ANOMALOUS TRANSPORT INDUCED BY FIELD ALIGNED CURRENTS AND ITS RELATION TO ELECTROMAGNETIC COUPLING

Christian T. Dum
Max-Planck-Institut für Physik und Astrophysik
Institut für extraterrestrische Physik, D-8046 Garching
Federal Republic of Germany

The wealth of detailed observations on transport in turbulent plasmas that has become available over the last decade from laboratory experiments, in situ space craft observations and computer simulation demonstrates that in contrast to classical transport, the various steps in the analysis of anomalous transport, involving microscopic processes and the global dynamics, are closely coupled. It also points to many new, exciting, and truly anomalous phenomena. These statements apply especially to the highly dynamic processes connected with field aligned currents. The usually vast difference in time or length scales must allow for considerable simplications in the analysis, depending on the system at hand, but requires careful consideration of the microscopic or macroscopic physics that of necessity is to be treated in a simplified manner. This point is demonstrated by using a marginal stability approach in a numerical model for field aligned currents and electromagnetic coupling in an extended system. Its aim is to see how energy is supplied to a localized dissipation region from a distant generator and how this dissipation in turn affects the global electro-dynamic structure. In addition to the earth's auroral flux tubes, for which this model was primarily designed, these questions are of importance to other extended current systems in astrophysics. Microscopic processes supporting enhanced dissipation and leading to other truly anomalous processes such as acceleration of selected particle groups are then discussed in relation to the global problem.

The aim of this paper is primarily to describe some of the main issues to be adressed in the talk and to provide some key references. In order to keep the list of references manageable, preference is given to the most recent papers that also contain extensive references to important earlier work in which many ideas may have originated.

APPROACHES TO ANOMALOUS TRANSPORT

The traditional approach to anomalous transport consists of five steps: 1) Identification of a free energy source for wave growth, i.e. the relative drift $u = -J/ne$ between electrons and ions in our case. 2) Selection of a plausible instability, usually the one with the lowest threshold $u_c < u$ for a

M. R. Kundu and G. D. Holman (eds.), Unstable Current Systems and Plasma Instabilities in Astrophysics, 329–340.

given set of plasma parameters, using linear instability theory. 3) Determination of a quasi-steady fluctuation level for the ensuing turbulence, usually from some nonlinear theory for saturation of wave growth. 4) Relation of this fluctuation level to some effective collision frequency ν_{eff} which is supposed to replace the frequency ν_{cl} of Coulomb collisions in the transport relations for the fluid variables. 5) Solution, of the electrodynamic problem for the system at hand in the usual manner, except that ν_{cl} is replaced by ν_{eff}. In spirit this approach exactly follows classical transport theory, and thus may be termed "Enhanced classical transport theory". The effective collision frequency, however, is usually estimated only for the transport process considered to be dominant, anomalous resistivity in our case, and the resulting transport relation corresponds more closely to elementary kinetic theory than the complete transport theory that is available for Coulomb collisions (e.g. Braginskii, 1967).

