ADVANCES IN NUMERICAL MODELING OF ASTROPHYSICAL AND SPACE PLASMAS

Part II. Astrophysical Force Laws on the Large Scale

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Abstract. Advances in the simulation of astrophysical and cosmic plasmas are the direct result of advances in computational capabilities, today consisting of new techniques such as multilevel concurrent simulation, multi-teraflop computational platforms and experimental facilities for producing and diagnosing plasmas under extreme conditions for the benchmarking of simulations. Examples of these are the treatment of mesoscalic plasma and the scaling to astrophysical and cosmic dimensions and the Accelerated Strategic Computing Initiative whose goal is to construct petaflop (10^{15} floating operations per second) computers, and pulsed power and laser inertial confinement plasmas where megajoules of energy are delivered to highly-diagnosed plasmas. This paper concentrates on the achievements to date in simulating and experimentally producing plasmas scaled to both astrophysical and cosmic plasma dimensions. A previous paper (Part I, Peratt, 1997) outlines the algorithms and computational growth.

Keywords: Numerical modeling, numerical simulation, electric space, plasma universe, cosmology, galaxies, filamentation, electrical currents, quasars, double radio galaxies

1. History of Models of Astrophysical Phenomena

While this year marks the one-hundred and second anniversary of the discovery of electric space (Peratt, 1995), i.e., the realization of the need to apply plasma physics and electromagnetic forces to the understanding of the dynamical properties, evolution, and radiation to astrophysical data was lost with the death of Kristian Birkeland (1867–1917) and not to be resurrected until two decades later by Hannes Alfvén (1908–1995). However, by that time mathematicians had devised a new model for the state of the universe, one based entirely on gravitation relying solely on the only known states of matter at that time: solids, liquids, and gases.

This paper explores the reasons why the plasma state* was so long neglected and its necessity now for explaining the dynamics of the solar system and, undoubtedly, the 'space' beyond. As space is plasma, the necessity of very large scale computational platforms are invaluable for studying its properties because of space's extreme, if not infinite, dimensions.

* The term 'plasma' was not known until coined by the Nobel chemist Irving Langmuir in 1923.

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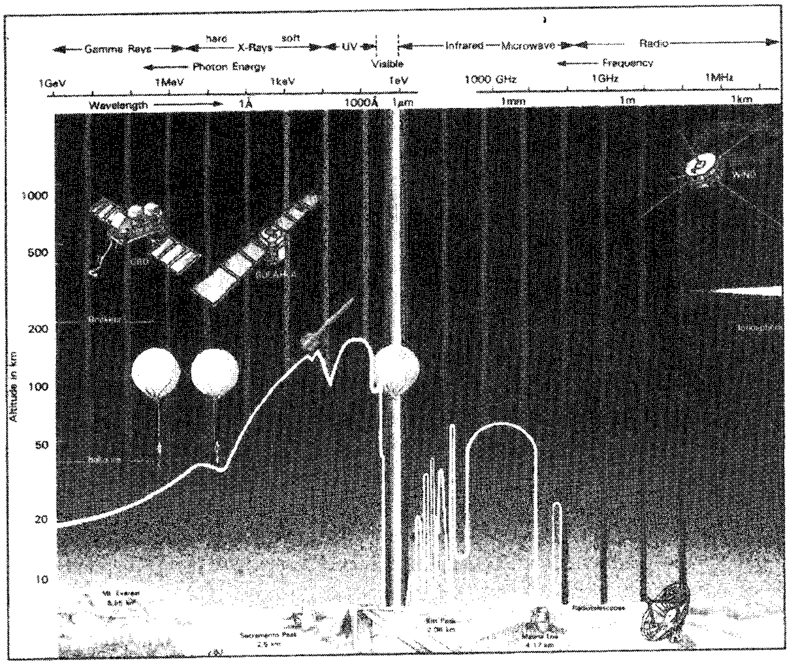

Figure 1. Altitude of penetration in the earth's atmosphere of electromagnetic radiation.

