sheared core must contain enough nonpotential magnetic energy. To estimate this initial magnetic energy E_0 of the erupting core field, following Moore (1988), we approximate the preflare core field as a cylinder of length L_0 and radius r_0 , which gives

$$E_0 \sim \pi r_0^2 L_0 \frac{B_0^2}{8\pi}, \quad (5)$$

where B_0 is the average strength of the roughly horizontal magnetic field in the core. For L_0 we take the distance along the inversion line spanned by the inner pair of flare ribbons at the peak of the explosive phase: $L_0 \approx 65,000$ km. For r_0 we take (from the vector magnetogram) half the width of the preflare shear channel: $r_0 \approx 5000$ km. The average field strength in this strip of the vector magnetogram is roughly 1000 G. For these values, equation (5) gives $E_0 \sim 2 \times 10^{32}$ ergs. Thus, we find that the preflare sheared core field did contain a total nonpotential magnetic energy of the order needed to fuel a great flare such as ours.

3.2.2. Reconnection Wall

As we noted in § 3.1, from the three-dimensional form and proportions of the model erupting magnetic field (Fig. 2), it appears that the length l of the turbulent reconnection wall in the explosive phase of the flare should be about the same as the length of each of the inner flare ribbons, which gives $l \approx 40,000$ km at the peak of the impulsive phase. We now proceed to combine this observed length with the other empirical constraining quantities found in § 3.1 to estimate the required vertical extent h and thickness d of the reconnection wall in the explosive phase.

First, from equation (1), we can estimate the strength B_{vert} of the vertical component of the magnetic field flowing into the sides of the reconnection wall. We suppose that the electron density in this flow is roughly that of the preflare corona in the active region; we take $n_e \sim 10^{10}$ cm^{-3} . Densities of this order are typically found from coronal observations of active regions that are not in the act of flaring (Moore & Fung 1972; Vaiana & Rosner 1978). The next question is that of what we should take for the average energy $\mathcal{E}_e$ of the bulk-energized electrons in the reconnection wall, the electrons that make most of the hard X-ray emission as they stream to the chromosphere upon exiting the top and bottom of the reconnection wall. The observed spectrum of hard X-rays from flares decreases steeply with increasing energy; this means that the spectrum of source electrons is also steep, and hence that most of the energy in the source electrons is in the low-energy end of their spectrum. For this reason, and because the spectrum of the energized electrons may extend to somewhat lower energies than the lowest energy (25 keV) hard X-rays that HXRBS could observe, we somewhat arbitrarily take $\mathcal{E}_e \approx 25$ keV = 4×10^{-8} ergs. This value is probably in error by no more than a factor of 2. Equation (1) then gives $B_{\text{vert}} \sim 140$ G. Next, from equation (2), with $v_{\text{ribbon}} \approx 50$ km s^{-1} , $B_{\text{phot}} \approx 1000$ G, and $B_{\text{vert}} \sim 140$ G, we obtain $v_{\text{in}} \sim 350$ km s^{-1} . Finally, with $\dot{E} \sim 10^{29}$ ergs s^{-1} , we estimate h from equation (3): $h \sim 4500$ km. Thus, we find that the reconnection wall should have a vertical extent that is about 1/10 of its length. Although this is shorter relative to the length of the wall than is depicted in Figures 2 and 3, it is quite permissible, whereas an h 10 times greater than l could not be accommodated. That is, the vertical extent of the reconnection wall required by the observations is quite feasible for the flare model.

To finish, we can now use equation (4) to obtain an estimate of the wall thickness. With $B_{\text{vert}} \sim 140$ G and $n_e \sim 10^{10}$ cm^{-3} , the exit speed = $v_{\text{out}} = (V_A)_{\text{vert}}/2^{1/2} \sim 2000$ km s^{-1} . So, from equation (4), $d = (v_{\text{in}}/v_{\text{out}})h \sim 0.18h \sim 800$ km. Thus, we find that the observations require the reconnection wall to have a height-to-thickness ratio of order 5. That is, we find that the required region of turbulent reconnection does have the overall proportions of a long wall, which is entirely compatible with the flare model.