This traditional approach may give some indication of the possible effects of anomalous transport. The detailed observations that are now available show, however, that the potential of anomalous transport is far greater but also that the five steps listed above, traditionally treated independently, often by different people, are in fact strongly coupled. The dominant instability often switches to other wave modes as the system evolves, depending on how the free energy sources for wave growth are maintained. The fluctuation level, as a result, is more often determined simply by the macroscopic dynamics and the evolution of the microscopic distribution functions, rather than any fancy nonlinear saturation mechanism. Theories of the latter generally assume fixed plasma parameters and (Maxwellian) distribution functions, as do the linear stability calculations that are carried out by so many people in such detail. Scattering of particles by turbulent fluctuations has a speed and angle dependence that strongly depends on the underlying wave mode but in any case is quite different from the velocity dependence of scattering by Coulomb collisions. A major reason for this fact is that in contrast to the very broad and isotropic collisional fluctuation spectrum, turbulent spectra are much more restricted in wave number and nearly always strongly anisotropic. Interaction with these spectra is in essence restricted to particles that satify certain resonance conditions (e.g. Galeev and Sagdeev, 1979). There is no known mechanism in a turbulent, collisionless plasma that would maintain for any length of time the Maxwellian distributions that are generally assumed for computational convenience. Although it is difficult, distribution functions must be determined in order not only to carry out step 4, but also for steps 2 and 3. For example, scattering of electrons by ion acoustic turbulence makes distribution functions nearly isotropic, similar to electron-ion collisions, but does not maintain Maxwellians. An anomalous transport theory for the electrons was developed which in completeness corresponds to classical transport theory (Dum, 1978 a, b). Even in this case, however, transport relations differ in structure and not just in magnitude of the effective collisions frequency, from the corresponding classical relations. Different approaches will be necessary for transport theories connected with other wave spectra.

Laboratory experiments and especially particle simulation experiments show a strong dependence of microscopic processes on macroscopic boundary conditions, e.g. whether, in current driven turbulence, the current or the applied electric field is kept constant (Dum et al., 1974; Dum and Chodura, 1979). They also show invariably that turbulence is of a transient nature. Computer experiments of course have grossly simplified boundary conditions and they cannot handle the vast difference in time or length scales that exists in astrophysical systems. This difference in scales must allow for considerable simplifications in the analyis. Microscopic processes should enter the global dynamics (step 5) only in some averaged sense. All that may matter to lowest order for the global evolution is, for example, a very rapid increase in anomalous transport once some threshold is exceeded. The system will then stay close to marginal stability, often with relaxation oscillations around this state, thus providing on the average the required dissipation, as can be demonstrated explicitly for anomalous resistivity due to ion sound turbulence (Dum, 1981). Thus, in contrast to step 3, which explicitly assumes a quasi-steady dependence of the fluctuation level on the evolving plasma parameters, no steady state is reached, and wave growth will not even enter into the nonlinear regime.

The marginal stability approach to anomalous transport has been used since the early days of plasma physics with various degrees of sophistication and success. It can be applied not only to quasi-steady states with a balance between sources and sinks but also to rapidly evolving systems such as compression by a turbulently resistive shock. The analysis proceeds essentially in the opposite direction from the traditional approach listed above, i.e. it starts with the global dynamics and ends with the microscopic physics (Manheimer and Boris, 1977). The shock wave experiments provide us with other important points for this approach. It has been shown that the unknown coefficient in one of the best known anomalous resistivity formulas would have to be varied by orders of magnitude for agreement with measured shock widths. Agreement with marginal stability for ion sound is reasonable, provided one takes the critical drift velocity for a plasma with high energy ion tails and not the much lower threshold for Maxwellian ions (Eselevich et al., 1971). The instability criterion for Maxwellian distributions in fact becomes irrelevant already very early in the growth phase of the instability, because electrons evolve to a strongly non-Maxwellian distribution for which instability is no longer sustained solely by the current, but largely by effective drifts related to density and temperature gradients (Dum, 1978b), as demonstrated by the experiments of Söldner et al. (1977). Excellent agreement between detailed measurements and a numerical code can be found by taking into account the interrelationship between wave growth and the various anomalous transport processes.

A much simpler model using the marginal stability approach is presented in the following for the global problem of field aligned currents and electromagnetic coupling in extended systems. It uses a nonlinear Ohm's law in which coefficients, although derived from microscopic theory, can be varied in order to check the marginal stability assumption. Other microscopic processes can be included step by step. It should be noted, however, that the total size of the largest particle simulation systems is at most comparable to the numerical grid spacing in our fluid code (Lysak and Dum, 1983). Owing to the high electron mobility along magnetic field lines some intrinsically microscopic features arise for field aligned currents, such as runaway acceleration and formation of nonuniform potential drops, which cannot directly be described by this approach, but for which the macroscopic model provides the proper boundary conditions. An ad hoc model of anomalous resistivity has recently been used by Sato and Hayashi (1979) in a numerical study of externally driven reconnection. The current flows perpendicular to the magnetic field in this case. Although anomalous resistivity is the primary cause for abrupt onset of reconnection, the key features of the process are ultimately controlled by the boundary conditions. This can be verified by varying the resistivity law, see also Ugai (1982).