1.1. Bias of a Visual Universe

For millenia man has been privileged to observe the universe only in the visible. Thus, in the development of astronomy and astrophysics, what could be seen in a very narrow region, approximately 4000–7000 Angstroms, came to dominate the interpretation of the observed data (Figure 1). While radio astronomy became important in the 1950s, it had only minimal impact on already well-developed world models and in fact, some of the data could be claimed to support existing models. Not until the 1980s did much of the electromagnetic spectrum become known (or was even suspected to exist).*

With the exception of plant life, sight is one of the most important senses to life on earth and, neglecting phenomena such as lightning, the aurora, and the stars, favors the existence of the predominant three states of matter as found on the surface of earth: solids, liquids, and gases.

* The observation of a three degree Kelvin background temperature has, since 1965, been used to argue that the universe is finite-dimensioned. However, as early as 1896 Charles Edouard Guillaume in Meudon, France, estimated the temperature of space to be 5–6 K blackbody (Peratt, 1995). No dimension restrictions were placed on the prediction. Guillaume, together with his colleague Birkeland, advocated the dominance of electric forces in space, thus pioneering what is now called 'Electric Space'. Birkeland died as a working committee was nominating him for the Nobel prize in physics in 1917; Guillaume was awarded the Nobel prize in physics in 1920.

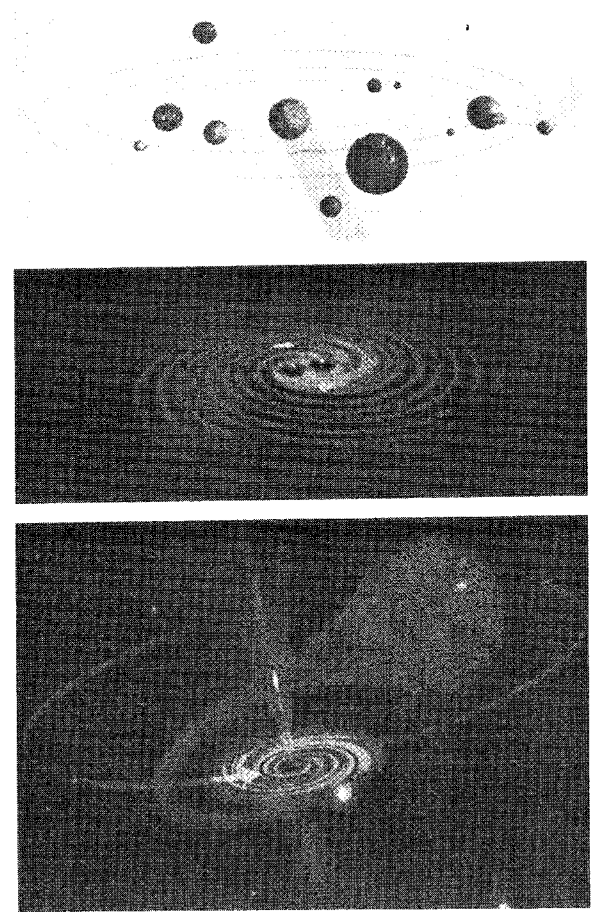

Figure 2. Newton's legacy: solid masses interacting gravitationally throughout the universe. (a) The planets and their satellites in serene and clocklike-motion that validated Newton's law of gravitation. This viewpoint, when applied to cosmic dimensions, encourages the advocacy of a mechanical clockwork universe favored since medieval times. (b) Artist's conception of astrophysical masses in gravitational interaction producing mass-density waves. (c) Artist's conception of matter at its highest density, a 'black-hole', gravitationally stripping solid and gaseous mass from a nearby star.

Thus, solids, liquids, and gases are the most identifiable forms of matter on earth and their transference to other 'masses' in the universe, such as the planets and their satellites, but also to the stars and galaxies seemed reasonable in the development of astronomical theories (Figure 2).

