

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

ACCELERATION OF CHARGED PARTICLES IN MAGNETIC RECONNECTION:
SOLAR FLARES, THE MAGNETOSPHERE, AND SOLAR WIND

M. L. Goldstein

Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center

W. H. Matthaeus

Bartol Research Foundation, University of Delaware

J. J. Ambrosiano

Berkeley Research Associates

Abstract. A possible source of free energy available for accelerating charged particles is conversion of magnetic energy to particle energy in reconnecting magnetic fields. Recent simulations using test particles suggests that reconnection may efficiently accelerate particles to the maximum energies that are observed in several astrophysical contexts. A simple analytic formula is used in conjunction with the simulation results to predict the maximum energy achievable in a particular plasma environment with the result that in solar flares reconnection is capable of accelerating particles to several GeV. In magnetospheric substorms the predicted maximum can reach several hundred keV, and near magnetic sector crossings in the solar wind the maximum energy can approach 100 keV.

Introduction

Magnetic reconnection is thought to be an important source of energetic particles in solar flares and in magnetospheric substorms. While it is relatively straightforward to show that plasma heating can result from magnetic reconnection [see Giovanelli, 1947 and the review by Axford, 1984] acceleration of particles to high energies requires that they spend a significant amount of time close to the strong electric fields expected near an X-type magnetic neutral point in non-steady reconnection. It is generally argued that for X-point configurations that are stationary in time, test particles will remain near the region of strong electric field for a relatively short time [Sonnerup, 1971; Stern, 1979]. Such a scenario probably precludes significant energization of a sub-population to high energies.

Recently we have investigated the behavior of test particles in two-dimensional, incompressible, magnetohydrodynamic (MHD) fields produced from a spectral method simulation of a sheet pinch [Matthaeus and Montgomery, 1981; Matthaeus, 1982; Matthaeus et al., 1984; Matthaeus and Lamkin, 1985]. The nonlinear MHD equations were solved as an initial value problem in which reconnection began when a low level of random-phased noise was added to the sheet pinch configuration. For the duration of the simulation, fluctuations in velocity, current, vorticity

and electric field appeared near the nominal X-point. Small closed magnetic "bubbles" were observed to convect out of the reconnection zone [Matthaeus and Lamkin, 1985]. Associated with these bubbles, magnetic irregularities in the reconnection zone formed multiple X-points. Reconnection proceeded rapidly in these simulations.

A small fraction of the test particles introduced into the simulation fields appeared to get trapped in the vicinity of magnetic bubbles. Because the bubbles remained in the reconnection zone for times of order an Alfvén transit time, they encountered large electric fields capable of accelerating particles to high energies [Matthaeus et al., 1984]. An analytic formula accounting for energization of the test particles was derived in Matthaeus et al. [1984]. In this letter, we use this formula to demonstrate the possibility that reconnection may be capable of accelerating electrons and/or protons to significant energies — several GeV in solar flares and up to an MeV in the earth's magnetotail. In the solar wind near magnetic sector crossings, magnetic reconnection, if it occurs, may produce energetic particles with energies of tens of keV.

Before applying these ideas to heliospheric phenomena, a brief review of the simulations and derivation of the energy formula is necessary. In the simulation the magnetic field \mathbf{B} and the velocity field \mathbf{v} lie in the x-y plane and vary only in that plane. The electric current density, magnetic vector potential, fluid vorticity and electric field are designated by \mathbf{J} , \mathbf{a} , ω and \mathbf{E} , respectively, and lie in the z direction. The Alfvén speed V_a is defined in terms of the arbitrary length scale L , and a transit time for unit distance τ so that $V_a = L/\tau$.

The reconnection simulation used in this study was a 128^2 spectral truncation with an explicit time step of $1/512$. The parameters of the simulation were chosen so that the dimensionless fluid and magnetic Reynolds numbers each equaled 1000. The fields (in the form of $\omega(\mathbf{k},t)$ and $\mathbf{a}(\mathbf{k},t)$) were stored every 10 time steps. Test particles were introduced into these fields at $t=0$ and their three dimensional trajectories were computed in space \mathbf{X} and velocity \mathbf{U} by solving $d\mathbf{X}/dt = \mathbf{U}$ together with

$$d\mathbf{U}/dt = \alpha(\mathbf{U} \times \mathbf{B} + \mathbf{E}) \quad (1)$$

where $\alpha \equiv \Omega\tau$, $\Omega = ZeB/mc$ is the gyrofrequency of

Copyright 1986 by the American Geophysical Union.