SYSTEMS WITH FIELD ALIGNED CURRENTS

Strictly speaking, a system with field aligned currents corresponds to non-uniform magnetic fields

$$\nabla \times \underline{B} = (4\pi/c)\underline{J}_{\parallel} = \alpha \, \underline{B}$$

so called force free configurations, that are considered to be of great importance in astrophysics for two reasons. The equation of motion

$$\rho(d\underline{u}/dt)+\nabla.\underline{\underline{P}} = (\underline{J}/c)x\underline{B} = \nabla.\left[(B^2/8\pi)\underline{\underline{I}}-(\underline{BB}/4\pi)\right]$$

implies that near equilibrium configurations with small ratios $\beta = 8\pi n(T_e + T_i)/B^2$ of plasma and magnetic pressure must be largely force free. Also, such a magnetic field pattern contains an excess energy over a system with current free, potential magnetic field. By a change in the configuration some of this energy may be released to produce solar flares (Gold and Hoyle, 1960; Barnes and Sturrock, 1972). More generally, we consider currents that are essentially along an ambient magnetic field B_o, such that the selfconsistent magnetic field produced by the current can be neglected to lowest order. In the laboratory B_o is produced by external field coils in order to confine the plasma. The internal magnetic field of planets provides the ambient magnetic field for the surrounding plasma, e.g. the earth's ionosphere and lower magnetosphere. The interplanetary solar magnetic field ($\nabla xB \approx 0$) carried by the solar wind, plays of course an increasingly important role in the more distant magnetosphere. Interaction with the solar wind not only determines the shape of the magnetosphere but also leads to exciting events, magnetospheric substorms, in which this shape undergoes sudden transitions (Akasofu, 1977). The solar wind, as modulated by solar activity, provides the primary energy input, with secondary dynamos related to reconnection of magnetic field lines in the distant magnetotail. Geomagnetic disturbances and the spectacular auroral displays are manifestations of these impulsive events in the earth's polar regions (Kan, 1982; Sato, 1982). High latitude magnetic field lines are thus transmission lines for an extended electromagnetic system with a magnetospheric generator, field aligned currents and an ionospheric load, where closure of the current is through Pedersen and Hall currents perpendicular to the ambient magnetic field. According to ideal MHD, the electric field satisfies $\underline{E}+(\underline{u}/c)\times\underline{B} = 0$, implying that $E_{\parallel} = 0$ and that convection is perfectly mapped along the magnetic flux tubes, if it is also assumed that the electric field is potential, $E = -\nabla\phi$. These assumptions provide a reasonable description of the global current system, during quiet periods. Some potential drop is expected to be present also in this case. It is connected with the injection of various particle populations at the magnetospheric and ionospheric ends of the flux tubes, similar to sheath effects in laboratory devices, and the electric field that is required to overcome the magnetic mirror force in converging flux tubes (Chiu and Schulz, 1978; Kan, 1982).