The merits of the artist's concepts depicted in Figure 2 are straightforward. This is a picture fully consistent with Newton's laws and the general development of astrophysics since his time. The only unknowns have to do with the properties of the solid (or gaseous or liquid) matter itself. The basic force law is

$$\mathbf{F} = m\mathbf{G} + \text{radiation forces}, \tag{1}$$

where **G** is the gravitational constant. The force between two objects separated a distance r is

$$F = -\frac{G m_1 m_2}{r^2}, \tag{2}$$

where m_1 and m_2 are the respective masses of the objects. In this scenario, space, being treated as a vacuum, is safely ignored.* As **G** is assumed constant, all interpretations of observed astrophysical forces **F** are then determined by m. Generally and especially at galactic and super-galactic dimensions, **F** is too large to be explained by the observed mass leading to the necessity of unobserved masses of various and differing magnitudes to balance Equations (1) and (2). Because the observed forces are so much greater than that predicted in this model, hypotheses such as 'black-holes' have arisen and the search for their existence has been of the highest priority in the field since their suggestion in 1969.

Today, one can question the relevance of Equations (1) and (2) to the study of the dynamical properties of astrophysical objects and the evolution of the universe.† Contrary to popular and scientific opinion of just a few decades ago, space is not an 'empty' void. Planetary and interplanetary spacecraft probes have shown space to be filled with high energy particles, magnetic fields, electric fields, and highly conducting plasma. The ability of plasmas to produce electric fields, either by instabilities brought about by plasma motion or the movement of magnetic fields, has popularized the term 'Electric Space' in recognition of the electric fields systematically discovered and measured in the solar system.

1.2. The Fourth, or 'Fundamental', State of Matter

For *plasma*, now often popularly referred to as the 'fourth state of matter',‡ the force laws are given by (Figure 3).

$$\mathbf{F} = m\mathbf{G} + e\,(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \text{radiation forces}, \tag{3}$$

where **E**, **B**, and **v** are the electric and magnetic field strengths, and the plasma velocity across field lines, respectively. The force between charges q is

$$F = -\frac{q^2}{4\pi\varepsilon_0 r^2}, \tag{4}$$

* Space, being the most voluminous of the cosmos, when treated as pure vacuum, gives a false sense that most of the universe is in a known state, the only unknowns being the point-like masses occupying Newton's universe. The discovery of the complexity of the planetary plasma magnetospheres proved that space is plasma with an electrodynamic complexity that exceeds that of the first three states of matter.

† At the time, the justification for the use of Equations (1) and (2) even in the near-earth environment was that any plasma ought to be electrically neutral and cancel out any electric forces.

‡ The first known use of the term '4th state of matter' occurs in Kristian Birkeland: Om Verdners Tilblivelse (On the creation of the Worlds), a lecture given in the Norwegian Academy of Science and Letters, January 31, 1913. Aars og Voss' Skoles festskrift p. 234.