Paper number 6L6002
0094-8276/86/006L-6002\$03.00

the test particles, and $\mathbf{E} = -\nabla\phi + \mu\mathbf{j}$ is the electric field from the MHD simulation. The magnetic Reynolds number is $1/\mu$ where μ is the resistivity.

From the MHD simulation, it was found that the average reconnection electric field, in the units of $B_0 V_a$, was $\epsilon \approx 0.1$. As mentioned above, some of the test particles were trapped near small magnetic bubbles for about one Alfvén transit time. It follows from the z-component of eq. (1) that (conservation of canonical momentum)

$$U_z + \alpha a = \text{const}$$

Consequently, after spending approximately one Alfvén transit time trapped in the strong reconnection electric fields associated with the multiple X-points, a particle's velocity change will be $\Delta U_z \approx \epsilon a$. If the initial speed of the particle is assumed to be negligible compared with its final speed, then the maximum kinetic energy of a test particle in this two-dimensional geometry is

$$T_{\text{max}} = (1/2)m(\Delta U_z)^2 = (1/2)\epsilon^2 \alpha^2 m V_a^2 \quad (2)$$

where T_{max} and V_a are in laboratory units and, as before, ϵ is the dimensionless reconnection rate. This expression for T_{max} assumes that there are no boundaries in the z direction.

To apply the results of this simulation to physical situations, it is necessary to make some assumption about the extent of the reconnection zone in the third dimension, perpendicular to the plane of the simulation. The simplest assumption is to allow the accelerating fields to act only until the particle has travelled a distance L in the z direction (assuming that this takes less time than the nonlinear trapping time τ). With that constraint, the estimated time during which particles can be accelerated is $\tau^* = [2/(c\alpha)]^{1/2} L$ provided that $\tau^* < \tau$. Consequently, the maximum energy becomes

$$T_{\text{max}} = m_0 V_a^2 \epsilon (L \omega_p / c) (Z/Z_0) \quad (3)$$

where ω_p , Z_0 , and m_0 are the plasma frequency, charge, and ion mass of the background plasma, respectively. This expression is independent of test particle mass and depends only on the test particle charge. We will use $\epsilon \approx 0.1$ in the examples below, and interpret T_{max} as an approximate upper limit to the acceleration.

In the first test particle experiment $\alpha = 643$ and the maximum particle speed seen was about 64. When α was reduced to 321.5, the highest speed in the simulation dropped to about 30, consistent with the estimate based on eq. (2). We will assume that the scaling argument given above is approximately valid and further assume that particle motion in the third dimension is constrained to a distance L so that eq. (3) becomes an appropriate estimate of the maximum acceleration expected. We now explore briefly the consequences of these assumptions in three physical environments: solar flares, magnetospheric substorms, and interplanetary sector crossings.

Solar Flares

To evaluate eq. (3) for parameters germane to solar flare conditions one must know the ambient

density, n_0 , the magnetic field B_0 far from the current sheet, and the scale size of the reconnection region, L . All of these parameters are relatively uncertain and probably vary considerably from flare to flare but we have chosen values that we feel are representative. We take L to be the size of a coronal loop so that $L \approx 5 \times 10^8$ cm. The density within the loop we take to be $n_0 \approx 10^9$ cm $^{-3}$ and the magnetic field $B_0 \approx 300$ G [see, for example, Forman et al., 1985 and Colgate, 1978] with the result

$$T_{\text{max}} \approx 3 \text{ GeV}$$

In very large flares, solar cosmic rays can be detected by neutron monitors and so have energies of ≈ 20 GeV [Duggal, 1979]. Given the uncertainties in our dimensional analysis arguments, this result suggests that reconnection may in principle be an important mechanism for the generation of very energetic particles. Eq. (3) can be shown to be relativistically correct, although the derivation is then somewhat different. Therefore our results are valid for GeV protons and MeV electrons; however, the simulations that provided the physical motivation for the derivation were not relativistic.

Substorms

The tail of the earth's magnetosphere is also thought to be the site of magnetic reconnection [see the review by Nishida, 1984]. Gross changes in the topology of the tail field during magnetospheric substorms have been associated with observations of energetic protons and electrons [for example, Scholer, 1984]. In contrast to solar active regions, the magnetotail is a low density, low magnetic field plasma. Again the parameters vary greatly depending on where in the tail reconnection occurs. Two likely possibilities are in the near earth tail (at $\approx 15R$) and in the distant tail (at $\approx 50R$). In so far as application of eq. (3) is concerned, the parameters are quite similar, but we shall discuss the two regions separately.

