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About FPPT-4

The International Conference on the Frontiers of Plasma Physics and Technology (FPPT-4) was organized jointly by the Central Department of Physics, Tribhuvan University, Kirtipur, Nepal; Department of Natural Sciences (Physics), Kathmandu University, Dhulikhel, Nepal; National Research Institute for Applied Mathematics, Bangalore, India; and Università degli studi di Milano-Bicocca, Milano, Italy during April 6-10, 2009 at Hotel Yak and Yeti, Durbar Marg, Kathmandu, Nepal. The Conference was supported by the Abdus Salam International Centre for Theoretical Physics (ICTP), Italy; CZT Technologies, Lawrence (KS), USA; Institute for Plasma Research, Gandhinagar, India; Instituto de Fusión Nuclear (DENIM), Universidad Politécnica de Madrid, Spain; International Atomic Energy Agency (IAEA), Vienna, Austria; Ministry of Environment, Science and Technology (Government of Nepal); Nepal Tourism Board; and University Grants Commission, Nepal.

This was the 4th conference in the series of "International conference on the Frontiers of Plasma Physics and Technology" and the series is being organized in different developing countries to encourage a large number of local researchers to participate in the conference. The earlier three conferences were held in Bangalore 2002, Goa 2005 (India) and Bangkok (Thailand) in 2007. This series is planned to provide a unique opportunity to the researchers to directly interact with the worldwide experts and acquaint with the latest research topics.

The Conference was attended by **123 participants from 28 different countries** out of which 41 were the local participants (from Nepal). Altogether **67 oral talks** and **44 posters** were presented during 11 Scientific Sessions and 1 poster session.

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The Earth's Magnetosphere as a Key to the Plasma Universe

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ABSTRACT

In situ measurements in the Earth's magnetosphere have led to a substantial and ongoing revision of our understanding of cosmic plasmas. The real cosmic plasmas behave in ways different than predicted by traditional idealized models in respects as fundamental as plasma dynamics, conduction of electric current and energization of charged particles. As almost all (known) matter in the Universe is in a state of magnetized plasma, this is an important basis for interpretation of astrophysical phenomena that are accessible only to remote observation. The magnetosphere contains plasma populations covering more than eight powers of ten in density and in equivalent temperature and is the venue of a number of fundamentally important plasma physical processes, which are studied in detail with space instrumentation. Ubiquitous features of cosmic plasmas are their ability to generate high energy particles and to rapidly release large amounts of magnetically stored energy. In these processes, as well as in plasma dynamics in general, a key role is played by the electric field, which is difficult or impossible to measure remotely. In the Earth's magnetosphere it is accessible to *in situ* measurements and even active experimentation. Of particular importance is the existence of magnetic-field aligned electric fields, which were considered non-existent on the basis of idealized models but have proved to play a key role both in acceleration processes and in plasma dynamics.

Key words: Magnetosphere, Solar wind, Cosmic plasma, Plasma universe

INTRODUCTION

Of the *known* matter in the Universe almost all is in the plasma state, and all astrophysical phenomena take place in a plasma environment. This led 1970 Nobel Laureate Hannes Alfvén to pronounce a new paradigm, for which he coined the term *Plasma Universe* (Alfvén, 1986).

For our understanding of the Plasma Universe it has been unfortunate that naturally occurring plasma is rare on the Earth, and until not so long ago, the technical capabilities of producing plasmas artificially were very limited. Therefore the empirical basis for understanding the plasma state, and especially the cosmic plasma, was

correspondingly limited. Two events drastically changed this state of affairs.

1) The thermonuclear research effort provided the capability of producing high temperature plasmas in the laboratory. This greatly extended the parameter range in which an empirical basis could be laid, and led to new and sometimes surprising insights into the behavior of matter in the plasma state. Modern thermonuclear research can benefit from a close interplay between experimental and theoretical research in solving plasma physical problems vastly more complex than envisioned in classical plasma theory.

2) Space technology made it possible to place scientific instruments outside the Earth's

atmosphere. This had two important consequences. One is that it became possible to make remote observations of astrophysical objects using the entire electromagnetic spectrum instead of only the visual and radio windows that were accessible before. This has led to dramatic advances in observational astrophysics and provided us with breathtaking images that give the Plasma Universe a face.

