3-DIMENSIONAL PARTICLE-IN-CELL SIMULATIONS OF SPIRAL GALAXIES

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ABSTRACT. The advent of 3-dimensional, electromagnetic, and fully relativistic particle simulations allows a detailed study of a magnetized plasma galaxy model. When two such models are simulated, an interaction yielding results resembling observational data from double radio sources, including the emission of synchrotron radiation, are obtained. Simulation derived morphologies, radiation intensities, frequency spectra and isophote patterns are produced by the model which can be directly compared to observational data. Long time simulation runs (~10^9 years) show the evolution of barred spiral galaxies with large scale bisymmetric magnetic field distributions having 100μG field strengths.

1. Introduction

The idea of a galactic magnetic field was first introduced by Alfvén (1937) to explain the isotropy of cosmic radiation. At that time no other apparent observational methods were available to test the possible existence of magnetic fields of large dimensions in space.

During the years following the development of radio astronomy, it became apparent that a large fraction of extra-galactic radio sources had a double structure, comprising two "clouds". It is now widely recognized that the radiation mechanism of these cosmic radio sources is the synchrotron process (Alfvén and Herlofson, 1950), so that each radio cloud contains, as essential ingredients, relativistic electrons (which must be accompanied by sufficient ions to preserve mean charge neutrality) and a magnetic field.

More recently, it has been suggested that the formation and evolution of nonhomogeneous cosmic clouds of plasma are controlled by magnetic fields of cylindrical symmetry (Alfvén, 1981). Others strongly advocating the importance of the magnetic field in galactic plasma formation include Vorontsov-Velyaminov (1959), Arp (1966), and Piddington (1981), who propose this field as the main ingredient in the morphology exhibited by peculiar and spiral galaxies. Synchrotron emission observed from a large number of peculiar, "interacting", and barred-spiral galaxies has led to theories suggesting an evolutionary connection between radio sources, peculiar, and normal galaxies (Shklovsky, 1960; Sturrock, 1969; Alfvén, 1971).

2. Filamentary Current Model

2.1 BIRKELAND CURRENTS

R. Beck et al. (eds.), Galactic and Intergalactic Magnetic Fields, 143–150.

An electromotive force $\int \mathbf{v} \times \mathbf{B} \cdot ds$ giving rise to electrical currents in conducting media is produced wherever a relative perpendicular motion of plasma and magnetic fields exists. An example of this is the (nightside) sunward-directed magnetospheric plasma that cuts the earth's dipole field lines, therby producing a potential supply that drive currents within the auroral circuit. The tendency for charged particles to follow magnetic lines of force and therefore produce field-aligned currents has resulted in the widespread use of the term "Birkeland currents" in space plasma physics (Dessler, 1984). Their discovery in the earth's magnetosphere in 1974 has resulted in a drastic chage in our understanding of aurora dynamics, now attributed to the filamentation of Birkeland charged-particle sheets follwing the earth's dipole magnetic-field lines into vortex bundles. The importance of Birkeland currents in astrophysical setting has been stressed by Fälthammar (1986).

Laboratory analogs to the magnetospheric Birkeland currents and a tabulation of possible occurances of Birkeland currents in astrophysical plasmas, with dimensions ranging from 10^2 m to nearly 10^{21} m, and currents of 10^5 A to 10^{20} A, have been given (Peratt, 1986).

2.2 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, 1986), including the "unfreezing" of magnetic fields, the acceleration of electrons to very high energies, the generation of magnetic fields, and the 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 wave-particle interactions, collisionless thermoelectric effects, magnetic mirror effects and double layers due to local charge separations. While all of the above have been studied in the laboratory and simulated by computers, 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 and computer simulations have shown the formation of a series of double layers along current-carrying plasma filaments.

When a double layer forms in a Birkeland current filament, a field-aligned electric field is generated which accelerates electrons and ions through the double layer, thereby producing a time-increasing, azimuthal magnetic field which serves to confine plasma in the filament.

3. Galactic Currents and Magnetic-Field Forces

3.1 GALACTIC-DIMENSIONED BIRKELAND CURRENTS

By extrapolating the size and strength of magnetospheric currents to galaxies, Alfvén (1981) suggests a number of current-conducting regions in interstellar clouds, the currents of which assist in cloud formation. For example, a galactic magnetic field of the order

$B_G = 10^{-5} - 10^{-6}$ G associated with a galactic dimension of $10^{20} - 10^{21}$ m suggests the galactic current be of the order $10^{17} - 10^{19}$ A. As a natural extension of the size hierarchy in cosmic plasmas, the existence of galactic dimensioned Birkeland currents or filaments has been hypothesized (Peratt and Green, 1983; Peratt 1986).