The scale size L in eq. (3) is effectively the limit on a particle's travel in the direction perpendicular to the dawn-dusk meridian plane of the tail. At 50 earth radii the cross tail dimension is approximately $25R$ [e.g. Siscoe et al., 1984] or 1.5×10^{10} cm. For the plasma density in the lobes, we let $n_0 = 2.5 \times 10^{-2}$ cm $^{-3}$ [for example, Schindler, 1985]. The magnetic field intensity in the distant tail near $60R$ has been studied by Meng and Anderson [1974] who found that during slightly disturbed conditions ($K_p > 2$) the average value was ≈ 14 nT. In a more recent study using ISEE-3 data, Slavin et al. [1985] found $B \approx 15$ nT. The Alfvén speed is then 2×10^8 cm/s so that from eq. (3)

$$T_{\text{max}} \approx 500 \text{ keV}$$

Observations of proton and electron energies in the magnetosphere typically extend up to approximately 1 MeV. For example, Baker and Stone [1977a,b] and Baker and Stone [1978] have discussed observations of electrons (and protons) with energies > 200 keV in the magnetotail. They suggest that at least some of the observed electron events come from sites of magnetic reconnection. Reviews of energetic electron and

proton observations in the tail can be found in Bieber [1984], Baker [1984], and Scholer [1984].

Somewhat higher particle energies are predicted from eq. (3) if one assumes that the reconnection zone is in the near tail at $\approx 15 R_e$. There the ambient magnetic field intensity is slightly higher (> 30 nT) [cf. Figure 7 in Baker, 1984] and the cross tail scale size is somewhat smaller ($\approx 20 R_e$) so that from eq. (3),

$$T_{\max} \approx 2 \text{ MeV}$$

Solar Wind

The last region we explore in this letter is the solar wind in the vicinity of magnetic sector crossings [Hundhausen, 1972]. It is not known if magnetic reconnection occurs at sector boundaries, nor are there observations of interplanetary energetic particles whose origin can be traced back to the sector boundaries. Furthermore, from the study of Klein and Burlaga [1980] sector crossings near 1 AU only occasionally contain magnetic null regions. More often the sector crossings resemble tangential discontinuities. Slightly different results have been reported by Behannon et al. [1981] who examined sector crossings using high time resolution magnetometer data from Helios 1. They reported that a notable characteristic of many sector transitions was the decrease in magnitude of B to low, often near-zero values within the current sheet. Another difference seen in the Helios data compared with the 1 AU analysis of Klein and Burlaga was that the sector crossings in the Helios data tended to be thin (thicknesses $\approx 10^9$ cm) whereas Klein and Burlaga [1980] found that the crossings tended to cluster into two groups -- "thin", corresponding to distances of $\approx 10^9$ cm, and "thick" ($\approx 10^{11}$ cm).

In applying eq. (2) to these sector crossings we will assume that the sectors are "thin" and contain current sheets in which $|B| \approx 0$. At 1 AU the proton density is typically 5 cm^{-3} and $B \approx 5$ nT. With $L \approx 10^9$ cm, we find

$$T_{\max} \approx 100 \text{ keV}$$

We are unaware of any observations of energetic particles that provide direct evidence of acceleration at sector boundaries.

Conclusions

In this letter we have illustrated the potential importance of magnetic reconnection in producing energetic particles in several relatively nearby sites of astrophysical interest where in situ measurements can be made. The theory of neutral point acceleration is not as well developed as are other theories of particle acceleration [such as shock acceleration theory -- see Forman and Webb, 1985 for a review] and the foregoing discussion is primarily meant to motivate further research in this area rather than as a proof that acceleration in reconnection is a dominant process in any particular physical environment. There are many limitations to what we have done thus far. For example, we cannot as yet estimate what fraction of the thermal or suprathermal ambient plasma population is likely to be accelerated. To do so is beyond the capabilities of the test particle model used.

Progress has been made, however, on determining the spectrum of the energetic population and that work will be reported in a separate publication.

Acknowledgments. We acknowledge helpful discussions with R. Ramaty, D. Fairfield, L. Burlaga, and R. Lepping. This work was supported in part by a NASA Solar Terrestrial Theory grant to the Goddard Space Flight Center and National Science Foundation Grant ATM-8408449 to the Bartol Research Foundation.