It also became possible to perform *in situ* measurements and even active experiments in the real cosmic plasma that surrounds the Earth. This led to an enormous further widening of the empirical basis, not only in terms of parameter range covered but also in terms of natural plasma processes available for investigation.

The access to the cosmic plasma immediately gave dramatic results even with primitive instrumentation. A rocket borne electron spectrometer (McIlwain, 1960) revolutionized our knowledge of the auroral primary electrons and a Geiger counter on the satellite Explorer 1 revealed that the forbidden Størmer orbits in the geomagnetic field were not empty but populated with magnetically trapped high energy electrons and ions that form the Van Allen radiation belts (Van Allen and Frank, 1959). A magnetometer showed that the Earth's magnetic field does not become more and more dipole-like with distance, but is abruptly terminated on the dayside at about ten Earth radii (Cahill and Amazeen, 1963), so as to form what we now call the magnetosphere. Since then, an impressive evolution of space instrumentation has given us tools to measure all relevant properties of particles, fields and waves in our

own magnetosphere, in the solar wind and to some extent in the environments of other planets in our solar system. Even the distribution of neutral atoms can be imaged remotely using the ENA (Energetic Neutral Atoms) technique, based on detection of energetic neutral atoms formed in charge exchange reactions (Williams *et al.*, 1992).

THE EARTH'S MAGNETOSPHERE

The cosmic plasmas most readily available for *in situ* observations and experimentation are the Earth's own magnetosphere and the surrounding solar wind. It is therefore fortunate that the magnetosphere contains a rich variety of plasma populations with densities ranging from more than 10^{12} m^{-3} in the F-region of the ionosphere to less than 10^4 m^{-3} in the polar plumes, and equivalent temperatures from about 10^3 K in the low ionosphere to more than 10^7 eV in the radiation belts. Even more importantly, this accessible cosmic plasma is the site of numerous and complex plasma physical processes.

A basic reason why the magnetospheric plasmas are so active is the coupling that the geomagnetic field imposes between the hot thin plasma in the outer magnetosphere, which is dynamically coupled to the solar wind dynamo, and the cool, dense ionospheric plasma, which is tied by friction to the Earth's rotating atmosphere. This situation causes a complex exchange of mass, momentum and energy between the regions. A key role in this exchange is played by electric currents that connect the ionosphere with the outer magnetosphere and ultimately the solar wind.

The exchange of matter is selective, so that the chemical composition of ionospheric plasma in the outer magnetosphere is very different from that in its region of origin (Hultqvist, 1983). This efficient chemical separation was unexpectedly discovered in the near-Earth plasma but should take place in other cosmic plasmas, too.

The early exploration of the magnetosphere taught us how easy it is to get lost for lack of a sufficiently solid empirical basis. For example, even after ground-based observations of whistler waves had revealed the existence of a space plasma above the ionosphere, none of the complexities of the real space plasma were anticipated. On the basis of generally accepted theories, it was believed that the nearly collisionless cosmic plasma would behave essentially as an ideal MHD medium. As a consequence, the electric field was considered to be a secondary parameter of little importance, and magnetic-field aligned electric fields, for brevity often called “parallel” electric fields, were considered impossible.

Therefore, the role of electric fields and especially of magnetic-field aligned electric fields, which are now considered to be of crucial importance, was disregarded. It was also almost universally assumed that all except the innermost regions of Earth’s magnetosphere were populated by hydrogen plasma from the solar wind, and hence ultimately from the Sun. When *in situ* measurements became possible, it was quite unexpectedly discovered (Shelley *et al.*, 1976) that sometimes huge fountains of ionospheric plasma originating in the Earth’s own atmosphere supply oxygen ions to the

magnetosphere on such a scale that oxygen plasma becomes the dominant component (Shelley *et al.*, 1982).

Thus, until *in situ* measurements were made, the generally accepted picture of our space environment was erroneous in aspects as fundamental as the prevalence and role of electric fields, and the origin and chemical composition of matter in Earth’s own neighborhood. Therefore, if we are to make reliable interpretations of distant astrophysical phenomena that can be observed only remotely, we very much depend on what has been learned and what still remains to be learned from *in situ* observations and experiments in accessible regions of the space plasma.

