1995Ap&SS.227...97P

PLASMA AND THE UNIVERSE: LARGE SCALE DYNAMICS, FILAMENTATION, AND RADIATION

ANTHONY L. PERATT
Los Alamos National Laboratory
Los Alamos, New Mexico, USA

Abstract. One of the earliest predictions about the morphology of the universe is that it be filamentary (Alfvén, 1950). This prediction followed from the fact that volumewise, the universe is 99.999% matter in the plasma state. When the plasma is energetic, it is generally inhomogeneous with constituent parts in motion. Plasmas in relative motion are coupled by the currents they drive in each other and nonequilibrium plasma often consists of current-conducting filaments.

In the laboratory and in the Solar System, filamentary and cellular morphology is a well-known property of plasma. As the properties of the plasma state of matter is believed not to change beyond the range of our space probes, plasma at astrophysical dimensions must also be filamentary.

During the 1980s a series of unexpected observations showed filamentary structure on the Galactic, intergalactic, and supergalactic scale. By this time, the analytical intractibility of complex filamentary geometries, intense self-fields, nonlinearities, and explicit time dependence had fostered the development of fully three-dimensional, fully electromagnetic, particle-in-cell simulations of plasmas having the dimensions of galaxies or systems of galaxies. It had been realized that the importance of applying electromagnetism and plasma physics to the problem of radiogalaxy and galaxy formation derived from the fact that the universe is largely a *plasma universe*. In plasma, electromagnetic forces exceed gravitational forces by a factor of 10^{36}, and electromagnetism is $\approx 10^7$ times stronger than gravity even in neutral hydrogen regions, where the degree of ionization is a miniscule 10^{-4}.

The observational evidence for galactic-dimensioned Birkeland currents is given based on the direct comparison of the synchrotron radiation properties of simulated currents to those of extra-galactic sources including quasars and double radio galaxies.

Key words: Plasma Cosmology, Galaxies, Filamentation, Electrical Currents, Quasars, Double Radio Galaxies, Jets

1 Introduction

Among the earliest predictions about the morphology of the universe is that it be filamentary (Alfvén, 1950, 1981, 1990). This prediction follows from the fact that volumewise, the universe is 99.999% matter in the plasma state. For the most part, plasma consists of particles at high temperature, *i.e.*, an energetic state. And like all energetic plasma, the volume of plasma is inhomogeneous and consists of plasmas with differing temperatures, magnetization, degree of ionization, chemical constituency, and relative motion. It is this latter property, often the result of the first four properties, that

Astrophysics and Space Science **227**: 97–107, 1995.
© 1995 *Kluwer Academic Publishers. Printed in Belgium.*

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

produces the filamentation. Plasmas in relative motion are coupled by the currents they drive in each other.

In the laboratory and in the Solar System, filamentary and cellular morphology is a well-known property of plasma. As the properties of the plasma state of matter is believed not to change beyond the range of our space probes, plasma at astrophysical dimensions must also be filamentary.

Additionally, transition regions have been observed that delineate the 'cells' of differing plasma types (Eastman, 1990). On an astrophysical scale, these transition regions should be observable at radio wavelengths via transition radiation signatures.

The suggestion that the universe be filamentary and cellular was generally disregarded until the 1980s, when a series of unexpected observations showed filamentary structure on the Galactic, intergalactic, and supergalactic scale. By this time, the analytical intractibility of complex filamentary geometries, intense self-fields, nonlinearities, and explicit time dependence had fostered the development of fully three-dimensional, fully electromagnetic, particle-in-cell simulations of plasmas having the dimensions of galaxies or systems of galaxies. It had been realized that the importance of applying electromagnetism and plasma physics to the problem of radiogalaxy and galaxy formation derived from the fact that the universe is largely a *plasma universe*.