References

- Axford, W. I., Magnetic field reconnection, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 1, American Geophysical Union, Washington, D. C., 1984.
- Baker, D. N., and E. C. Stone, The magnetopause electron layer along the distant magnetotail, Geophys. Res. Lett., **4**, 133, 1977a.
- Baker, D. N., and E. C. Stone, The relationship of energy flow at the magnetopause to geomagnetic activity, Geophys. Res. Lett., **4**, 395, 1977b.
- Baker, D. N., and E. C. Stone, The magnetopause electron layer 1. Observations along the distant magnetotail, J. Geophys. Res., **83**, 4327, 1978.
- Baker, D. N., Particle and field signatures of substorms in the near magnetotail, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 193, American Geophysical Union, Washington, D. C., 1984.
- Behannon, K. W., F. M. Neubauer, and H. Barnstorff, Fine-scale characteristics of interplanetary sector boundaries, J. Geophys. Res., **86**, 3273, 1981.
- Bieber, J. W., Streaming energetic electrons in reconnection events, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 185, American Geophysical Union, Washington, D. C., 1984.
- Colgate, S. A., A phenomenological model of solar flares, The Astrophys. J., **221**, 1068, 1978.
- Duggal, S. P., Relativistic solar cosmic rays, Rev. Geophys. Sp. Sci., **17**, 1021, 1979.
- Forman, M. A., R. Ramaty, and E. G. Zweibel, The acceleration and propagation of solar flare energetic particles, in The Physics of the Sun, edited by P. A. Sturrock, p. 251, D. Reidel, 1985.
- Forman, M. A., and G. M. Webb, Acceleration of energetic particles, in Collisionless Shocks in the Heliosphere: A Tutorial Review, edited by R. G. Stone and B. T. Tsurutani, p. 91, American Geophysical Union, Washington, D. C., 1985.
- Giovanelli, R. G., Magnetic and electric phenomena in the sun's atmosphere, Mon. Not. Roy. Astron. Soc., **107**, 338, 1947.
- Hundhausen, A. J., Coronal Expansion and Solar Wind, Springer-Verlag, 1972.
- Klein, L. W., and L. F. Burlaga, Interplanetary sector boundaries: 1971-1973, J. Geophys. Res., **85**, 2269, 1980.
- Matthaeus, W. H., Magnetic reconnection in two dimensions, Geophys. Res. Lett., **9**, 660, 1982.
- Matthaeus, W. H., J. J. Ambrosiano, and M. L. Goldstein, Particle acceleration by turbulent magnetohydrodynamic reconnection turbulence, Phys. Rev. Lett., **53**, 1449, 1984.

- Matthaeus, W. H., and S. L. Lamkin, Rapid reconnection caused by finite amplitude fluctuations, Phys. Fluids, **28**, 303, 1985.
- Matthaeus, W. H., and D. C. Montgomery, Nonlinear evolution of the sheet pinch, J. Plasma Phys., **25**, 11, 1981.
- Meng, C.-I., and K. A. Anderson, Magnetic field configuration in the magnetotail near $60 R_E$, J. Geophys. Res., **79**, 5143, 1974.
- Nishida, A., Reconnection in the earth's magnetotail: An overview, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 159, American Geophysical Union, Washington, D. C., 1984.
- Schindler, K., Plasmoids in planetary magnetic fields and the solar corona, in Future Missions in Solar, Heliospheric & Space Plasma Physics, edited by E. Rolfe and B. Battick, ESA SP-235, p. 101, ESA Sci. & Tech. Publ., Noordwijk, Holland, 1985.
- Scholer, M., Energetic ions and electrons and their acceleration processes in the magnetotail, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 216, American Geophysical Union, Washington, D. C., 1984.
- Siscoe, G. L., D. G. Sibeck, J. A. Slavin, E. J. Smith, B. T. Tsurutani, and D. E. Jones, ISEE3 Magnetic field observations in the magnetotail: Implications for reconnection, in Magnetic Reconnection in Space and Laboratory Plasmas, edited by E. W. Hones, Jr., p. 240, American Geophysical Union, Washington, D. C., 1984.
- Slavin, J. A., E. J. Smith, D. G. Sibeck, D. N. Baker, R. D. Zwickl, and S.-I. Akasofu, An ISEE-3 study of average and substorm conditions in the distant magnetotail, J. Geophys. Res., **90**, 10875, 1985.
- Sonnerup, B. U. O., Adiabatic particle orbits in a magnetic null sheet, J. Geophys. Res., **76**, 8211, 1971.
- Stern, D., The role of O-type neutral lines in magnetic merging during substorms and solar flares, J. Geophys. Res., **84**, 63, 1979.
- M. L. Goldstein, Code 692, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
- W. H. Matthaeus, Bartol Research Foundation, University of Delaware, Newark, DE 19716.
- J. J. Ambrosiano, Berkeley Research Associates, Springfield, VA 22150.

(Received January 6, 1986;
accepted January 21, 1986.)