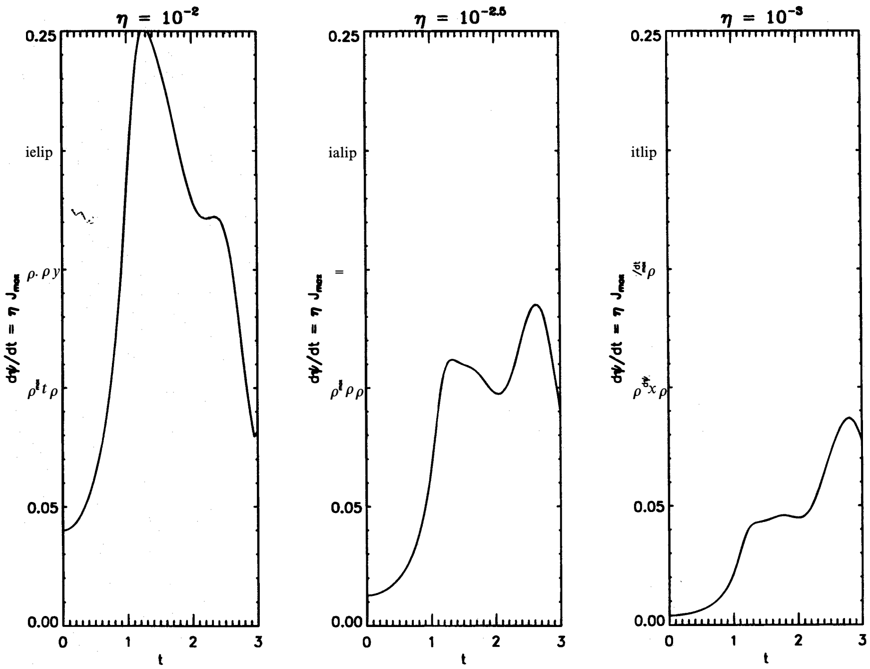

FIG. 6.—Evolution of the reconnection rate, eJneba= ,isa i n the presence o f gas pressure, $\beta = 0.1$, fo r three different resistivities, $\eta = 10^{-2}$, $\eta = 10^{-2.5}$, and $\eta = 10^{-3}$. The peak reconnection rate attained on the initial implosion drops rapidly as η is decreased, because the gas pressure prevents the current sheet from thinning enough to maintain dissipation. It is this drop that is analyzed in Fig. 4. However, a second peak in the reconnection rate occurs when the system bounces back after gas has been ejected from the sheet along the separatrices. The reconnection rate at the second peak drops off more slowly with decreasing resistivity, suggesting that fast reconnection may be possible following the expulsion of gas.

perturbation wave overwhelms the background potential field (Craig & Watson 1992; Craig 1994). We equate this energy to the energy $\langle \frac{1}{2} B_1^2 \rangle$ of the initial perturbation (assumed to cover a substantial volume of space). We then find that, if the system comes to equilibrium without resistive dissipation (as in the "magnetofrictional" collapse to a singular current sheet), the magnetic field at the edge of the current sheet is f bffa fi—fff" c. Since the equivalent equilibrium field strength in the one-dimensional case is just $B_s = \frac{1}{2}$, in the two-dimensional case the magnetic pressure is effectively reduced by the factor B_1 0ϕThe net effect is then to replace β by β/B_{ofi}throughout the analysis. We then find that the condition }B: β requires

$$\beta/B_1 \ll 0.070 . \quad (3.3)$$

Provided this condition is satisfied, the gas trapped in the current sheet should be ejected in a few Alfvén times. (The condition is not satisfied for the example shown in Fig. 6 for which $B_1 \simeq \beta = 0.1$.) Whether *all* the gas is expelled may depend (according to a steady state argument) on the pressure built up in the outflow lobes. However, we also note that the simulations indicate that the ejecta leave behind a partial vacuum in the current sheet. This highly dynamical event could be of major importance. In general, it seems that a major restructuring of the magnetic field has a better chance of producing fast reconnection than a small perturbation.

It is apparent in Figure 6 that a third peak seems to rise between the main peaks. The peaks are caused by the interactions of waves reflecting from the boundaries in both the inflow and outflow region, as noted by Sato et al. (1992), and by Sakai and collaborators (e.g., Sakai & Ohsawa 1987), who also obtain an approximate analytic description of such oscillations. A similar oscillating or steplike structure during the rise to peak current density is seen in the simulations of Strauss (1990), in which a strong axial magnetic field is present, but no gas pressure. All the above authors claim that the reconnection they observe is "fast," but only Strauss investigates the scaling of the reconnection rate with resistivity—unfortunately only over less than a decade in η. The others base their claims on the fact that the reconnection takes place in a few Alfvén times, which we do not believe to be an adequate criterion at the large resistivities typical of numerical simulations. For instance, while we have argued above that gas is ejected from the current sheet, it is not certain that all the gas is expelled. A remnant will have much greater consequences at $\eta = 10^{-8}$ than at $\eta = 10^{-4}$. Nevertheless, condition (3.3) suggests that fast reconnection in the low-β solar corona remains a possibility.