Any imbalance in the constituitive properties of a plasma can set it in motion [if, in fact, it has not already derived from an evolving, motional state (Bohm, 1979)]. The moving plasma, *i.e.,* charged particle flows, are currents that produce self magnetic fields, however weak. The motion of any other plasma across weak magnetic fields produces and amplifies electromotive forces, the energy of which can be transported over large distances via currents that tend to flow along magnetic lines of force. These 'field-aligned currents,' called *Birkeland currents* in planetary magnetospheres, should also exist in cosmic plasma. The dissipation of the source energy from evolving or moving plasma in localized regions can then lead to pinches and condense states. Where double layers form in the pinches, strong electric fields can accelerate the charged particles to high energies, including gamma ray energies (Alfvén, 1981). These should then display the characteristics of relativistic charged particle beams in laboratory surroundings, for example, the production of microwaves, synchrotron radiation, and non-linear behavior such as periodicities and 'flickering.'

2 Filamentation by Birkeland Currents

An electromotive force $\int \mathbf{v} \times \mathbf{B} \cdot \mathbf{dl}$ giving rise to electrical currents in conducting media is produced wherever a relative perpendicular motion of plasma and magnetic fields exist (Akasofu, 1984; Alfvén, 1986). An example

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

of this is the (nightside) sunward-directed magnetospheric plasma that cuts the earth's dipole field lines near the equatorial plane, thereby producing a potential supply that drives currents within the auroral circuit. The discovery of these Birkeland currents in the earth's magnetosphere in 1974 (Dessler, 1984) has resulted in a drastic change in our understanding of aurora dynamics, now attributed to the filamentation of Birkeland charged-particle sheets following the earth's dipole magnetic-field lines into vortex current bundles.

The remainder of this paper is devoted to analyzing Birkeland currents in astrophysical settings (Fälthammar, 1986).

3 Field Aligned Electric Fields

Recent literature in the area of magnetospheric physics reflects considerable interest in magnetic-field-aligned electric fields Such electric fields can have important consequences in cosmic plasma (Fälthammar, 1983), including the "unfreezing" magnetic fields, the acceleration of electrons to very high energies, and filamentation of the plasma itself.

In magnetized nonhomogeneous astrophysical plasma, a number of mechanisms are present that can generate field-aligned electric fields. These include anomolous resistivity caused by wave-particle interactions, collisionless thermoelectric effects due to energy-dependent wave-particle interactions, magnetic mirror effects involving trapped particles in magnetic-field gradients, and electric double layers due to localized charge separation. While all of the above mechanisms have been studied in the laboratory and simulatied by computer, it is the last mechanism that has been found to be remarkably prolific in producing appreciable potential drops in neutral plasma. Moreover, Birkeland currents and double layers appear to be associated phenomena, and both laboratory experiments (Chan & Hershkowitz, 1982) and computer simulations (Peratt & Jones, 1986) have shown the formation of a series of double layers along current-carrying plasma filaments or beams.

When double layers (or a series of double layers) form in adjacent Birkeland current filaments, field-aligned electric fields are generated, which then serve to accelerate electrons and ions within these regions.

4 Galactic Dimensioned Birkeland Currents

Extrapolating the size and strength of magnetospheric currents to interstellar space leads to the suggestion that confined current flows in interstellar clouds assists in their formation (Alfvén, 1981).

As a natural extension of the size hierarchy in cosmic plasmas, the existence of galactic dimensioned Birkeland currents or filaments was hypothesized (Alfvén & Fälthammar, 1963; Peratt, 1986).

A galactic magnetic field of the order $B_G = 10^{-9} - 10^{-10}$T associated

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

with a galactic dimension of $10^{20} - 10^{21}$m suggests the galactic current be of the order $I_G = 10^{17} - 10^{19}$A.

In the galactic dimensioned Birkeland current model, the width of a typical filament may be taken to be 35 kpc ($\approx 10^{21}$m), separated from neighboring filaments by a similar distance. Since current filaments in laboratory plasmas generally have a width/length ratio in the range $10^{-3} - 10^{-5}$, a typical 35 kpc wide filament may have an overall length between 35 Mpc and 3.5 Gpc with an average length of 350 Mpc. The circuit, of course, is closed over this distance (Peratt, 1990).

5 The Large Scale Structure of the Plasma Universe

Surface currents, delineating plasma regions of different magnetization, temperature, density, and chemical compositon give space a cellular structure (Alfvén & Fälthammar, 1963). As current-carrying sheet beams collect into filaments, the morphology of the surface currents is filamentary.