Cosmic plasmas cover still much larger ranges in parameters, such as density and (equivalent) temperature, than the magnetospheric plasmas. But like the magnetospheric plasmas, they are all magnetized, and magnetized plasmas can be classified into three main categories, each with certain characteristic properties (Alfvén and Fälthammar, 1963). The categories are based on the magnitude of the mean free path, λ , of the charged particles relative to the characteristic magnitudes of the gyro radius, ρ_c , and the characteristic dimension, l_c as follows: *High density plasmas* $\lambda \ll \rho_c$, *Medium density plasmas* $\rho_c \ll \lambda \ll l_c$, *Low density plasmas* $l_c \ll \lambda$. All three of these categories are represented in the Earth’s magnetosphere.

In cosmos as a whole, low and medium density plasmas occupy limited regions such as low and intermediate altitudes in planetary ionospheres, and in interiors and

lower atmospheres of the sun and stars. Low density plasmas constitute the dominating part of planetary magnetospheres, solar and stellar atmospheres, solar and stellar winds, interstellar and intergalactic plasma. Low density plasmas are also those which exhibit most deviations from classical plasma behavior. It is for those plasmas the need of a better empirical basis is the greatest.

LESSONS FROM THE AURORA

The aurora is not only one of nature's most spectacular phenomena. It is also highly interesting from a scientific point of view, because its very existence depends on previously unknown behaviour of matter in the plasma state. And many of the plasma physical phenomena studied in the magnetosphere are directly or indirectly related to the aurora.

The immediate cause of the aurora is of course energetic electrons in the keV range that impinge on the Earth's upper atmosphere. But the mystery used to be how these electrons gain their energy. The resolution of this mystery is a powerful object lesson on the danger of conclusions based on an insufficient empirical foundation.

In 1958 Hannes Alfvén published a paper (Alfvén, 1958) where he suggested that the auroral primary electrons gain their energy by falling through an electric potential drop along the magnetic field lines somewhere above the ionosphere. This idea was discarded or even ridiculed because it was incompatible with generally accepted theories. These theories claimed that such electric fields are impossible because of the

unimpeded motion of electrons and ions along the magnetic field.

And yet, when *in situ* measurements above the ionosphere became possible, one of the earliest discoveries (McIlwain, 1960) was that the velocity space distribution of the auroral primary electrons sometimes looks as if the electrons came directly out of an electrostatic accelerator. Subsequently, enormous amounts of data have confirmed not only the existence of magnetic-field aligned potential drops in the space plasma, but also that that acceleration by such potential drops is an essential part of the auroral acceleration process (for a review see Fälthammar, 2004, and references therein).

But these fields are far from the whole story. The auroral acceleration process is a complicated interplay between plasma and electromagnetic fields. Auroral particle populations are subject to acceleration and other modifications of the phase space distribution both by electrostatic fields and various kinds of wave particle interactions. In particular, Alfvén waves appear to be responsible for certain kinds of auroras (Stasiewicz *et al.*, 2000; Keiling *et al.* 2003; Chaston *et al.* 2003, 2007; Janhunen *et al.*, 2006), and recent observations (Chaston *et al.*, 2009) indicate that they play an important role in magnetic reconnection. Alfvén wave acceleration of auroral electrons also involves magnetic-field aligned electric fields although in this case not potential fields.

Alfvén waves are commonly observed not only in the auroral acceleration region but in the geomagnetic tail (for a review see Keiling, 2009) and almost everywhere else in the magnetosphere. As shown already in

1971, they occur ubiquitously in the solar wind (Belcher and Davis, 1971) and are one of the agents proposed to drive the solar wind (for a review see Hollweg, 2008). As almost any dynamic event in a magnetized plasma will give rise to Alfvén waves, these waves can be expected to be a prominent phenomenon throughout the universe. The magnetosphere and accessible parts of the solar wind allow us to study them *in situ*.

But of all lessons from the aurora, the most fundamental is that – contrary to previously firm beliefs – electric potential fields can and do exist in collisionless space plasma. The most dramatic demonstration of a magnetic-field aligned electric field was achieved with a rocket experiment, where a cloud of Barium ions was ejected upwards on an auroral magnetic field line (Haerendel *et al.*, 1976). At an altitude of about 10 000 km the velocity of the ions suddenly jumped from 10 km/s to 102 km/s as they fell through a potential drop of 7.3 kV.