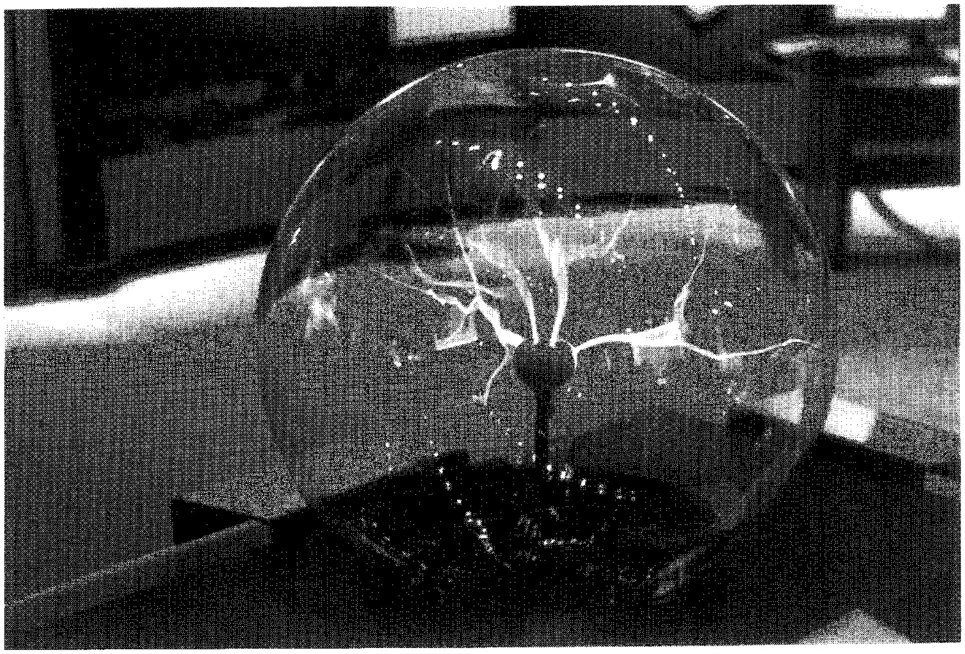

Figure 3. The fourth, or *fundamental*, state of matter. Unlike the so-called first three states of matter, the plasma state is highly energetic, filamentary, possesses a magnetic field, and is a prodigious producer of electromagnetic radiation over large regions of the electromagnetic spectrum. Courtesy of the Space Science Institute's Electric Space museum exhibition.

where ε_0 is the permittivity of free space. When the charges q are in motion with velocity v, the forces between the resulting currents $I = qv$ are

$$F = -\frac{\mu_0 I_1 I_2}{2\pi r} . \tag{5}$$

It is noteworthy that Equations (4) and (5) are inherently 10^{36}–10^{39} orders of magnitude stronger than are Equations (1) and (2). It is especially noteworthy that Equation (5) follows an r^{-1} dependency instead of the r^{-2} dependencies of the gravitational and electrostatic force laws Equations (2) and (4), making it the longest range force law in the universe. In addition, Equation (5) can be positive in sign, i.e., repulsive, when the interacting currents flow in the opposite sense. This can lead to scenarios where matter distributed for hundreds of megaparsecs can appear to fall towards no observable matter (e.g., a missing 'great attractor'). The importance of electromagnetic forces on cosmic plasma cannot be overstated; even in neutral hydrogen regions ($\sim 10^{-4}$ parts ionized), the electromagnetic force to gravitational force ratio is 10^7.

But perhaps the most profound difference between plasma and the first three states of matter is that plasma is a prodigious producer of electromagnetic radiation. In high-energy pulsed power and inertial confinement fusion (ICF) experiments, plasmas are intense producers of x-rays and even gamma rays. At cosmic di-

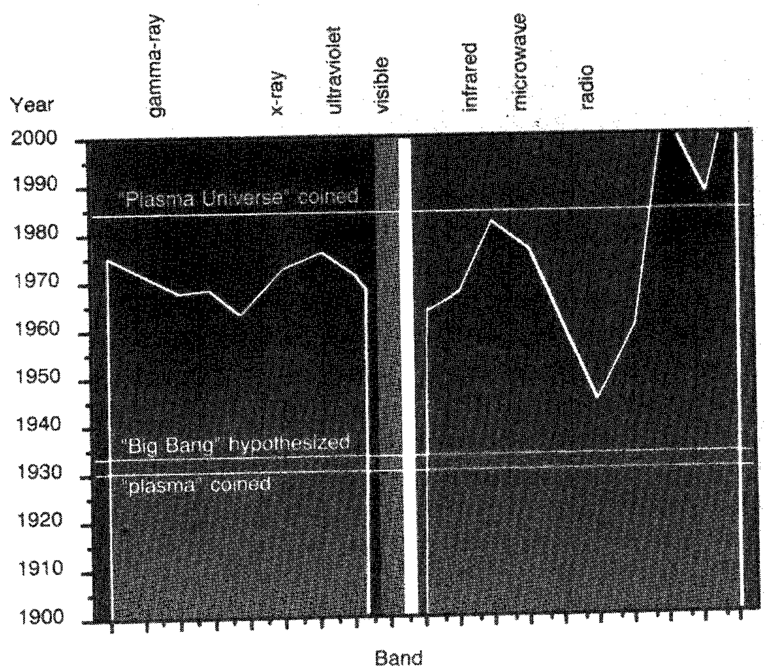

Figure 4. Measurement of the electromagnetic spectrum by wavelength by year.

mensions, charged particles accelerated by electric fields can produce energies as high as 10^{21} eV. Likewise, in the presence of magnetic fields, relativistic electrons produce synchrotron radiation, the source of much of the fluence observed by radio telescopes at radio and microwave wavelengths. Large scale plasma filaments ought also to produce very large fluences of electromagnetic radiation at extremely low frequencies, although these will be shielded by the earth's ionosphere and are yet to be observed. Figure 4 delineates the year of observational capability *versus* band that a particular portion of the entire electromagnetic spectrum became measurable. As illustrated, most of the spectrum, excluding very low frequencies, was not known prior to 1980.