The observation of energetic particles with energies much above thermal level, e.g. 10 keV as compared to thermal energies of less than 1 eV for electrons causing aurora, and especially the more recent, detailed in situ measurements of particles and electromagnetic fields by satellites with polar orbits and of apogees ranging from about 8000 km (Mozer et al., 1981) to 1500 km (Burke et al., 1980) demonstrate, however, that both assumptions fail for active periods. The fields are not static, but correspond to electromagnetic low frequency pulsations that propagate along the magnetic flux tubes, i.e. shear Alfvén waves. There are also regions of intense parallel electric fields that not only should accelerate particles but also lead to a partial decoupling of magnetospheric and ionospheric convection. In the same hightly localized regions it can be shown that field aligned currents are sufficiently intense to excite microinstabilities. Indeed, intense turbulence is observed, that correlates reasonably with the intensity of field aligned currents. Since waves, such as electrostatic ion cyclotron waves are destabilized by low energy electrons and not directly by the current, and other nonthermal features such as ion beams are often present which could also have a cause or effect relationship to these waves, identification of the free energy sources is not unambiguous however (Cattell, 1981). Intense escaping radio emission, auroral kilometric radiation is also closely related to the auroral particle acceleration process (Lee et al., 1980; Gurnett and Anderson, 1981). From what has been said already it is clear that these microscopic processes must be seen in conjunction with the global problem.

Some of the same basic microscopic and electrodynamic processes that operate in the earth-solar wind interaction for auroral regions, also operate in the interaction of Jupiter's moon Io with the Jovian magnetosphere-ionosphere. This interaction plays an important role in Jovian decametric radiation. The recent Voyager 1 and 2 encounters with Jupiter have shed new light on these processes and significant advances have been made in our understanding. Radiation is due to accelerated particles, similar to the processes along auroral flux tubes. Field aligned currents and electric fields are generated, but in this case by Io's rapid motion through the Jovian magnetic field which at Io's orbit is embedded in a dense plasma torus. The rapid motion of Io in this environment invalidates earlier, static current circuit models. Instead, a standing pattern of Alfvén waves is excited which provides the electromagnetic coupling and carries the field aligned currents (Neubauer, 1980; Goertz, 1980; Gurnett and Goertz, 1981).

It is not intended to enter into a discussion of the merits of the many solar flare models. For an excellent recent review, see the articles edited by Priest (1981). There is general agreement that the flare energy is derived from largely force free current carrying magnetic field configurations. Coronal currents are related to photospheric motions that twist the flux tubes (e.g. Heyvaerts, 1974). Whether this process is directly reponsible for the sudden energy release (Piddington, 1974) or whether this energy release is related to newly emerging flux that triggers impulsive reconnection in narrow current sheets (Heyvaerts et al., 1977) does not matter for our purpose. In both cases, the sudden changes that occur in the configuration must be communicated between photosphere and low corona by shear Alfvén waves propagating along the flux tubes. In the first type of model, Alfvén waves play a fundamental role, but they are also expected to be excited by the sudden expansion of the current sheet in the second type of model and perhaps trigger an additional release of energy in other parts of the system . Direct disruption of field aligned currents as envisioned by Alfvén and Carlquist (1967) also would produce Alfvén waves. Finally, pulsars are assumed to be rotating neutron stars which provide us with a very different range of physical parameters and fascinating new phenomena. Field aligned currents and two stream instabilities are also thought to be of importance to the electrodynamics and the radiation from these objects (Sturrock, 1971).

A MODEL FOR ELECTRODYNAMIC COUPLING IN EXTENDED FIELD ALIGNED CURRENT SYSTEMS

Our model for electromagnetic coupling (Lysak and Dum, 1983) derives from the extensive observations made along auroral magnetic field lines and the approach to anomalous transport outlined here and in a previous paper (Dum, 1981). In its present simple form it is, however, designed mainly for an answer to some fundamental questions concerning current driven turbulence in extended system. The aim is to see how energy is supplied from a distant generator to a localized dissipation region and how this dissipation in turn affects the global electromagnetic structure. As demonstrated above, these questions are not only of importance to the global aspects in a number of extended current systems, but also are a neccessary input for a study of the microscopic processes connected with field aligned currents.