Another beautiful example (among many) comes from NASA's FAST satellite, which measured (1) the variations of the electric potential along the satellite orbit as it passed above the auroral acceleration region, and (2) the energy of positive ions that had been accelerated by the potential drop below the satellite. These quantities showed an excellent agreement (Ergun *et al.* 2004).

SUPPORTING MAGNETIC-FIELD ALIGNED ELECTRIC POTENTIAL FIELDS

For a finite magnetic-field aligned electric field to exist in a collisionless plasma – other than as a brief transient or as part of a wave –

the momentum that is continually imparted to the charged particles by the electric field must be balanced by some other force. A number of possibilities have been identified, in particular

The mirror force in a converging dc magnetic field

Charge carrier inertia

Forces due to waves or solitary structures

All three of these have been proposed to support the electric fields that accelerate the auroral particles (see *e. g.* Fälthammar, 2004). Two of them have definitely proved to do so, and recent results indicate that the third may play a role, too.

Magnetic mirror force

Of the three main mechanisms, the magnetic mirror force is the one that has been most extensively confirmed by observations. The aurora is associated with magnetospheric currents that flow to and from the ionosphere. The role of current systems in cosmic plasmas was emphasized already by Alfvén (1977: 1981) and measurements with the Cluster satellites have shown the importance of coupling between the different branches of the auroral current system (Marklund *et al.*, 2004). The upward branch of the auroral current is carried mainly by downward going electrons, which cause the aurora when they strike the upper atmosphere. To get there, they have to overcome the mirror force of the geomagnetic field.

Without a potential drop, only those electrons that are in the loss cone of the magnetospheric source plasma, can come through and contribute to the current density. In the source plasma of the aurora this loss

cone is extremely narrow, and the loss cone current density correspondingly small. Any larger current density than that requires a magnetic field aligned potential drop that widens the loss cone into a loss hyperboloid. With a typical mirror ratio of 1 000 on auroral field lines, the current that can flow without a potential drop is very small. At the other extreme, a voltage drop much larger than the voltage equivalent of the electron temperature of the source plasma can push the entire downward half of the electron distribution through the mirror. This represents a saturation current that cannot be exceeded. The relation between the applied voltage and the current density (measured at ionospheric altitude) was derived by Knight (1973) for the simple case of Maxwellian electron. It reads

$$i = en_{e2} \sqrt{\frac{kT_{e2}}{2\pi m_e}} \frac{B_2}{B_1} \left[1 - \left(1 - \frac{B_2}{B_1} \right) \exp \left\{ -\frac{eV}{kT_{e2}(B_1/B_2 - 1)} \right\} \right]$$

This formula has been generalized by many authors (Lemaire and Scherer, 1974; Friedman and Lemaire, 1980; Chiu *et al.*, 1981; Pierrard, 1996; Janhunen and Olsson, 1998) to cover other types of electron velocity distributions that can be expected to occur. But already the simplest relation has been found in many cases to agree extremely well with observational data.

In the case of the aurora, there is a range, typically three powers of ten wide, where the current density is proportional to the applied voltage. This is due to the large mirror ratio on auroral flux tubes. In other cosmic plasmas the current-voltage curves can be different, depending on the mirror ratio and the distribution function of the electrons.

The constant ratio between current density and total voltage in the middle parameter range represents a constant *conductance* per unit area. The concept of *conductivity* is not meaningful in this case, because the current density at a given location is not determined by the electric field at that location but by the total potential drop between the ionosphere and the magnetospheric source plasma. This illustrates the non-local character of the current-voltage relation. Another aspect of this is that whereas the relation between the current density and voltage above the aurora has been observationally confirmed in many cases and with high accuracy, the spatial distribution of the voltage drop is still largely unknown.

The first observational confirmation of the linear current-voltage relation by Lundin and Sandahl (1978) was followed by numerous others (Lyons *et al.*, 1979, Menietti and Burch, 1981, Weimer *et al.*, 1987, Lu *et al.*, 1991, Haerendel *et al.*, 1994, Sakanoi *et al.*, 1995, Olsson *et al.*, 1996, 1998, Olsson and Janhunen, 1998). Menietti and Burch (1981) found excellent agreement even with a higher approximation to the full current-voltage relation and Brüning *et al.* (1990) reported observation of saturation current.