Figure 5 illustrates where matter in the solid, liquid, and gaseous states is known to exist. Above the stratosphere, in the ionosphere and magnetosphere and as far beyond as we can observe, is matter in the plasma state. Below the lithosphere is again highly conducting, magnetized magma characterized by the hot plasma state of matter. Thus, the only places where the first three states of matter are know to exist with certainty in the universe are the crustal regions of the planets and their satellites in the solar system surrounding our plasma sun.*

* This observation must also be true about other stars and their surrounding systems.

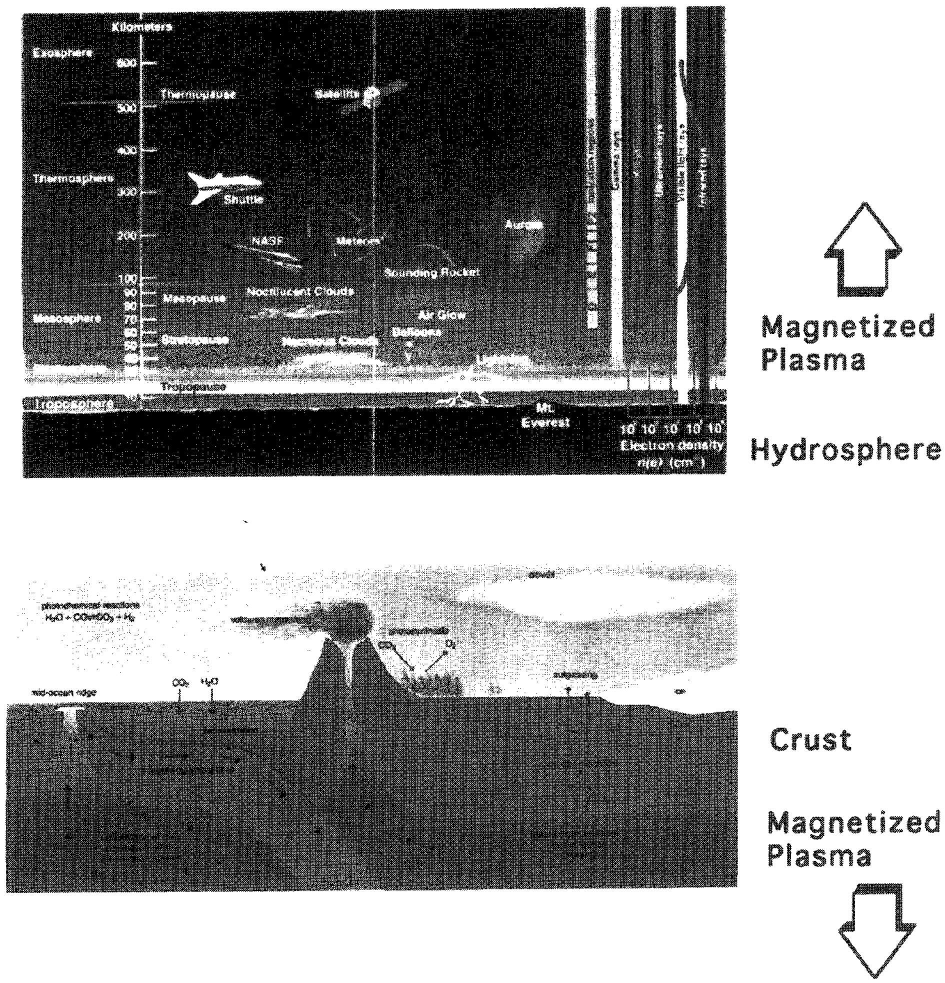

Figure 5. The planetary/satellite crusts and hydrospheres are the only known regions where a non-magnetized fluid treatment of matter is valid.

Today it is recognized that 99.999% of all observable matter in the universe is in the plasma state and plasmas are found at temperatures and densities far exceeding those that will support matter in the first three states (Figure 6).