For the case of tenuous cosmic plasmas, the thermokinetic pressure is often negligible and hence the magnetic field is force-free. Under the influence of the electromagnetic fields the charged particles drift with the velocity

$$v = (\mathbf{E} \times \mathbf{B}) / E^2 \tag{1}$$

The overall plasma flow is inwards and matter is accumulated in the filaments which, because of their qualitative field line pattern, are called "magnetic ropes". Magnetic ropes should therefore tend to coincide with material filaments that have a higher density than the surroundings. The cosmic magnetic ropes or current filaments are not observable themselves, but the associated filaments of condensed matter can be observed by the radiation they emit and absorb.

It is because of the convection and neutralization of plasma into radiatively cooled current filaments (due to synchrotron losses) that matter in the plasma universe should often display a filamentary morphology (Figure 1).

6 Confining and Interacting Forces Between Cosmic Currents

If the cosmic current is cylindrical and in a rotationless, steady-state condition, it is described by the *Carlqvist Relation*:

$$\frac{\mu_0}{8\pi} I^2 (a) + \frac{1}{2} G \bar{m}^2 N^2 (a) = \Delta W_{Bz} + \Delta W_k \tag{2}$$

for a current of radius $r = a$ where μ_0 is the permeability of free space, G is the gravitational constant, $\bar{m}$ is the mean particle mass, N is the number of particles per unit length, and ΔW_{Bz} and ΔW_k are the differential beam

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

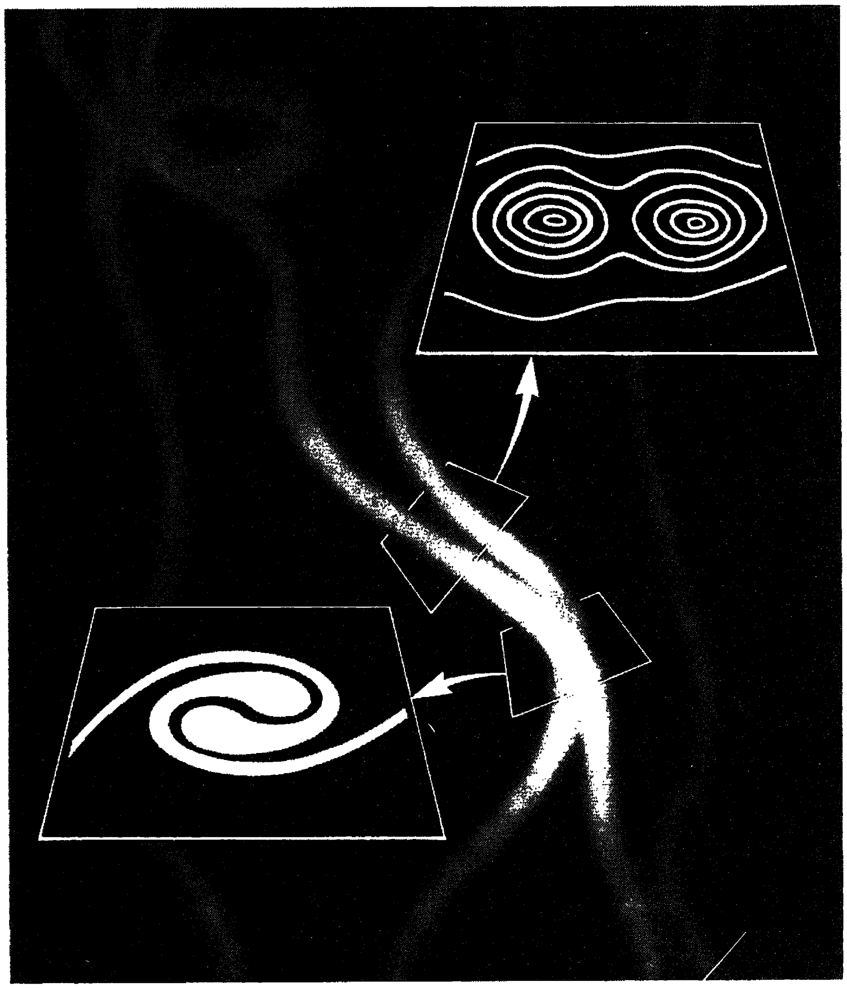

Fig. 1. The plasma universe may be eternal and infinite. Large scale field-aligned filaments may extend hundreds of megaparsecs or more in space. Where pairs of these spaghettilike structures interact, the particles gain kinetic energy and at narrow pinch regions produce the entire range of galaxy types as well as the full spectrum of electromagnetic radiation. Thus galaxies must lie along filaments, much as they are observed to do on a large scale. The bulk of the filaments are invisible from a distance, like the Birkeland currents that circle the Earth but are unobservable from its surface.