3.5. *Summary*

We have confirmed by analysis and by numerical simulation that the fast reconnection rate of the linear theory, which is valid in the absence of gas pressure and axial magnetic field, and for small perturbation amplitudes, is maintained for large-amplitude perturbations. The nonlinear results agree excellently with the analytic description of one-dimensional dynamic collapse developed by Forbes (1982).

If an appreciable backpressure is exerted by the plasma ($\beta \gtrsim \eta$) or by an axial component of the magnetic field (}B; $\gtrsim \eta$), the current sheet is prevented from thinning, and the efficiency of reconnection on the initial collapse falls to a slow rate. However, there are indications that gas trapped in the current sheet can be subsequently expelled along the separatrices, allowing a faster reconnection rate to be attained ultimately. We have not yet investigated thoroughly the complex dynamics subsequent to the initial implosion.

4. DISCUSSION

In the absence of gas pressure and axial magnetic field, magnetic reconnection is fast, even for large nonlinear perturbations. In this case there is no physical parameter other than resistivity to determine the current sheet thickness, so flux is reconnected as fast as it is carried into the diffusion region.

It is not clear yet whether reconnection remains fast in the presence of significant gas pressure or axial magnetic field. A quasi-steady balance between the pressure of gas (or axial field) swept into the current sheet and the external magnetic forces driving the collapse could be set up, in which the current sheet is not controlled by resistivity and therefore cannot thin enough for fast reconnection. This is what appears to happen on the "first bounce." But gas compressed by the imploding magnetic field then begins to stream from the ends of the current sheet. Provided the magnetic perturbation is large and the plasma β is small, it seems possible that fast reconnection can be ultimately attained. It is possible that the period of gas expulsion from the current sheet corresponds to the "preheating" phase of a flare, and that particle acceleration in the "vacuum hole" left behind by the streams of ejected gas produces the impulsive phase of a flare.

How do our results compare with previous work? The variety of contradictory answers that have emerged to date seems baffling. Previous studies fall into three classes: steady state incompressible, dynamical incompressible, and dynamical compressible. Steady state solutions have either no exterior boundary conditions imposed, "flow through" boundaries, or periodic boundary conditions. Dynamical simulations generally have "closed box" boundaries, with the advantage that the system is isolated and perfectly defined.

Proponents of analytic studies of steady state incompressible reconnection which rely in patching together solutions and which have no exterior boundary conditions imposed (see Priest & Forbes 1992) are confident of fast incompressible reconnection, yet the analyses have been shown to have some fundamental problems (Craig & Rickard 1994; Craig & Henton 1994). Specifically, in the usual sub-Alfvénic approximation neglecting $\boldsymbol{v} \cdot \nabla \boldsymbol{v}$, there is no flow across the separatrices, and so no reconnection. Relaxing this restriction, it is found that a plasma β of at least $\eta^{-1/2}$ is required in the advection region to drive fast reconnection. That is, if the plasma is incompressible throughout, reconnection is driven by thermal, rather than magnetic, forces, and the magnetic energy released is negligible compared to the thermal energy of the plasma. This implies that the incompressible solution can only describe a small volume of the reconnection region: it must ultimately merge into a low β plasma with magnetic pressure comparable to the gas pressure in the sheet.

Numerical studies of incompressible reconnection with periodic boundary conditions (Biskamp & Welter 1980; Biskamp 1986; Deluca & Craig 1992; Craig et al. 1993) have found either that reconnection is slow, or that reconnection which appeared to be fast for large resistivities drops to the Sweet-Parker rate for smaller resistivities ($\eta \lesssim 10^{-4}$). Important criticisms of the boundary conditions used in numerical simulations (Forbes & Priest 1987; Priest & Forbes 1992) do not seem to apply to these periodic cases.

Strauss (1990) shows evidence for fast reconnection in a system dominated by a strong axial magnetic field, with zero gas pressure. However, the minimum resistivity he studies is $\eta \simeq 4 \times 10^{-4}$, approximately the value at which Biskamp & Welter (1980) and Craig et al. (1993) find that incompressible reconnection begins dropping to a slower rate, so the result cannot be regarded as conclusive. Ugai (1993) finds that the introduction of a B_z component does not substantially affect the reconnection rate.

Ofman et al. (1993) study reconnection in a closed box with $\eta = 10^{-4}$, but they did not study the dependence of the reconnection rate on η. They claim that the same (fast) reconnection rate applies in an incompressible gas as in the $\beta = 0$ case, and that reconnection is even faster for $\beta \simeq 0.1$. On the other hand, Sato et al. (1992) claim that compressibility is essential to fast reconnection. Studies which introduce compressibility as a perturbation on incompressible reconnection (Jardine & Priest 1989; Parker 1963) find that compressibility has a minor effect.