4. SUMMARY AND DISCUSSION

We have found that the standard model for the gross three-dimensional form and action of the magnetic field in two-ribbon eruptive flares is in good accord with the observed large-scale morphology of the preflare vector magnetogram and the observed form and development of the flare ribbons and flare spray in the great flare of 1984 April 24/25. In addition to this global configurational confirmation of the model, the feasibility of the entire flare's being driven by the eruption

of the strongly sheared field from the core of the flare bipole—that is, that core field contained enough nonpotential energy to produce this great flare—is verified to order of magnitude by the vector magnetogram. Finally, the vector magnetogram and the explosive-phase H α and hard X-ray observations together yield an order-of-magnitude estimate of the overall size and form of the turbulent reconnection region under the erupting core flux rope. This empirically constrained volume for the reconnection region is a long wall that fits well within the span and form of the flaring field in the explosive phase of the flare. Thus, the standard model (a single bipole with erupting sheared-field core and turbulent reconnection wall) appears to be an entirely viable model for this great two-ribbon flare.

High time-resolution observations show that the flare explosive-phase hard X-ray and microwave burst is usually largely composed of many overlapping spikes, each ~ 0.3 s in duration (Benz & Aschwanden 1992; Machado et al. 1993). In each of these energy release fragments, 10^{33} – 10^{34} electrons are energized to ~ 25 keV, amounting to a total energy of $\sim 10^{26}$ ergs. LaRosa & Moore (1993) pointed out that such bursts of energized electrons could be produced by turbulent cascade in the flare reconnection wall if in addition to having $n_e \sim 10^{10}$ cm $^{-3}$ and $B_{\text{vert}} \sim 10^2$ G, the eddies at the large end of the turbulence spectrum are 10^8 cm in diameter. The largest eddies could well be about that size because the reconnecting coronal magnetic field is expected to consist of close-packed elementary flux tubes of diameter $\sim 10^8$ cm (Sturrock et al. 1984). The turbulent outflows from the driven reconnection of opposing pairs of these flux tubes—and the largest eddies in these outflows—plausibly would have diameters of the order of the diameters of the tubes. On this basis, LaRosa & Moore proposed that the observed energy release fragments are a natural consequence of the elementary flux tubes in the reconnecting field and of the electron bulk energization by turbulent cascade in the reconnection outflows. Our estimate of the thickness of the turbulent reconnection wall is an upper bound on the diameter of the eddies in the turbulence, an estimate that is independent of any consideration of elementary flux tubes. It is interesting that this separate empirical estimate also gives $\sim 10^8$ cm for the largest eddies. This suggests that the thickness of the reconnection wall is determined by the diameter of the elementary flux tubes making up the reconnecting field and that the resulting wall thickness is of order the tube diameter.

There is an alternative explanation for the thickness of our reconnection wall, one in which the wall thickness does not depend on the elementary flux tubes, but only on the vertical extent of the reconnection region. Parker (1973), from physical reasoning and estimates of the reconnection speeds in solar flares and in Earth's magnetosphere, proposed that the reconnection region should be highly disordered and turbulent (more or less as in our model) and that this would result in the aspect ratio of the reconnection region (d/h in our notation) having a characteristic value in the range 0.1–1 [or, equivalently, that the ratio $v_{\text{in}}/v_{\text{out}}$ should be in this range, or, because $v_{\text{out}} \sim (V_A)_{\text{vert}}$, v_{in} should be somewhat less than $(V_A)_{\text{vert}}$ by a factor in the range 0.1–1]. In the explosive phase of our flare, taking $n_e \sim 10^{10}$ cm $^{-3}$ in the reconnection wall, we found $d/h \sim 0.2$. It could be that n_e was significantly less than 10^{10} cm $^{-3}$ because of the expansion in the magnetic field as it approached the sides of the reconnection wall. We estimate (§ 3.2.2) that the field at the sides of the reconnection wall in the explosive phase was expanded by a factor of ~ 10 . The reduction in density could be less than this due to flow of

plasma along the field lines into the low-density (and hence low-pressure) expanded region on each side of the reconnection wall. So, n_e in the explosive-phase reconnection wall probably was not less than $\sim 10^9$ cm $^{-3}$. In our model for the reconnection wall, h scales as $n_e^{-1/2}$ and d scales as n_e^{-1} , so d/h scales as $n_e^{-1/2}$. Hence, for our model applied to our flare, with $10^{10} \gtrsim n_e \gtrsim 10^9$ cm $^{-3}$, we have $4500 \lesssim h \lesssim 15,000$ km, $800 \lesssim d \lesssim 8000$ km, and $0.2 \lesssim d/h \lesssim 0.5$. Thus, a robust result for our flare is that the aspect ratio d/h of the reconnection region was in the range proposed by Parker (1973).