In the galactic dimensioned current model, the width of a typical filament may be taken to be 35 kpc (10^{21} m), separated from neighboring filaments by a similar distance. Since current filaments in laboratory plasmas generally have a width/length ratio of the range 10^{-3} to 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. It is expected that galaxies will form and evolve, from radio to barred spiral types, along the filaments where local electric fields occur.

3.2 BIOT-SAVART FORCES

In addition to confining plasma in filaments radially, the axial current flow produces another important effect; a long-range interactive force on other galactic filaments. Because of the guiding magnetic field B_z, the particles spiral as they drift (or accelerate, because of E_z), thereby producing an azimuthal component in the generalized current $\mathbf{I} = \mathbf{z} I_z + \theta I_\theta$. The resultant forces are long-range attractive ($F \sim -r^{-1}$) and short-range repulsive ($F \sim +r^{-3}$). The resultant forces are depicted in Fig. 1.

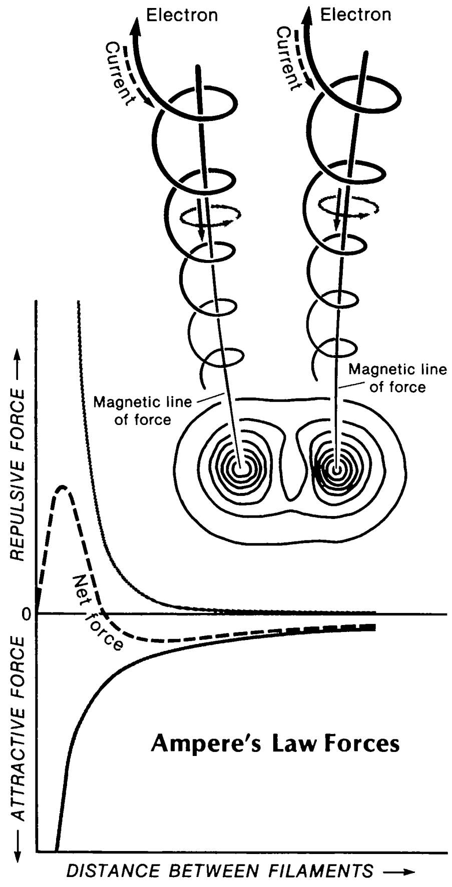

FIGURE 1. The forces between two adjacent galactic Birkeland currents. The parallel components of current (dark gray lines) are long-range attractive, while the counter-parallel azimuthal currents (light gray rings) are short-range repulsive. A projection of the current-induced magnetic fields is shown above the graph.

4. Double Radio Galaxies

Whenever the attractive force between simulation filaments causes their separation to be reduced to a distance such that the repulsive force becomes comparable to the attractive force, a burst of synchrotron radiation occurs. This burst occurs because the counterparallel azimuthal current force brakes the circular electron flow in both filaments, releasing the energy stored in the induced axial magnetostatic field. For the parameters used in these simulations (Peratt, 1986), 1.5×10^{51} joules of energy are released over about 5 Myr, producing 1.2×10^{37} W of synchrotron peak power. The power persists, but at lower levels, over some hundreds of Myr. Figure 2 compares isophotes of the simulation electromagnetic energy distribution at the filament cross-sections (where E_z is present) to the isophotes of synchrotron radiation of various double radio galaxies. A more complete sample appears elsewhere (Peratt, 1988).

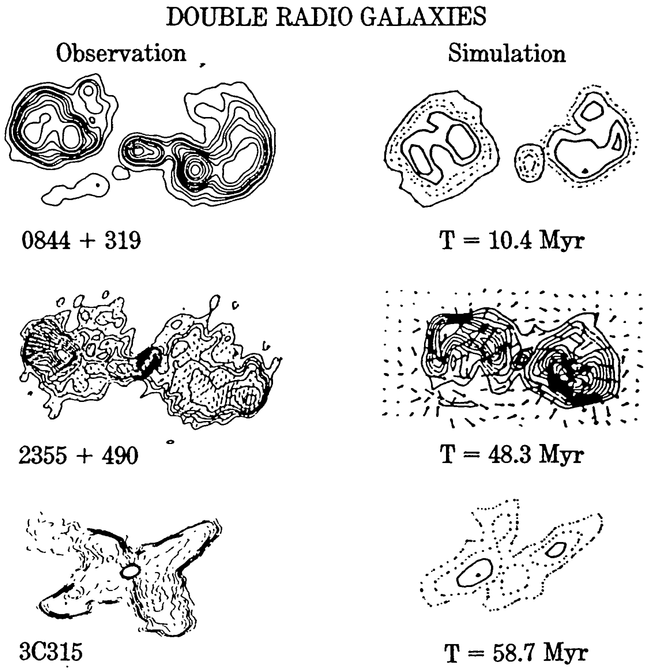

FIGURE 2. (left column) Synchrotron isophotes (various frequencies) of double radio galaxies. (right column) Simulation analogs. The width of the simulation in the axial direction (out of plane of page) is approximately 10kpc. Separation between lobes is 80kpc.