The information on transient phenomena in an extended current system such as the earth's magnetosphere-ionosphere must be carried by low frequency hydromagnetic waves. Shear Alfvén waves are the only credible candidate for this purpose. Even for wave vectors with large angles to be magnetic field, the group velocity for energy transport is essentially along the magnetic field. These oblique wave modes carry the field aligned current. It is agreed that Pi 2 pulsations with periods between 40 and 150 sec are transient Alfvén waves that are directly associated with the magnetospheric substorm onset and auroras as they travel along magnetic flux tubes (Southwood and Stuart, 1979; Baumjohann and Glassmeier, 1983). A number of models for electromagnetic magnetosphere-ionosphere coupling have seen constructed on this basis (e.g. Mallinckrodt and Carlson, 1978;

Nishida 1979). More generally, any disturbance along the field lines, wether it is the release of an artificial ion cloud (Scholer, 1970), modifications of ionospheric conductivity (Maltsev et al., 1977; Sato, 1982) or sudden changes of resistivity along the field line due to some anomalous process (Lysak and Dum 1983; Arykov and Maltsev, 1983) must create shear Alfvén waves, bouncing between the origin of the disturbance and the northern and southern ionospheres. For extended structures, the electromagnetic field is across the magnetic field, according to ideal MHD. It has been pointed out by Fejer and Kan (1969) that highly oblique waves must also produce a field aligned electric field, that is related to kinetic effects such as inertia and Landau damping (see Hasegawa and Uberoi, 1982 for a recent review). These electric fields may be of some importance in the narrow structures corresponding to auroras (Goertz and Boswell, 1979).

To produce greatly enhanced parallel electric fields in localized acceleration regions, as required by observation, other effects which are connected with an instability of the field aligned current must be considered, however. We consider electrostatic ion cyclotron waves which, as has been shown by many in situ observations, are driven to large turbulence levels in these regions. Very similar fluctuation levels are observed in ingeniuous laboratory experiments (Corell et al., 1975; Böhmer and Fornaca, 1979) in, even for a parent, amazingly detailed agreement with nonlinear theory (Dum and Dupree, 1970). For the auroral acceleration zone, boundary conditions for particles and the current are likely different in some respects from the laboratory experiments and thus should be studied in more detail.

For definiteness we choose an anomalous resistivity law derived from the nonlinear theory of ion cyclotron waves (Dum, 1981). However, any other threshold dependent sink for the Alfvén wave energy, e.g. double layers, would modify the propagation of Alfvén waves in a similar manner. This point, in agreement with our discussion of marginal stability, can be demonstrated by a series of numerical experiments in which the amplitude, wave form and perpendicular wavelength of the current generator and the parameters of the dissipation region, including the anomalous resistivity law are varied (Christiansen et al., 1982). Due to self regulatory macroscopic effects, total voltage drops and dissipation become remarkably insensitive so some of these details. The basic effect on the global electrodynamic structure is a partial decoupling of the generator from the ionospheric load with multiple wave reflections from the dissipation region and the ionosphere (Lysak and Dum, 1982). In the absence of anomalous dissipation, ionospheric reflection would be the only process that eventually can establish a steady state electrostatic potential structure. Many bounces of the waves between the generator and the ionospheres would be required, however, owing to large ionospheric conductivity. In the presence of an anomalous dissipation region this process takes place much faster. Nearly electrostatic potential structures may be established for field lines in contact with the enhanced dissipation region. Details depend, however, also on boundary conditions at the generator. The model has been extended to include a moving generator or equivalently plasma convection normal to the magnetic field lines. Feedback to the generator is naturally much weaker in this case. The electric field structure stays, however, essentially electromagnetic, with large enhancements of the parallel electric field in the localized dissipation region. The interference pattern produced by a moving generator and multiple wave bounces between the dissipation region and the ionosphere corresponds to the narrow structures associated with discrete auroral arcs, in an Alfvén wave model of auroral arc formation by Haerendel (1982). Its key features can be examined with our numerical code. We have extended the uniform magnetic field model to include dipole-like ambient magnetic fields and cross tail currents near open field lines. The code thus contains the mapping of steady state structures along converging magnetic flux tubes. The variation of Alfvén speed and critical drift velocity for instability with height arises now naturally from the ambient non-uniform density and magnetic field profiles.