2. Large Scale Structure of the Plasma Universe

Among the earliest predictions about the morphology of the universe that differed significantly from the common astrophysical assumption is that the universe be filamentary (Alfvén, 1950, 1981, 1990). Plasmas in electric space are energetic (because of electric fields) and they are generally inhomogeneous with constituent

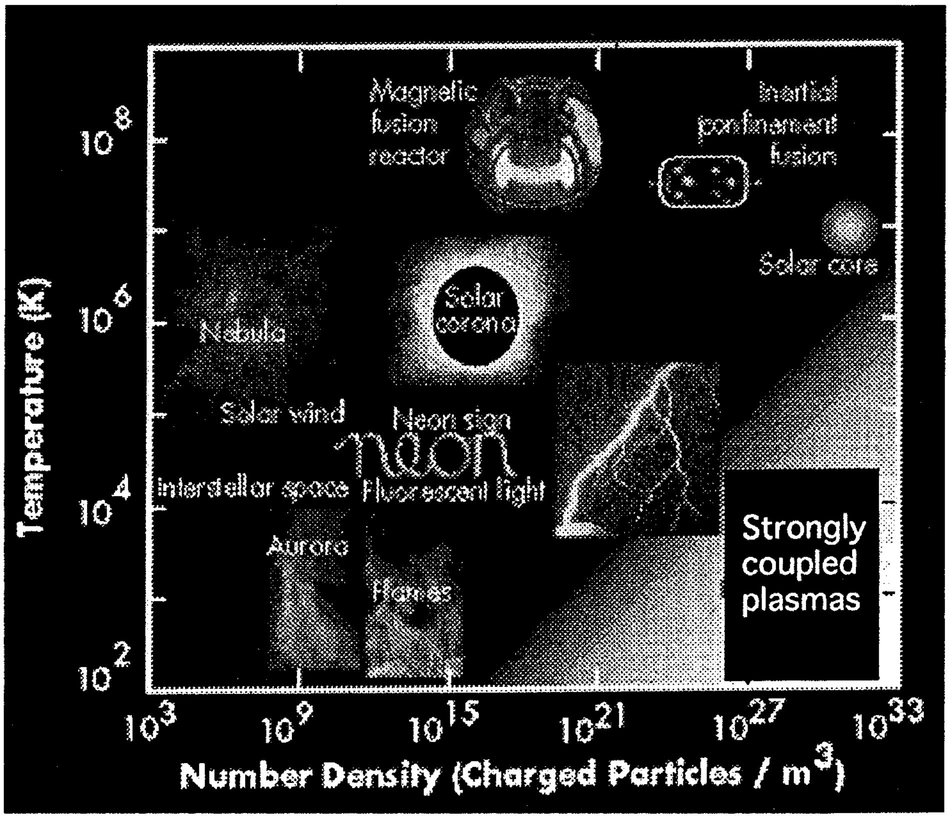

Figure 6. Remarkable range of temperatures and densities of plasmas. Courtesy of the Princeton Plasma Physics Laboratory.

parts in motion. Plasmas in relative motion are coupled by the currents they drive in each other and non-equilibrium 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 with 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 intractability of complex filamentary geometries, intense self-fields, non-linearities, 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 constitutive 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'.

In contrast to the viewpoint depicted in Figure 2 is the approach by Alfvén, who reduced cosmic problems to laboratory plasma physics problems whose properties could be investigated *in situ*.* The plasma analog of Figure 2 is shown in the circuit diagram of Figure 7. The attributes of the circuit approach is that both mechanical and electrical mechanisms, including the radiation observed at non-visual wavelengths, can be studied in great detail. The circuit, which conducts currents, allows the study of the flow of charged particles in the presence of electromagnetic fields, and includes discrete particle effects such as double layers (charge separation from current instabilities) and synchrotron radiation (fast electrons in the presence of a magnetic field). When the currents are smoothed out, the fluid magnetohydrodynamic equations are obtained, which Alfvén used to great success in his study of the sun. Thus, spicules, prominences, flares, and other temporal inhomogeneities can be brought under investigation via the circuit description approach that has been highly successful in modern space science. Moreover, the circuit approach allows for the reproduction of the entire electromagnetic spectrum as well as the pinch dynamics important to the study of the formation of stars in primordial plasma

* Laboratory astrophysics, pioneered by Birkeland and used extensively by Alfvén, is a revolutionary change from classical astronomy reaching back to Ptolemy. Classical astronomy divided the study of earth and the heavens into the 'mundane' and the 'celestial', respectively, and no study of the mechanisms of the heavens could be performed on earth. The modern trappings of celestial *versus* mundane remain with us today in the form of 'black holes' and 'dark matter' whose theories are not falsifiable and therefore not open to scientific inquiry.