5. Spiral Galaxies

The long-term evolutionary sequence of interacting plasma filaments is shown in Fig. 3. Depicted in this figure are the cross sections of the dense plasma regions within two parallel current-conducting filaments. The morphologies and radiation properties of the simulated plasmas shown suggest a transistion through the following sequence of cosmic objects: double radio galaxy to radioquasar; radioquasar to radio quiet QSO's; radio quiet QSO's to peculiar and Seyfert spiral galaxies; and finally to normal or barred spiral galaxy types. The rotation curve associated with the last frame in Fig. 3 is in close agreement with curves typical of Sc type spirals (Peratt, 1986).

The magnetic fields in the simulated spiral galaxies were found to extend over the entire dimension of the galaxy and possess the following properties (Peratt, 1984): poloidal-toroidal field components; field strengths reaching 100μG, and a bisymmetric field configuration. [The bisymmetric or doubleness has been identified in many cosmic objects where the magnetic field plays a principle role (Peratt, 1990)]. These properties share many of the characteristics of recent galaxy observations (Beck, 1986). (Fig. 4).

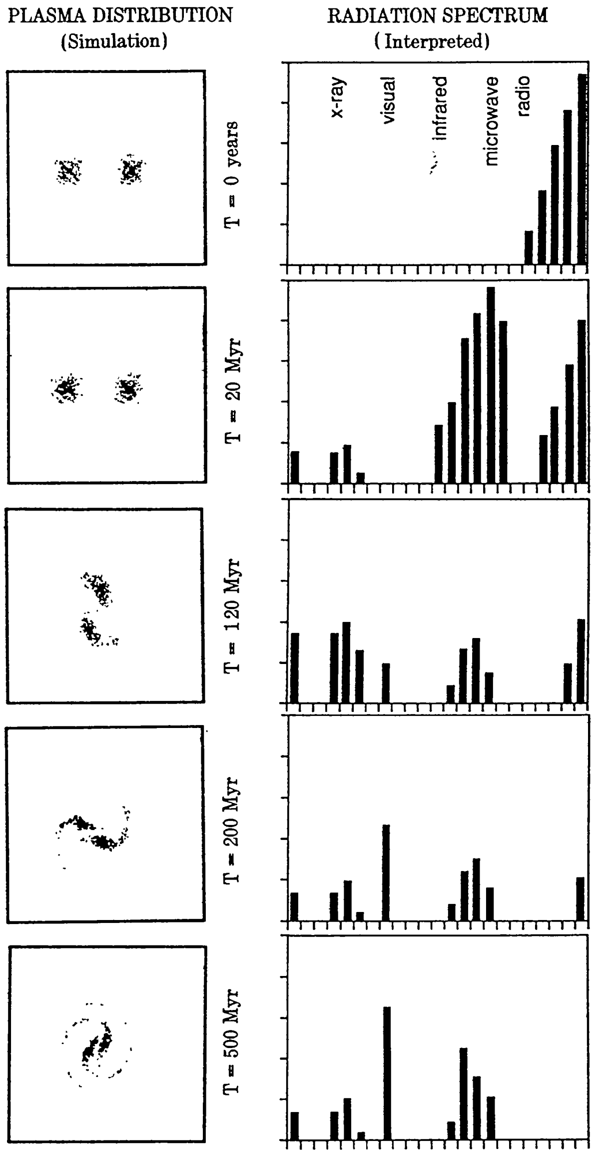

FIGURE 3. Simulation of spiral galaxy evolution. The radiation spectrum has been compiled from simulation results, laboratory measurements, and cosmic plasma theory (Peratt, 1990).