Mirror supported magnetic-field aligned electric fields are possible also without an electric current. The principle was demonstrated by Alfvén and Fälthammar (1963) who showed that such fields are generated by differential anisotropy between trapped populations of electrons and positive ions (cf also Jasperse *et al.*, 2000). Such differential anisotropy can be generated in many ways. For example, Serisawa and Sato

(1984) showed that in plasma jetting into a magnetic mirror, which is a phenomenon frequently observed in the magnetosphere, electrons and positive ions will automatically get different velocity distributions and cause an outward pointing magnetic-field aligned electric field. Most interestingly, Le Contel (1999; 2000) showed by means of a self consistent simulation that basically any unsteady plasma transport in the presence of a magnetic mirror field will lead to differential anisotropy and magnetic-field aligned electric fields.

Current carrier inertia

A second way to support magnetic-field aligned electric fields is by current carrier inertia. Such is the case in an electric double layer. This is a phenomenon well known from gas discharges and it inspired Hannes Alfvén's 1958 suggestion that auroral electrons are electrostatically accelerated. The electric double layer is a local potential drop with a width depending on the Debye length and the magnitude of the potential drop (for a review, see Raadu 1989). In an electric double layer, the voltage drop is sustained by the inertia of the current carrying electrons themselves.

Current carrying electric double layers are of two kinds, *weak* double layers with potential drops comparable to the voltage equivalent of the ambient electron thermal energy ($V \leq kT_e/e$), and *strong* double layers with potentials much greater than that ($V \gg kT_e/e$).

Weak electric double layers (as well as soliton-like structures with zero net potential drop) occur profusely in regions

where upward flowing ions are observed. They move rapidly upward along the magnetic field (from 5 km/s to 50 km/s or more). First detected with the S3-3 satellite (Temerin *et al.*, 1982) they have been studied in detail by many authors, see *e.g.* Eriksson *et al.* (1997) and references therein. Although each of the weak double layers has a potential drop of less than 1 V, they are so numerous that they might conceivably account for a total potential drop of several kV. The observed correlation between occurrence of ion beams and weak double layers may or may not mean that the ions are accelerated by the double layers. It may also be that ion beams accelerated by some other mechanism are the cause of the double layers, or that both are independent consequences of a common physical process (Mälkki and Lundin, 1994). So far, the role, if any, that the weak electric double layers play in auroral region particle acceleration remains an open question.

Strong electric double layers are hard to observe because they are not only thin but also few. A small number of observations do, however, exist (*e.g.* Boehm and Mozer, 1981; Mozer and Kletzing, 1998; Ergun *et al.*, 2001a; Mozer and Hull, 2001).

An important feature of electric double layers in space is that the energy imparted to electrons and ions that fall through them is not deposited locally. For example, auroral primary electrons can gain energy by falling through a double layer at high altitude and deposit that energy in the dense ionosphere thousands of kilometers below. Therefore there is no problem of excessive local heating as in the case of anomalous resistivity.

In the downward branch of the auroral current circuit, the so called return current region, the current is mainly carried by electrons from the ionosphere. As these are in copious supply and are unimpeded by the magnetic mirror, it came as a surprise that magnetic-field aligned electric fields are observed there, too. The support mechanism there is not well understood, but there are indications that strong electric double layers may be at least partly responsible (Ergun *et al.* 2001b). A recent review of electric fields and plasma processes in the downward current region has been given by Marklund (2009).

Electric double layers with *no net current* (e. g. wall sheaths) are well known from laboratory plasma experiments, where their function is to equalize the flux of positive and negative charges to the wall surrounding the plasma. Electric double layers of this nature and with a corresponding function have also been observed in the magnetosphere, as reported by Mozer and Hull (2001).

Much still remains to be learned about electric double layers in the magnetosphere, but the results will be important for understanding other magnetospheres, too. For example, in a Vlasov simulation of auroral arcs observed at Jupiter, Su *et al.*, (2001) found localized potential drops at 2-3 Jupiter radii.