magnetic and kinetic energies, respectively (Peratt, 1992a)[1]. Thus, whether

[1] When current rotation and transient phenomena are important, the *Generalized Ben-*

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

or not a current or beam is gravitationally balanced, electromagnetically balanced, or force-free, depends on the magnitude of the individual terms in Eq.(2). Applications of the Carlqvist Relation are presented in this journal (Verschuur, 1995).

In contrast to the gravitational and electromagnetic forces that determine the characteristic of an individual beam, interactions between beams are always dominated by electromagnetic *Biot-Savart* forces,

$$\mathbf{F_{21}} = \int \mathbf{j_2} \times \mathbf{B_{21}} d^3r \tag{3}$$

for all space, where $\mathbf{j_2} \times \mathbf{B_{21}}$ is the Lorentz force between the field B_{21} induced by a current I_1 on the current density j_2 at current I_2.[2]

Parallel axial currents within the filaments are long-range attractive, while circular (helical) currents within the filaments (as the electrons gyrate along the axial magnetic field) are short-range repulsive. If the axial currents are able to bring the filaments close enough together so that the repulsive component of the Lorentz force becomes important, the circular currents repulse and brake, and release energy in the form of synchrotron radiation.

While a complete description of the evolution of interacting galactic currents is given elsewhere (Peratt, 1992a,b), it is useful to reproduce the evolutional sequence in this paper. Figure 2 illustrates the cross-sections of the filaments over a 10^9 yr period. The remainder of this paper is devoted to the radiation properties of the interaction as shown in the first frame of Figure 2, approximately 60 Myr.

7 Synchrotron Emission from Pinched Particle Beams

One of the most important processes that limit the energies attainable in particle accelerators is the radiative loss by electrons accelerated by the magnetic field of a betatron or synchrotron. This mechanism was first brought to the attention of astronomers by Alfvén and Herlofson (1950); a remarkable suggestion at a time when plasma, magnetic fields, and laboratory physics were thought to have little, if anything, to do with a cosmos filled with isolated "island" universes (galaxies). Synchrotron radiation is characterized by a generation of frequencies appreciably higher than the cyclotron frequency of the electrons; a continuous spectra (for a population of electrons) whose intensity decreases with frequency beyond a critical frequency (near intensity maxima); increasing beam directivity with increasing relativistic factor γ $\left(\gamma = (1-\beta)^{-1/2}\right)$; and polarized electromagnetic wave vectors.

---

nett Condition may be used in place of Eq.(2) (Peratt, 1992a, Chap. 2)

[2] The Biot-Savart force varies as r^{-1} and thus dominates gravitational attraction which varies as r^{-2}. 'Great Attractors', often attributed to gravitational forces between 'missing masses' display Biot-Savart, not mass attraction, characteristics.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