It is also interesting that the span and form of the erupting magnetic field in the explosive phase of our flare could accommodate a reconnection wall with vertical extent $h \sim 15,000$ km; the reconnection wall would then have roughly the proportions sketched in Figures 2 and 3. If h were $\sim 15,000$ km, then the wall thickness d would be ~ 8000 km, an order of magnitude thicker than the expected widths of the elementary flux tubes entering the reconnection region. This suggests that, rather than being set mainly by the diameter of the elementary flux tubes, the thickness of the reconnection wall may be more a consequence of the turbulence yielding a characteristic aspect ratio of ~ 0.3 . However, even if the turbulent wall is much thicker than an elementary flux tube, the size of the largest eddies in the turbulence might still be set mainly by the diameter of the reconnecting elementary flux tubes as proposed by LaRosa & Moore (1993).

Finally, we point out that the basic scheme of our flare model, the standard model for two-ribbon eruptive flares, permits but does not require that the shear in the magnetic field low along the inversion line decrease during the flare. In any case, as sketched in Figures 1 and 2, the shear along the inversion line is expected to still be large after the flare. The question is whether this shear should be less than it was before the flare. Melrose (1993) argues that the electric current flowing above the photosphere in an active region is a small part of a large circuit that runs to great depths below the photosphere. If so, the huge inductance of this circuit would prevent the total current above the photosphere from changing appreciably during the flare over times short compared to those for gross evolutionary changes in the magnetic field of the active region through emergence or submergence of magnetic field (and its electric current) through the photosphere. Melrose also points out that (in the standard model for eruptive flares) as the twisted core flux rope expands as it erupts, the current flowing along this flux rope decreases along with the magnetic energy in the flux rope. This suggests that as the core rope erupts, the preflare current flowing along it switches to the turbulent reconnection wall and reconnected sheared arcade below the rising core rope. In this case, the energy released by the core eruption would be replaced in the sheared arcade at nearly the same rate by energy carried by the current from below the photosphere, so that the core field after the flare would have practically the same shear as before the flare. Thus, under the plausible assumption that the preflare current system is deep seated, we should expect little or no decrease in the photospheric magnetic shear in even the largest flares. This idea is compatible with the recent observations of Wang et al. (1994) that the photospheric magnetic shear along the inversion line sometimes increases markedly during great flares. In these cases, apparently there is rapid emergence of enough new sheared magnetic field along the inversion line to override the constancy or slight decrease of magnetic shear expected by Melrose.

We thank Jess Smith for providing the H α filtergrams from the USAF SOON station at Holloman Air Force Base. Marcos Machado helped initiate the collaboration between R. L. M. and L. E. O. Jason Porter and Peter Ulmschneider

read the first draft; their comments helped us improve the paper. This work was supported by NASA's Office of Space Science through the Solar Physics Branch of its Space Physics Division.