The model still leaves room for many improvements. The inclusion of heating in the dissipation region should lead to a self-consistent evolution of the critical drift velocity for instability. This is likely to cause repeated excitation and self-quenching of current driven instabilities over small temporal or spatial periods, if heat conduction is also included. For larger ratios of magnetic to plasma pressure, pressure effects should also be included for wave propagation. The need for an improved treatment of the generator is indicated by the observed feedback from the dissipation region. Details depend, however, on the specific system to be considered.

MICROSCOPIC PROCESSES AND CONCLUDING REMARKS

Microscopic processes should be discussed in relation to the global problem of field aligned currents. Fairly recent reviews of microscopic processes supporting anomalous resistivity have been given by Papadopoulos (1977) and Dum (1981). Heyvaerts (1981) has given an extensive review of microscopic processes related to particle acceleration in solar flares. We thus confine ourselves to mentioning a few very recent developments and concluding remarks relating to the topics that have been discussed in this paper.

We discussed the propagation of electromagnetic signals and currents along magnetic flux tubes. Propagation by hydromagnetic shear Alfvén waves bears great resemblance to wave propagation on metallic transmission lines, the reflection processes included. It is also assumed that the speed of the current carrying particles is far smaller than the phase speed of wave propagation. For a copper wire this is trivial, but for the plasma it means restriction to electron thermal velocities below the Alfvén speed, i.e. ratios of plasma pressures to magnetic pressure, smaller than the electron-ion mass ratio. This assumption can easily be relaxed for kinetic Alfvén waves,with minor effects on wave propagation. For the localized dissipation region with turbulence driven by field aligned currents, the particle populations supporting this current and the turbulence must be examined in detail, however.

It appears unlikely that the plasma in the dissipation region, which for the earth's auroral field lines is at roughly 6000 km altitude retains a perfect memory of boundary conditions at distant sources of particle injection, as is implied by laminar double layer models for potential drops. For computer simulations and laboratory experiments where boundaries are much closer and can be carefully tailored this is much more likely. These structures are nevertheless, even in these cases, associated with intense small scale turbulence. This is in sharp contrast to the purely laminar solutions of the Vlasov equation that are usually considered for an explanation (see e.g. the experiments of Guyot and Hollenstein, 1983; Hollenstein and Guyot, 1983). The problem of particle supply nevertheless is important in connection with low frequency current driven instabilities in a magnetized plasma, such as ion cyclotron waves. Conventional quasilinear theory would predict very rapid stabilization by plateau formation in the low energy electron distribution. This is confirmed by particle simulations in a homogeneous plasma. If fresh particles are injected at the boundary this process still occurs, but subsequent quenching of waves by interaction with the ions in the heated regions allows a step by step spread of the dissipation zone (Okuda and Ashour-Abdalla, 1983). Mechanisms for the spreading of microscopic dissipation processes in solar flares are reviewed by Heyvaerts (1981).

A conflict between laminar and turbulent theories for electric fields associated with field aligned currents arises only, if by analogy with a metallic conductor, one assumes enhanced steady state resistivity for current driven instabilities. The large drifts required for such instabilities or double layer mechanisms represent a very strong perturbation of the system. In contrast, perturbations introduced even by sizable currents in metallic conductors are quite negligible. This fact and high electron mobility along the magnetic field make an intermittent process with periods of nearly free acceleration much more likely for low density plasmas (Dum, 1981).