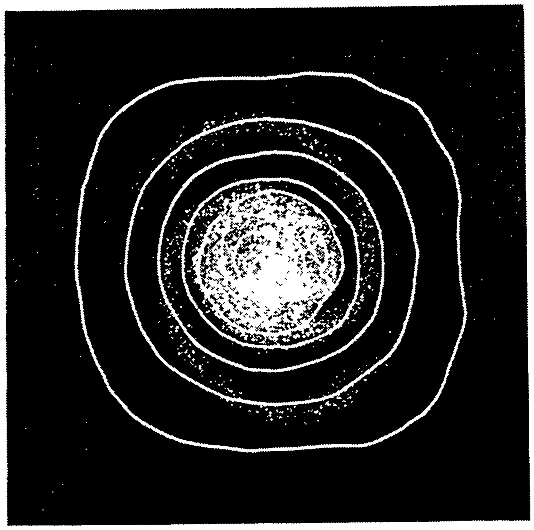

FIGURE 4. Computed magnetic field strength (squared) isobars overlayed on simulation galaxy.

Acknowledgement

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KAHN: It should be mentioned that Sydney Chapman worked on Birkeland's ideas more than 60 years ago, but he did not agree with Alfvén's later ideas on the subject.

PERATT: Sydney Chapman's scathing criticism of Kristian Birkeland's ideas (Proc. Birkeland Symp. on Aurora and Magnetic Storms, 1967, Ann. de Geophysique **24**, 1–490) is one of the most interesting chapters in the history of space science. The existence of field-aligned "Birkeland" currents was disputed because it is not possible to distinguish unambiguously between current systems that are field-aligned and those that are completely ionospheric from a study of surface magnetic field measurements. Sydney Chapman developed models of currents that were contained completely within the Earth's ionosphere which could adequately account for ground-based magnetic field observations obtained during magnetic storms.

Hannes Alfvén supported the concept of Birkeland currents and developed a theory for the generation of these currents by the solar wind.

This half-century long dispute was decided in Birkeland's favor in 1967 with the discovery of Birkeland currents by the U.S. Navy navigation satellite 1963–38C at ~1100 km altitude (Potemra, 1988, Laser and Particle Beams **6**, 503). Today, Birkeland currents are routinely measured and mapped within the magnetosphere and the discovery of a 5-megaampere Birkeland current connecting Io to Jupiter suggests that Birkeland currents exist on yet larger scales.

VERSCHUUR: You have a model in which very long Birkeland filaments interact. Are we to understand that at discrete intervals along these filaments the interactions you discussed occur? Then, if you twist the filaments a little, would you envisage the creation of clusters of galaxies?

PERATT: Yes. As with the case of filamentary laboratory plasma, where Birkeland filaments flare out, pinch, and twist at discrete intervals along the plasma, we expect the same to be true with galactic-dimensioned, current-carrying filaments. In the laboratory, the width/length ratio is generally in a range 10^{-3}–10^{-5} so that a typical cosmic Birkeland filament length may be of the order of 350 Mpc (Peratt, 1986, IEEE Trans. Plasma Sci. **16**, 639). This size is the same as that of the recently discovered supercluster complex filaments and ribbons.

KOUPELIS: Do I understand it correctly that the observed double radio sources are the cross-sections of the interacting magnetic filaments? What about the (commonly accepted) mass "outflows" connecting the "source" with the lobes? Could you tell us how your model explains the way they are formed, their direction of "flow", confinement, and "flow" velocities?

Also, would the interaction of magnetic filaments lead to the formation of both elliptical and spiral galaxies? How important is the gravitational (compared to the electromagnetic) interaction between the filaments?

PERATT: Double radio galaxies are the cross-sections of the interacting Birkeland filaments where double layers (i.e. thin regions of charge separation with $\vec{B}$ aligned $\vec{E}$ fields) occur. The simulations show that as the filamental currents increase through the charge-separation regions (because of the double layer $\vec{E}$ field), azimuthal magnetic isobars are produced which connect the two filaments. These isobars collect inter-filament plasma into an elliptical shaped void between filaments and also into two flat, narrow "jets" on either side of the central ellipse. The converging magnetic fields confining plasma in the "jets" also produce an induction accelerating field into the plane of the cross section, which causes the "jets" to synchrotron radiate out of the plane. Simulation field probes show that the field polarity can alternate on either side of the ellipse.

In contrast to the outflow model, the Birkeland filament model shows that the trapped synchrotron radiating plasma is not flowing out of a "central source" but can appear superluminal (up to 7c) because of the acute angle of the converging $\vec{B}$ fields along the "jet". As with the aurora, the source of energy is simply the motion of plasma across magnetic field lines on a Mpc scale, the energy of which is carried by the filaments. This process is invisible at optical wavelengths. At early time (10^7 yr), an elliptical galaxy is produced between filaments; at late time (10^9 yr), the thin charge-layer cross-sections converge and coalesce about the elliptical galaxy to produce a spiral galaxy. Gravitation becomes important when the plasma is converted into stars.