The beams of accelerated electrons interact with the plasma to generate Auroral Kilometric Radiation (AKR) of such an intensity that the Earth is a major radio source. This radiation bounces off the ionosphere and does not reach the ground, so

its existence was unknown until the advent of *in situ* measurements. Other planets are strong radio sources based on the same generation mechanism. But only in the magnetosphere is it conveniently accessible to empirical study *in situ*.

Waves and solitary structures

A third mechanism proposed to sustain magnetic-field aligned electric fields is “*anomalous resistivity*” (Papadopoulos 1977). It used to be frequently invoked, but its role in the magnetospheric plasma appears to be smaller than originally thought. (e. g. Coroniti, 1985). Supporting the auroral acceleration fields by anomalous resistivity would imply a local energy dissipation incompatible with observations (Block, 1984). However, recent work indicates that anomalous resistivity may play some role in the aurora and it has also been found to be a cause of unfreezing in the magnetotail (Lui 2007).

States similar to anomalous resistivity may also be created in other ways. Block (1984) suggested the possibility of an anomalous-resistivity like state formed by multiple weak double layers. Such double layers and other solitary structures have been observed to occur profusely in the auroral current circuit (Temerin *et al.* 1982), but their role remains to be clarified.

Other mechanisms

In addition to the main mechanisms discussed above, there are others that are more or less related to them. Hultqvist (1971) proposed what he termed *collisionless thermoelectric effect*. It relies on charge carrier inertia but

does not require a net current. Observations of downward accelerated ions in the sub keV energy range are in agreement with this mechanism (Hultvist, 2002). Still another inertia-based mechanism is *dynamic trapping* (Bohm *et al.* 1990). Electrons pulled in to neutralize a suddenly imposed excess positive charge will be prevented by inertia from attaining the optimum distribution in space. This mechanism successfully explained the magnetic-field aligned electric fields observed in the Porcupine rocket experiment (Haerendel and Sagdeev, 1981), where a beam of Xenon ions was injected into the ionospheric plasma (Bohm *et al.*, 1992).

SIGNIFICANCE OF MAGNETIC-FIELD ALIGNED ELECTRIC FIELDS

Magnetic-field aligned electric fields are important for three main reasons.

1. Magnetic-field aligned electric fields provide a very efficient means of accelerating charged particles. Charged particles can gain energy only by interaction with electric fields, because the magnetic force is always transverse to the velocity vector and can do no work. The acceleration can take place in a multi-step stochastic fashion by interaction with for example wave electric fields, or in a single step by falling through a potential drop. In the magnetosphere both kinds of acceleration takes place, as well as combinations of them, including Fermi-like acceleration (Perri *et al.* 2009). But by far the fastest acceleration possible is falling through a magnetic-field aligned electric field. From the aurora we know that such fast acceleration can and does take place in cosmic plasma. It has been argued that electrostatic acceleration

cannot work, because the electrostatic field is conservative (Bryant, 2007). As explained by Haerendel (2007), this is based on a misunderstanding. The electrostatic acceleration region is only part of an electric circuit that also includes a dynamo region with an electromotive force or a finite curl of the electric field.

2. Magnetic-field aligned electric fields make possible rapid release of magnetically stored energy. In collisionless plasmas, current flows most easily along the magnetic field lines. A potential drop in the path of the current can extremely efficiently energize the current carries at the expense of the magnetic field energy in the dynamo region.

3. Magnetic-field aligned electric fields allow violation of the frozen field condition.

The concept of frozen in magnetic field greatly simplifies thinking about plasma dynamics and is therefore frequently used. It has sometimes led to reasoning in terms of “moving magnetic field lines”. But the strict definition of the frozen field condition does not in any way imply that the field lines themselves “move”. It only prescribes that two elements of plasma that are at one instant of time on a common magnetic field line, shall be on a common magnetic field line at any other time.

