Double Layers in Astrophysics: Highlights of the 1986 MSFC Symposium

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Abstract—We review the discussions of the Third International Symposium on Double Layers in Laboratory and Space Plasmas. This symposium was held at Marshall Space Flight Center in Huntsville, Alabama, March 17-19, 1986. The symposium emphasized the applications of double layers in various astrophysical settings. Although the proceedings of the symposium will be published elsewhere, we give the main points of all of the discussions in this report. We also pass along a resolution which was adopted at the symposium to standardize the electrical circuit symbol for a double layer.

I. INTRODUCTION

An international symposium with the theme “Double Layers in Astrophysics” was held at Marshall Space Flight Center in Huntsville, Alabama, during March 1986. Participants from several different countries came together for three days to discuss their latest research efforts in the experimental, theoretical, and astrophysical application aspects of double layers.

This was the third such symposium. The other two were held at Riso National Laboratory in Roskilde, Denmark, and at the University of Innsbruck in Innsbruck, Austria. These were in 1982 and 1984, respectively. Whereas, these first two symposia concentrated on laboratory and simulation studies of double layers, the present symposium had emphasis on astrophysical applications of double layers. Most of the applications involved the magnetosphere–ionosphere plasma environment of the earth because of its accessibility to direct observations. However, other astrophysical applications of double layers were discussed. These will be highlighted later in this summary.

As the proceedings of this workshop will appear in a special issue of the journal Laser and Particle Beams (January 1987), the purpose of this paper is simply to highlight the results of the symposium and to emphasize the relevance that double layers have in the processes occurring in space plasmas. Hence, in Section II we will give the highlights of the keynote address of H. Alfvén. The entire discussion by Alfvén can be found in a separate paper in this issue. The highlights of the experimental and theoretical discussions will be given in Sections III and IV, respectively. Section V contains the astrophysical applications. Finally, in Section VI, we give a new electrical symbol for the double layer which was adopted by the participants in the symposium.

II. HIGHLIGHTS OF THE KEYNOTE ADDRESS BY HANNES ALFVÉN

The opening address of the symposium was given by H. Alfvén in which he not only outlined the historical and experimental status of double layers, but also gave several examples of their astrophysical applications. One point that stood out clearly in this opening discussion was the inadequacy of the widely used magnetofluid models of space plasma in describing phenomena for which double layers would be responsible. In order to understand double layers, it was suggested that one must go to a particle model [7] or to a circuit theory model [1].

Among the astrophysical examples cited by Alfvén are the following: 1) the earth’s auroral circuit; 2) the heliospheric circuits; 3) double radio sources; 4) the solar prominence circuit; 5) magnetic substorms; 6) X-ray and gamma-ray bursts; and 7) cosmic-ray acceleration.

In all of these applications, the double layer is a mechanism for energy release which was discussed in some detail by Alfvén. Here, it was argued that the electric circuit model of plasma would be the most convenient in understanding the processes that are occurring. In this model, all of the work goes into identifying the circuit elements (which may be distributed) such as the inductor, resistor, motor, and generator. However, once this is done, the energy of the circuit stored in the inductance and the power delivered by the double layer is easy to calculate.

In the circuit model, it was noted that every circuit that contains an inductance is intrinsically explosive. This is true because a conductive circuit will tend to supply all of the inductive energy to any point of interruption of the circuit. Double layers are known to tend to interrupt current in a plasma. Hence, the entire energy of a circuit can be released at the point where a double layer forms regardless of the source of the energy of the circuit.

Many problems in present-day approaches and attitudes toward double layers in space plasma were pointed out by Alfvén. Among these are 1) the negligence of educational books in covering the topic of double layers and related phenomena; 2) the blind application of the magnetohydrodynamic model of plasma to all of space plasma even though this model does not explicitly take the current into
consideration; and 3) failure to realize the value using “equivalent circuits” [3, 4] in describing the global aspects of processes in space plasma.

III. Laboratory Work Highlights

The papers presented at the symposium that dealt with work done in laboratory plasma covered the topics of formation mechanisms, dynamical properties, potential dips, and ion phase-space vortices dynamics. They covered both the strong and the ion-acoustic (weak) double layers. The experimental discussions were aimed at trying to understand the formation and properties of double layers in space plasma.

A summary of the results of these discussions would include the following.

1) The existence of a virtual cathode type potential well at the plasma boundary where a beam of electrons is injected can be the dominant triggering mechanism for double layer formation.

2) For weak double layers, collisionless ion trapping induced ion–ion streaming instabilities and the formation of ion phase-space vortices. This led to double layers that periodically turned off and on.

3) When reactances are minimized in a strong double layer circuit, the double layer tends to undergo a jitter-type motion in position with an amplitude approximately equal to the double layer thickness. The speed of the motion is two to three times the ion sound speed.

4) Several mechanisms were presented that solved the problem of ion accumulation in the double layer potential well, which would destroy the double layer.

5) It was shown experimentally that in a current-driven plasma, the space-charge effects of the injected current is a more dominating mechanism for the formation of double layers than wave instabilities.

6) One mechanism for the formation of ion-acoustic-type double layers is the injection of an electron beam into the plasma in such a way as to excite ion-acoustic fluctuation. The nonlinear extensions of the normally damped slow ion-acoustic modes then lead to double layer formation.

7) The dynamic properties of electron and ion phase-space vortices as observed in the laboratory are found to be significantly different from what one would expect from simple one-dimensional numerical codes. However, it is expected that these codes would do well in describing strongly magnetized plasmas.