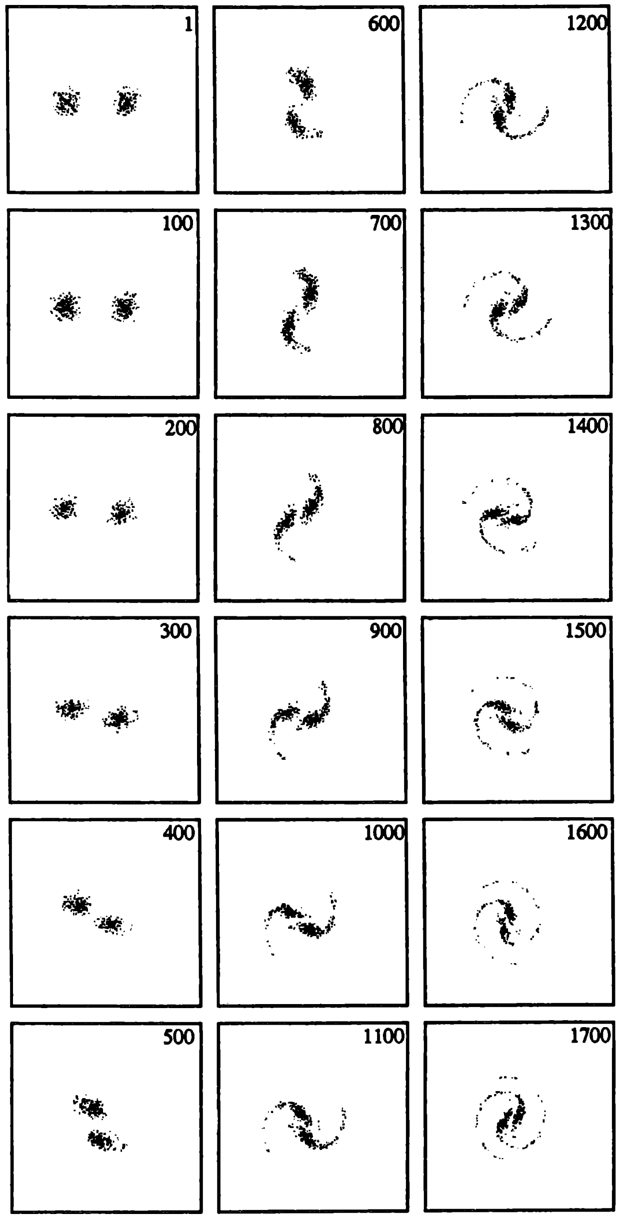

Fig. 2. Single frame stills of plasma in the simulation of two adjacent Birkeland filaments: ω_c/ω_p=3.0, $T_{e0} = T_{i0}$=32 keV, E_{z0}=62 mV/m. Total time elapsed: $\approx 10^9$ yr. The initial dimensions in frame 1 are: radius of filaments $r_{filament}$=17.5 kpc, distance between filaments $d_{filaments}$=80 kpc. The length over which E_{z0} exists in the filaments is taken to be $\approx$10 kpc.

Z-Pinches are among the most prolific radiators of synchrotron radiation known. In this regard, the Bennett-pinch, or Z-pinch, as a sychrotron source has been treated by Meierovich (1984) and Newberger (1984).

The radiation produced from the plasma configuration shown in the sec-

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

TABLE I
Simulation derived parameters based on the radiation properties of the double radio galaxy Cygnus A.

Parameter	*Simulation Value*
Galactic current, I_G	2.4×10^{19} A
Galactic magnetic field, B_θ	2.5×10^{-4} G
Galactic magnetic field, B_z	2.0×10^{-4} G
Plasma temperature, T	2.0 – 32.0 keV
Plasma density, n_e	1.79×10^{-3} cm^{-3}
Electric field strength, E_z	62 mV/m
Synchrotron power, P_{syn}	1.16×10^{37} W
Radiation burst duration	1.28×10^{14} s
Total energy	6.3×10^{62} J

ond frame of Figure 2 replicates both the isophotal and power spectra from double radio galaxies (Figure 3). Table I delineates the basic parameters used in the interacting galactic filament simulation.

Because the highly relativistic electrons depicted in Figure 2 flow in direction outwards from the plane of the figure, the synchrotron radiation is also beamed in this direction (Johner, 1988).

The monochromatic power of quasars and double radio galaxies span a range of about $10^{33}W - 10^{39}$W (Peratt, 1986b). For example, the "prototype" double radio galaxy Cygnus A has an estimated radio luminosity of 1.6-4.4 $\times 10^{37}$W. Together with the power calculated, the simulation isophotes are very close to those observed from this object (Peratt, 1986a). The left column of Figure 3 suggests that previously apparently unrelated double radio galaxies all belong to the same species but are simply seen at different times in their evolution.