"Anomalous" resistivity has been claimed as an essential ingredient for fast reconnection (Ugai 1986, 1992; Yokoyama & Shibata 1994). These authors find that uniform resistivity leads to slow Sweet-Parker reconnection, but that a resistivity which turns on locally when the current density surpasses a threshold yields unsteady Petschek-type fast reconnection.

Finally, we mention that Alfvén shear waves impinging on a neutral point avoid the problem of backpressure encountered in the fast mode waves considered here, but nevertheless do not lead to fast dissipation (Bulanov et al. 1990; Craig & Henton 1995; Craig & McClymont 1996).

Our experience has been that simulations with η larger than 10^{-4} do not provide sufficient separation between the advection and diffusion timescales to indicate behavior in more highly conducting plasmas. Craig & McClymont (1993) found their asymptotic analytic description of linear reconnection to be accurate only for $\eta \lesssim 10^{-6}$. We conclude that reconnection occurring in a few Alfvén times in the case of relatively large resistivity is not a conclusive indication that the reconnection is fast for smaller (realistic) resistivities, and that it is important to examine the dependence of the reconnection rate on η. Since direct numerical simulation of realistic resistivities does not seem to be feasible, it is important to understand the physical processes taking place, and to develop analytic models as a guide to extrapolating simulation results. We also note that the perturbation amplitude is a significant parameter.

We conclude that in a plasma of sensible gas pressure, such as the solar corona, the initial implosion onto the X-point of a magnetic disturbance does not yield fast reconnection. Plasma swept into the current sheet halts the collapse before significant dissipation occurs. If the disturbance is sufficiently large, however, the magnetic pressure of the imploding wave expels the trapped gas from the ends of the current sheet at the local sound speed, allowing the sheet to thin and faster reconnection to occur subsequently. The dynamics of wave interactions are interesting and complex, and not yet fully understood. Truly "fast" reconnection in this situation seems a distinct possibility, but we feel that none of the work to date has proved the case.

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REFERENCES

Biskamp, D. 1986, Phys. Fluids, 29, 1520
Biskamp, D., & Welter, H. 1980, Phys. Rev. Lett., 44, 1069
Bulanov, S. V., Shasharina, S. G., & Pegararo, F. 1990, Plasma Phys. & Controlled Fusion, 32(5), 377
Craig, I. J. D. 1994, A&A, 283, 331
Craig, I. J. D., & Henton, S. M. 1994, ApJ, 434, 192
———. 1995, ApJ, 450, 280
Craig, I. J. D., Henton, S. M., & Rickard, G. J. 1993, A&A, 267, L39
Craig, I. J. D., & McClymont, A. N. 1991, ApJ, 371, L41
———. 1993, ApJ, 405, 207
———. 1996, in preparation
Craig, I. J. D., & Rickard, G. J. 1994, A&A, 287, 261
Craig, I. J. D., & Watson, P. G. 1992, ApJ, 393, 385
Deluca, E. E., & Craig, I. J. D. 1992, ApJ, 390, 679
Forbes, T. G. 1982, J. Plasma Phys., 27, 491
Forbes, T. G., & Priest, E. R. 1987, Rev. Geophys., 25, 1583
Forbes, T. G., & Speiser, T. W. 1979, J. Plasma Phys., 21, 107
Hassam, A. D. 1992, ApJ, 399, 159
Jardine, M., & Priest, E. R. 1989, J. Plasma Phys., 42, 111
Mikic, Z., Barnes, D. C., & Schnack, D. D. 1988, ApJ, 328, 830
Ofman, L., Morrison, P. J., & Steinolfson, R. S. 1993, ApJ, 417, 748
Parker, E. N. 1963, ApJS, 8, 177
Potter, D. 1973, Computational Physics (New York: Wiley)
Priest, E. R., & Forbes, T. G. 1992, J. Geophys. Res., 97, 16,757
Rickard, G. J., & Craig, I. J. D. 1993, Phys. Fluids B, 5, 956
Roache, P. J. 1982, Computational Fluid Dynamics (Albuquerque: Hermosa)
Roumeliotis, G., & Moore, R. L. 1993, ApJ, 416, 386
Sakai, J.-I., & Ohsawa, Y. 1987, Space Sci. Rev., 46, 113
Sato, T., Hayashi, T., Watanabe, K., Horiuchi, R., & Tanaka, M. 1992, Phys. Fluids B, 4, 450
Strauss, H. R. 1990, J. Geophys. Res., 95, 17145
Tsuneta, S. 1993, BAAS, 25, 1177
Ugai, M. 1986, Phys. Fluids, 29, 3659
———. 1992, Phys. Fluids B, 4, 2953
———. 1993, Phys. Fluids B, 5, 3021
Yokoyama, T., & Shibata, K. 1994, ApJ, 436, L197