REFERENCES

- Antiochos, S. K., Dahlburg, R. B., & Klimchuk, J. A. 1994, *ApJ*, 420, L41
 Benz, A. O., & Aschwanden, M. J. 1992, in *Eruptive Solar Flares*, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer-Verlag), 106
 Bruzek, A. 1967, in *Solar Physics*, ed. J. Xanthakis (New York: Interscience), 399
 Cargill, P. J., et al. 1994, preprint
 Chiueh, T., & Zweibel, E. G. 1987, *ApJ*, 317, 900
 Cowling, T. G. 1957, *Magnetohydrodynamics* (New York: Interscience)
 Dennis, B. R. 1988, *Sol. Phys.*, 118, 49
 Dodson-Prince, H. W., & Bruzek, A. 1977, in *Illustrated Glossary for Solar and Solar-Terrestrial Physics*, ed. A. Bruzek & C. J. Durrant (Dordrecht: Reidel), 81
 Forbes, T. G. 1992, in *Eruptive Solar Flares*, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer-Verlag), 79
 Forman, M. A., Ramaty, R., & Zweibel, E. G. 1986, in *Physics of the Sun, 2, The Solar Atmosphere*, ed. P. A. Sturrock, T. E. Holzer, D. M. Mihalas, & R. K. Ulrich (Dordrecht: Reidel), 249
 Hagyard, M. J. 1990, *Mem. Soc. Astron. It.*, 6(2), 337
 Hagyard, M. J., Moore, R. L., & Emslie, A. G. 1984, *Adv. Space Res.*, 4(7), 71
 Hagyard, M. J., Venkatakrishnan, P., & Smith, J. B., Jr. 1990, *ApJS*, 73, 159
 Heyvaerts, J., Priest, E. R., & Rust, D. M. 1977, *ApJ*, 216, 123
 Hirayama, T. 1974, *Sol. Phys.*, 34, 323
 Kahler, S. W., Moore, R. L., Kane, S. R., & Zirin, H. 1988, *ApJ*, 328, 824
 Kopp, R. A., & Pneuman, G. W. 1976, *Sol. Phys.*, 50, 85
 LaRosa, T. N., & Moore, R. L. 1993, *ApJ*, 418, 912
 LaRosa, T. N., Moore, R. L., & Shore, S. N. 1994, *ApJ*, 425, 856
 Lin, R. P., & Hudson, H. S. 1976, *Sol. Phys.*, 50, 173
 Machado, M. E., Moore, R. L., Hernandez, A. M., Rovira, M. G., Hagyard, M. J., & Smith, J. B., Jr. 1988, *ApJ*, 326, 425
 Machado, M. E., Ong, K. K., Emslie, A. G., Fishman, G., Meegan, C., Wilson, R. B., & Paciesas, W. S. 1993, *Adv. Space Res.*, 13(9), 175
 Martens, P. C. H., & Kuin, N. P. M. 1989, *Sol. Phys.*, 122, 263
 Melrose, D. B. 1992, in *Eruptive Solar Flares*, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer-Verlag), 147
 ———. 1993, paper presented at the Kofu Symposium on Coronal Dynamics and Flares, Kofu, Japan
 Moore, R. L. 1988, *ApJ*, 324, 1132
 Moore, R. L., & Fung, P. C. W. 1972, *Sol. Phys.*, 23, 78
 Moore, R. L., Hagyard, M. J., & Davis, J. M. 1987, *Sol. Phys.*, 113, 347
 Moore, R. L., Hagyard, M. J., Davis, J. M., & Porter, J. G. 1991, in *Flare Physics in Solar Activity Maximum 22*, ed. Y. Uchida, R. C. Canfield, T. Watanabe, & E. Hiei (Berlin: Springer-Verlag), 324
 Moore, R. L., & LaBonte, B. J. 1980, in *Solar and Interplanetary Dynamics*, ed. M. Dryer & E. Tandberg-Hansen (Dordrecht: Reidel), 207
 Moore, R. L., & Roumeliotis, G. 1992, in *Eruptive Solar Flares*, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer-Verlag), 69
 Parker, E. N. 1973, *ApJ*, 180, 247
 Ramaty, R., et al. 1980, in *Solar Flares*, ed. P. A. Sturrock (Boulder: Colo. Assoc. Univ. Press), 117
 Spicer, D. S., Mariska, J. T., & Boris, J. P. 1986, in *Physics of the Sun, 2, The Solar Atmosphere*, ed. P. A. Sturrock, T. E. Holzer, D. M. Mihalas, & R. K. Ulrich (Dordrecht: Reidel), 181
 Sturrock, P. A. 1980, in *Solar Flares*, ed. P. A. Sturrock (Boulder: Colo. Assoc. Univ. Press), 411
 Sturrock, P. A., Kaufman, P., Moore, R. L., & Smith, D. F. 1984, *Sol. Phys.*, 94, 341
 Svestka, Z. 1976, *Solar Flares* (Dordrecht: Reidel)
 Svestka, Z., & Cliver, E. W. 1992, in *Eruptive Solar Flares*, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (Berlin: Springer-Verlag), 1
 Tanaka, K. 1987, *PASJ*, 39, 1
 Tandberg-Hanssen, E., & Emslie, A. G. 1988, *The Physics of Solar Flares* (Cambridge: Cambridge Univ. Press)
 Tandberg-Hanssen, E., Martin, S. F., & Hansen, R. T. 1980, *Sol. Phys.*, 65, 357
 Vaiana, G. S., & Rosner, R. 1978, *ARA&A*, 16, 393
 van Ballegoijen, A. A., & Martens, P. C. H. 1989, *ApJ*, 343, 971
 Wang, H., Ewell, M. W., Jr., Zirin, H., & Ai, G. 1994, *ApJ*, 424, 436
 Whang, Y. C. 1992, *ApJ*, 392, 637
 Zirin, H. 1966, *The Solar Atmosphere* (Waltham, MA: Blaisdell)
 ———. 1988, *Astrophysics of the Sun* (Cambridge: Cambridge Univ. Press)
 Zirin, H., & Liggett, M. A. 1987, *Sol. Phys.*, 113, 267