We should still discuss macroscopic effects of turbulence on the current carrying plasma column such as macroscopic stability, heat flow and filamentation of current channels, in more detail. Instead, we like to end on a note of curiosity. The pinching process in a tiny laboratory plasma (Bykowskii and Lagoda, 1982) is explained by the merging of current filaments with oppositely directed axial magnetic fields, which bears a striking resemblance to the solar flare model proposed by Gold and Hoyle (1960). In the region of reconnection intense current driven ion sound turbulence is assumed to build up. Changes in the current, intense ion fluxes and microwave radiation give evidence for this process.

REFERENCES

Akasofu, S.-I.: 1977, Physics of magnetospheric substorms, Reidel, Dordrecht.

Alfvén, H., Carlquist, P.: 1967, Sol. Phys., 1, 220.

Arykov, A.A., Maltsev, Yu.P.: 1983, Planet. Space Sci. 31, 267.

Barnes, C.W., Sturrock, P.A.: 1972, Astrophys. J. 174, 659.

Baumjohann, W., Glaßmeier, K.H.: 1983, subm. Planet. Space Sci.

Böhmer, H., Fornaca, S.: 1979, J. Geophys. Res. 84, 7239.

Braginskii, S.I.: 1967, in M.A. Leontovich (ed.), Reviews of Plasma Physics, Consultants Bureau, New York, Vol. I., p. 205.

Braginskii, S.I.: 1967, in M.A. Leontovich (ed.), Reviews of Plasma Physics, Consultants Bureau, New York, Vol.I, p. 205.

Burke, W.J., Hardy, D.A., Rich, F.J., Kelley, M.C., Smiddy, M., Shuman, J.: 1980, Geophys. Res. 85, 1179.

Bykowskii, Yu.A., Lagoda, V.B.: 1982, S. Phys. JETP 56, 61 (Zh. Eksp.Teor. Fiz. 83, 114).

Cattell, C.: 1981, J. Geophys. Res. 86, 3641.

Chiu, Y.T.: Schulz, M.: 1978, J. Geosphys. Res. 83, 629.

Christiansen, P.J., Dum, C.T., Lysak, R.L.: 1982, to be publ.

Correll, D.L., Rynn., Böhmer, H.: 1975, Phys. Fluids 18, 1800.

Dum, C.T.: 1978a, Phys. Fluids 21, 945.

Dum, C.T.: 1978b, Phys. Fluids 21, 956.

Dum, C.T.: 1981, in S.I. Akasofu and J.R. Kan (ed.), Physics of Auroral Arc Formation, Geophys. Monograph Ser., AGU, Washington, p. 408.

Dum, C.T., Chodura, R.: 1979, in P.J. Palmadesso and K. Papadopoulos (ed.), Wave instabilities in Space Plasmas, Reidel, Dordrecht.

Dum, C.T., Dupree, T.H.: 1970, Phys. Fluids 13, 2064.

Dum, C.T., Chodura, R., Biskamp, D.: 1974, Phys. Rev. Letters 32, 1231.

Eselevich, V.G., Eskov, A.G., Kurtmullaev, R.Kh., Malyutin, A.I.: 1971, Sov. Phys. JETP, 33, 898 (Zh. Eksp. Theor. Fiz. 60, 1658, 1971).

Fejer, J.A., Kan, J.R.: 1969, J. Plasma Phys. 3, 331.

Goertz, C.K.: 1980, J. Geophys. Res. 85, 2949.

Goertz, C.K., Boswell, R.W.: 1979, J. Geophys. Res. 84, 7239.

Gold, T., Hoyle, F.: 1960, Mon. Not. Roy. Astr. Soc. 120, 89.

Gurnett, D.A., Anderson R.R.: 1981, in S.-I. Akasofu , J.R. Kan (ed.) Physics of Auroral Arc Formation, Geophys. Monograph Ser., AGU, Washington, p. 341 .

Gurnett, D.A., Goertz, C.K.: 1981, J. Geophys. Res. 86, 717.

Guyot, M., Hollenstein, Ch.: 1983, Phys. Fluids 26, 1596.