8 Conclusions

The importance of applying electromagnetism and plasma physics to the problem of radio galaxy, galaxy and star formation derives from the fact that the universe is largely matter in its plasma state, i.e., a universe of plasma. The motion of this plasma in local regions can lead to pinches and ultimately condense states of matter. Where double layers form, strong electric fields can accelerate particles to high energies. The intensity and patterns of synchrotron radiation observed in the model simulations are in excellent agreement with those observed from double radio galaxies.

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

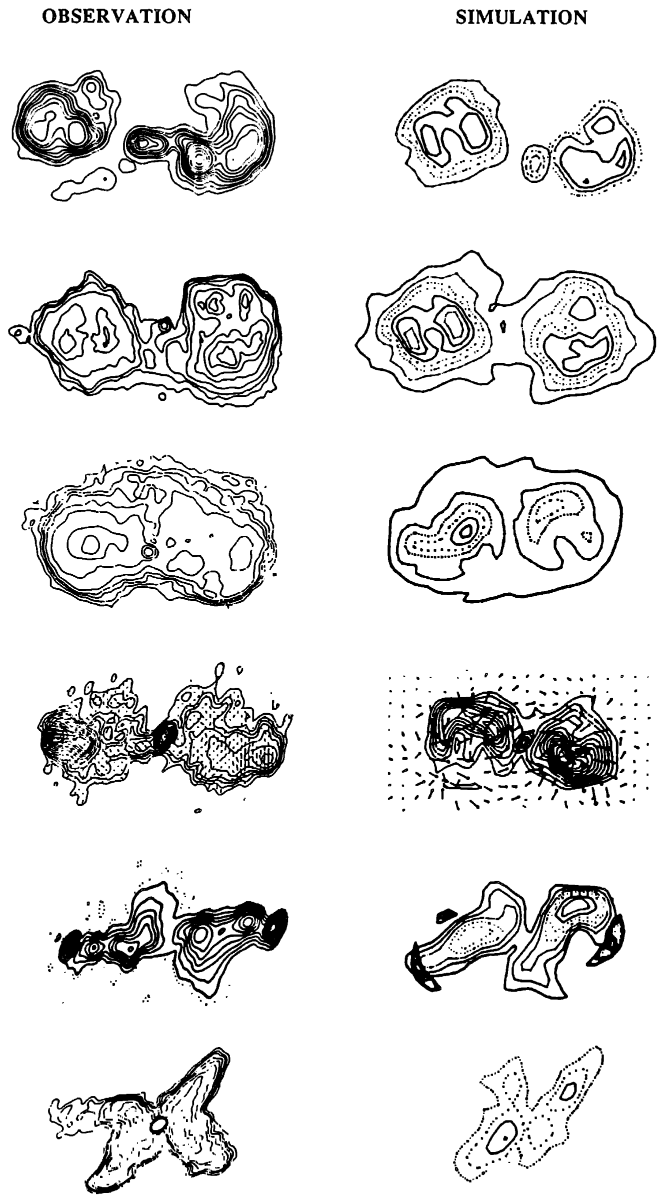

Fig. 3. (a) Synchrotron isophotes (various frequencies) of double radio galaxies, (b) Simulation analogs at time 10.4 Myr to 58.7 Myr. These times correspond to the epoch shown in frames 1 and 2 of Figure 2. Time increases from top to bottom.

This paper has summarized previous research relating to the morphology and large–scale dynamics of a plasma universe. It has also addressed the special case of the radiation seen by an observer when the observer happens to be located in the directed pattern of a synchrotron source. Many sources with this orientation can be expected in various regions of the sky from the

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

spaghetti of radiating filaments surrounding the viewer. The background spectrum caused by an extremely large number of synchrotron radiating filaments, when the observer is not in the directed beam, has been treated by Peratt & Peter (1988).

9 Acknowledgments

This project was supported by the Institute of Electrical and Electronics Engineers, the Division of Atmospheric Sciences of the National Science Foundation, The European Space Agency, and NASA Headquarters, Space Physics Division.