Cosmic plasmas are often assumed to be subject to the frozen field condition. But if magnetic-field aligned electric fields can exist in the cosmic plasma, as we now know they do, the frozen field condition can be violated, which of course has profound consequences for the dynamics of the plasma. The necessary and sufficient condition for violating the

frozen field condition was derived long ago (Newcomb, 1958) and is that

$$\mathbf{B} \times \text{curl} \left(\frac{\mathbf{B}(\mathbf{E} \cdot \mathbf{B})}{\mathbf{B}^2} \right) \neq 0$$

where \mathbf{B} and \mathbf{E} are the electric and magnetic vector fields. Thus, the key to violating the frozen field condition is a magnetic-field aligned electric field with a non vanishing curl transverse to the magnetic field.

The concept of a magnetic field frozen into the plasma was introduced by Hannes Alfvén (1942a,b) as a byproduct of his discovery of what we now call Alfvén Waves. But the derivation was made for an ideal, infinitely conducting medium, and Alfvén realized that real plasmas, and cosmic plasmas in particular, may not always satisfy the ideal conditions. Although he had introduced it himself, he described the concept of frozen field lines as easily misleading and, especially in his later years, strongly warned against its use (Alfvén, 1976).

RECONNECTION

A special kind of violation of the frozen field condition is the process of reconnection. In the classic review article by Vasyliunas (1975) reconnection was defined as “the process whereby plasma flows across a surface separating regions containing topologically different magnetic field lines” (cf. also Priest and Forbes, 2000). But change of connectivity between plasma elements is possible without a separator. Independently of topology, two elements of plasma that are at one instant of time on a common magnetic field line can be on different magnetic field line at another instant, if the condition given

above is satisfied somewhere between the plasma elements. This more general definition of reconnection was proposed by Schindler *et al.* (1988) and Hesse and Schindler (1988) and further elaborated by Birn *et al.* (1997), but the term reconnection is commonly used for reconnection at a separatrix.

Reconnection is considered to be one of the most important phenomena in cosmic plasma, as a means of topology change and energy release. In the Earth’s magnetosphere, reconnection takes place both at the magnetopause and in the tail current sheet. In addition, local reconnection of limited strands of magnetic flux, so-called flux transfer events, are also common (Le *et al.* 2008). The reconnection events in the geomagnetic tail that are associated with magnetospheric substorms have many similarities to the fast energy release that takes place in solar flares (Lin *et al.*, 2008). In the magnetosphere, the phenomenon can be studied empirically in great detail by means of *in situ* measurements (Paschmann, 2008). The value of this for understanding solar flares and other kinds of energy release in cosmic plasmas can hardly be exaggerated.

Reconnection is an extremely complicated phenomenon, and this makes it even more important to have actual measurements to guide theoretical work. One reason for complexity is that reconnection involves coupling between widely different spatial scales, from system-scale structure through ion scales and down to electron scales. Therefore, multipoint measurements are essential. Multipoint measurements are at present being made with the still operational Cluster satellites and the more recent five

satellites of the THEMIS project. For example, Cluster observations showed that the extent of the electron diffusion region can far exceed what is expected from simulations (Phan *et al.*, 2007) Substantial further progress can be expected from another four-spacecraft mission, Magnetospheric Multiprobes, which has recently been approved by NASA.

Due to the widely different spatial scales involved in reconnection, a major advance would be simultaneous multipoint measurements on each of the three spatial scales. Such a project, called Cross Scale, is part of ESA's long term plan *Cosmic Vision*. It involves 10 or 12 satellites forming tetrahedrons on each scale.

For the Cross scale mission, reconnection studies is only one of its purposes. It will, if it realized, be a formidable tool for studying many other space plasma phenomena. This is in particular true for two phenomena, namely collisionless shocks and turbulence. Both of these are of fundamental importance in cosmic plasmas and both are prominent in the magnetosphere and in accessible regions of the solar wind.

CONCLUDING REMARKS

Magnetospheric research can be divided into two phases. The *exploratory phase* is largely completed, although new features are still being discovered (*e. g.* Chappell *et al.*, 2008) We are now well into the *physics phase*, which is devoted to obtaining a full understanding of the many fundamentally interesting plasma processes that take place naturally, or can be induced artificially, in this complex plasma system. Many of these

processes take place also in the astrophysical plasma that constitutes the rest of the known matter in the universe. Therefore, the magnetosphere and the surrounding solar wind offer unique opportunities to build an empirical basis for understanding cosmic plasma processes, and thereby serve as a key to the plasma universe.

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