Haerendel, G.: 1983, in B. Hultquist, T. Hagfors (ed.), High Latitude Space Plasma Physics, Plenum, London.

Hasegawa, A., Uberoi, C.: 1982, The Alfvén Wave, Tech. Inform. Center, U.S. Dep. of Energy.

Heyvaerts, J.: 1974, Sol. Phys. 38, 419

Heyvaerts, J.: 1981, in E.R. Priest (ed.), Solar Flare Magnetohydrodynamics, Gordon + Breach, New York, p. 429

Heyvaerts, J., Priest, E.R., Rust, D.M.: 1977, Astrophys. J. 216, 123.

Hollenstein, Ch., Guyot, M: 1983, Phys. Fluids 26, 1606.

Kan, J.R.: 1982, Space Sci. Rev. 31, 71.

Lee, L.C., Kan, J.R., Wu, C.S.: 1980, Planet. Space Sci. 28, 703.

Lysak, R.L., Dum, C.T.: 1983, J. Geophys. Res. 88, 365.

Mallinckrodt, A.J., Carlson, C.W.: 1978, J. Geophys. Res. 83, p. 1426.

Maltsev, Yu.P., Lyatsky, W.B., Lyatskaya, A.M.: 1977, Planet. Spcae Sci. 25, 53.

Manheimer, W., Boris, J.P.: 1977, Comments Plasma Phys. Cont. Fusion 3, 15.

Mozer, F.S., Catell, C.A., Hudson, M.K., Lysak, R., Termin, N.N., Torbert, R.B.: 1981, Space Sci. Rev. 27, 155.

Neubauer, F.M.: 1980, J. Geophys. Res. 85, 1171.

Nishida, A.: 1979, J. Geophys. Rs. 84, 3409.

Papadopoulos, K.: 1977, Rev. Geophys. Space Phys. 15, 113.

Piddington, J.H.: 1974, Sol. Phys. 38, 465.

Priest, E.R. (ed.): 1981, Solar Flare Magnetohydrodynamics, Gordon + Breach, New York.

Okuda, H., Ashour-Abdalla, M.: 1983, J. Geophys. Res. 88, 899.

Sato, T.: 1982 in A. Nishida (ed.) Magnetospheric Physics, Reidel Dordrecht, p. 197.

Sato, T., Hayashi, T.: 1979, Phys. Fluids 22, 1189.

Scholer, M.: 1970, Plan. Space Sci. 18, 977.

Söldner, F., Dum, C.T., Steuer, K.H.: 1977, Phys. Rev. Letters 39, 194.

Southwood, D.J., Stuart, W.F.: 1979, in S.I. Akasofu (ed) Dynamics of the Magnetosphere, Reidel, Dordrecht, p. 341.

Sturrock, P.A.: 1971, Astrophys. J. 164, 529.

Ugai, M.: 1982, Phys. Fluids 25, 1027.

DISCUSSION

Kennel: Could you tell us what physical processes set the transverse (perpendicular to B) scale of the electron acceleration region in your Alfvén wave reflection model?

Dum: Primarily, the scale is set by the generator. The large effective collision frequency in the acceleration region leads to diffusion and, thus, broadening of this region. Also, reflection from the acceleration region and the ionosphere and the resulting interference between wave trains affect the complex pattern in this region. Reflection from the acceleration region is strongest for small scales and large current densities.

Kundu: I just would like to know more details about the experiment that was made to simulate the flare model of Gold and Hoyle. Specifically, I'd like to know if they should observe radiation at microwaves alone - why not over a much broader range of wavelengths? In our VLA observations, we detected a quadrupole structure only because we were observing at 6 cm.

Dum: No details on the radiation spectrum are given. Comparing with other experiments, I assume the spectrum was fairly broad. The experiment was designed to study filamentation for intense currents. The explanation for the collapse of filaments (pinching) apparently is independent of Gold and Hoyle's model, but bears a striking resemblence.