IV. Theory and Simulation Highlights

The simulations and theoretical discussions at the symposium were concerned with the formation, stability, evolution, and dynamics of double layers. A summary of the key results are as follows.

1) Simulation studies show more convincingly that weak double layers can evolve from instabilities of ion phase-space holes in a current-carrying plasma.

2) Double layers can be stochastic in nature. That is, the electron field associated with them can be microscopically intermittent. If the initial electron energy is small compared to the double layer potential energy, then stochastic heating of electrons becomes a significant competing process to directed electron acceleration.

3) The auroral arc circuit can be simulated in some approximation by a double layer in parallel with a resistive transmission line. It is found that the potential across the double layer is determined by the balance between the current through the double layer and current at the resistive element.

4) The ion–ion stability which dominates the ion-acoustic model at the bottom of the auroral acceleration region does not preclude double layer formation at higher altitudes.

5) Double layers will be formed in a plasma that contains an inhomogeneous dipole magnetic field with injected costreaming ions and electrons. This type of situation can model the auroral double layers with particle injections from both the magnetosphere and the ionosphere.

6) The key to the anomalous resistivity provided by a double layer, whether it is weak or strong, is the formation of a potential dip at its low-potential end.

7) By using a two-fluid model of a laser-produced plasma, it was shown that high-dynamic electric fields produced cavitous and inverted double layers in agreement with experiment.

V. Astrophysical Applications

As we stated previously, the astrophysical applications of double layers made this symposium unique when compared to the first two symposia. The astrophysical applications that were discussed included the earth’s auroral regions, extragalactic jets, X-ray and gamma-ray bursts, X-ray pulsars, double radio sources, solar flares, and the source of cosmic ray acceleration. Some of the key points that are to be noted in the applications are the following.

1) The physical reasons why double layers would form in the earth’s auroral regions were discussed. The primary reason given was that they form in order to maintain current continuity in the ionosphere in the presence of a magnetospheric electric field which has a nonzero divergence.

2) By using a time-dependent MHD model of auroral currents in the presence of a series of weak double layers, it was shown that narrow-scale current structures resulted. This result contrasts with a model of parallel electric fields caused by anomalous resistivity where the field-aligned current is diffuse.

3) Calculations were presented which indicate that thin (a few electron Larmor radii) electron layers, which can exist at the interface between two plasma clouds, can be regions that spontaneously generate large-amplitude electrostatic waves. These waves, in turn, can scatter the pitch angles of the ambient plasma-sheet electrons into the atmospheric loss cone.

4) Measurements in the earth’s auroral region made by
the S3-3 satellite suggest that two different kinds of double layers are associated with auroral precipitation. One is a strong double layer with an electric field oriented oblique to the magnetic field. The electric field associated with these double layers are 25 mV/m or less but in a few cases are up to about 100 mV/m. The other type of double layer evident in the observations is the weak ion-acoustic double layer. Although the potential drop for a single one of these is small, a series of such double layers is found to combine to give a substantial potential.

5) A very interesting astrophysical application of double layers which was discussed was in connection with extragalactic jets. It was shown that strong plasma double layers can exist within self-maintained density cavities. These double layers will emit relativistic electrons which, in turn, will produce synchrotron radiation making the plasmas in the immediate locality radio luminous.

6) Another novel application of double layers in astrophysics that was discussed was their possible connection with gamma-ray bursts. The observed spectral shapes of these bursts indicate a highly collimated beam coming from neutron stars. A strong double layer can explain this and other features of gamma-ray bursts.

7) Double layers are also suggested to be responsible for the radiation of X-ray pulsars, which consist of a strongly magnetized neutron star in a binary orbit with a normal star. The double layers here are strong and are suggested to be the dominant deceleration mechanism for the accreting ions.

8) The formation of a double layer was also proposed as a mechanism which can lead to the critical velocity phenomena which prevent a neutral gas beam from exceeding a certain critical velocity when passing through a magnetized plasma. Here, the double layer accelerates electrons, which ionizes the gas beam once this critical velocity is reached.

VI. ADOPTION OF AN ELECTRIC CIRCUIT SYMBOL FOR THE DOUBLE LAYER

One noteworthy outcome of the symposium was the adoption of a circuit symbol for the double layer. This symbol was proposed by H. Alfvén, and the participants agreed to adopt it and use it in future papers dealing with double layers. The symbol is shown in Fig. 1. An example of a circuit with a double layer is the prominence/solar flare circuit where an exploding double layer is assumed to be responsible for the flare [2], [5], [6]. Such a circuit was presented at the symposium by Alfvén and is shown in Fig. 2.

Although it is possible to have a plasma double layer without a net current, many applications will have a net current. In these applications the “L” in the double layer symbol would be most appropriately oriented so as to show the direction of the current. This is illustrated in Fig. 3.

Since the double layer will accelerate and decelerate particles depending upon their charge and direction of travel, power will be delivered to, as well as taken from, charged particles passing through it. The net power delivered to the charged particles passing through the double layer is the equation

\[ P = I\Delta V \]

where \( I \) is the net current and \( \Delta V \) is the potential difference across the double layer. In the case of no net current, the double layer simply serves as an energy transfer mechanism. It transfers energy from one species of charged particle to another. Applications of this type of double layer were discussed in the symposium by Williams.

It is hoped that researchers in this field, as well as all who refer to the double layer, will join with the participants of the symposium in adopting the double layer symbol in Fig. 1 in all future references.

REFERENCES