References

Akasofu, S.-I.: 1984, "The magnetospheric currents: An introduction to magnetospheric currents", in *Magnetospheric Currents*, T.A. Potemra, Ed. (Geophysical Monograph No.28), Washington, DC: Amer. Geophys. Union, pp.29–48

Alfvén, H.: 1950, *Cosmical Electrodynamics* Oxford, London

Alfvén, H.: 1981, *Cosmic Plasma* D. Reidel, Dordrecht

Alfvén, H.: 1986, "Double layers and circuits in astrophysics" *IEEE Trans. on Plasma Sci.*, bf Vol. PS-14, pp. 779-793

Alfvén, H.: 1987, "Electric currents in cosmic plasma", *Rev. Geophys. and Space Sci.* **Vol. 15**, pp. 271–284

Alfvén, H.: 1990, "Cosmology in the Plasma Universe", *IEEE Trans. Plasma Sci.* **Vol. 18**, pp. 5-10

Alfvén, H. and Herlofson, N.: 1950, *Phys. Rev.* **Vol. 78**, pp. 616

Alfvén, H., Fälthammar, C.-G.: 1963, *Cosmical Electrodynamics*, Oxford University Press

Bennett, W. H.: 1934, "Magnetically self-focusing streams", *Phys. Rev.* **Vol. 45**, pp. 890–897

Bohm, D. J.: 1979, in *A Question of Physics: Conversations in Physics and Biology*, Buckley, P., Peat, F. D. (eds.), University of Toronto Press, Toronto

Chan, C., Hershkowitz, N.: 1982, "Transition from single to multiple double layers", *Phys. Fluids* **Vol. 25**, pp. 2135–2137

Dessler, A. J.: 1984, "Evolution of arguments regarding existence of field aligned currents", in *Magnetospheric Currents*, T.A. Potemra, Ed. (Geophysical Monograph No.28), Washington, DC: Amer. Geophys. Union, pp.26–32

Eastman, T.: 1990, "Transition Regions in Solar System and Astrophysical Plasmas", *IEEE Trans. Plasma Sci.* **Vol. 18**, pp. 18-25

Fälthammar, C.-G.: 1983, "Magnetic-field aligned electric fields", *ESA J.* **Vol. 7**, pp.385–401

Fälthammar, C.-G.: 1986, "Magnetosphere-ionosphere interactions - near-earth manisfestations of the plasma universe", *IEEE Trans. on Plasma Sci.* **Vol. PS-14**, pp. 616–628

Johner, J.: 1988, "Angular distribution of the total cyclotron radiation of a relativistic particle with parallel velocity", *Phys. Rev. A* **Vol. 36**, pp. 1498–1501

Meierovich, B. E.: 1984, "Electromagnetic collapse, problems of stability, emission of radiation and evolution of a dense pinch", *Phys. Reports* **Vol. 104**, pp. 259–347

Newberger, B. S., M. I. Buchwald, R. R. Karl, D. C. Moir, and Starke, T. P.: 1984, "Synchrotron radiation from bennett beams", *Bull. Am. Phys. Soc.* **Vol. 29**, p. 1435

Peratt, A. L.: 1986a, "Evolution of the plasma universe: I. double radio galaxies, quasars, and extragalactic jets", *IEEE Trans. on Plasma Sci.* **Vol. PS-14**, pp. 639–660

Peratt, A. L.: 1986b, "Evolution of the plasma universe II. the formation of systems of galaxies", *IEEE Trans. on Plasma Sci.* **Vol. PS-14**, pp. 763–778

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System

1995Ap&SS.227...97P

Peratt, A. L.: 1990, "The evidence of electrical currents in cosmic plasma", *IEEE Trans. on Plasma Sci.* **Vol. 18**, pp. 26–32

Peratt, A. L.: 1992a, *Physics of the Plasma Universe*, Springer-Verlag, New York

Peratt, A. L.: 1992b, "Plasma Cosmology", *Sky and Tel.* **February**, p. 136

Peratt, A. L., Jones, M. E.: 1986, "Particle-in-cell simulations of heavy ion double layers", *IEEE Conf. Record.* Saskatoon, Canada

Peter, W., Peratt, A. L.: 1988, "Synchrotron radiation spectrum for galactic-sized plasma filaments", *Laser and Particle Beams* **Vol. 6**, Part 3, pp. 493–502

Verschuur, G. L.: 1995, "Interstellar Neutral Hydrogen Filaments at High Galactic Latitudes and the Bennett Pinch", *Astrophys. Space Sci.*

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System