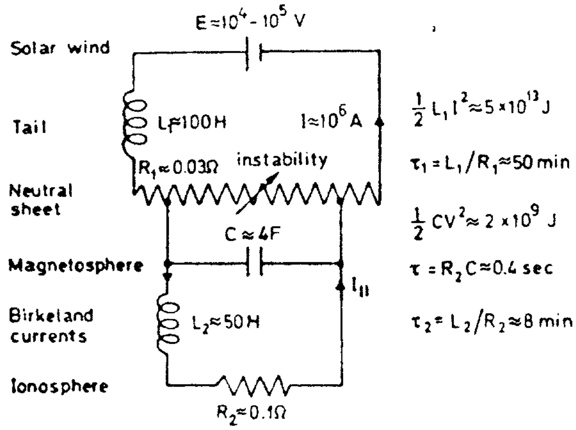

Figure 7. Generic circuit description of a space plasma problem (in this case, the flow of Birkeland currents in the Earth's magnetosphere/ionosphere.

flows. Unfortunately, the method appears unknown in classical astronomy when applied to problems of cosmic importance.

2.1. 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 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 the realization that the structure in auroral draperies are caused by the filamentation of Birkeland charged-particle sheets following the earth's dipole magnetic-field lines into vortex current bundles.

2.2. 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 and Fälthammar, 1963; Peratt, 1986).

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

2.3. Magnetic Ropes

Surface currents, delineating plasma regions of different magnetization, temperature, density, and chemical composition give space a cellular structure (Alfvén and 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

$$v = (\mathbf{E} \times \mathbf{B}) / E^2. \tag{6}$$

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.

3. Simulating the Astrophysical and Cosmical Plasma Phenomena

Because of the above, the modeling of astrophysical and cosmical phenomena requires a plasma treatment. This then requires a formidable computational platform: a full three-dimensional plasma treatment, with three spatial components each in electric and magnetic fields, and the inclusion of radiation packages. Because of **E** and **B**, the plasma charges tend to spiral around **B** as they accelerate along **E** or undergo other complex and unstable motion because of space-charge effects. This task of simulating electromagnetic plasma is an order of magnitude more complex than a simple gravitational simulation where gravity is the only force component on masses in simple free-fall. The remainder of this section describes the physical mechanisms and results in the simulation of cosmic plasma. A complete description of the algorithms and computational parameters have been given elsewhere (Peratt, 1996, 1997).

3.1. 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 ($\gamma = (1 - \beta)^{-1/2}$); and polarized electromagnetic wave vectors.

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

Because of their intense powers and complex morphologies, double radio galaxies and quasars have been an enigmatic problem to astronomy since their serendipitous discovery. Figure 8 illustrates the synchrotron isophotes of several of these sources.

However, if the filamentary plasma universe model is used, the isophotes of both double radio galaxies and quasars are readily explained. The radiation produced from the two nearest plasma filaments in interaction replicates both the isophotal and power spectra from double radio galaxies as shown in Figure 9. Table I delineates the basic parameters used in the interacting galactic filament simulation which are consistent with a number of previous estimates.

Because the highly relativistic electrons depicted in Figure 9 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}–10^{39} W (Peratt, 1986b). For example, the 'prototype' double radio galaxy Cygnus A has an estimated radio luminosity of 1.6–4.4×10^{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 9 suggests that previously apparently unrelated double radio galaxies all belong to the same species but are simply seen at different times in their evolution.

3.2. 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*:

$$\frac{\mu_0}{8\pi} I^2(a) + \frac{1}{2} G\bar{m}^2 N^2(a) = \Delta W_{Bz} + \Delta W_k \tag{7}$$

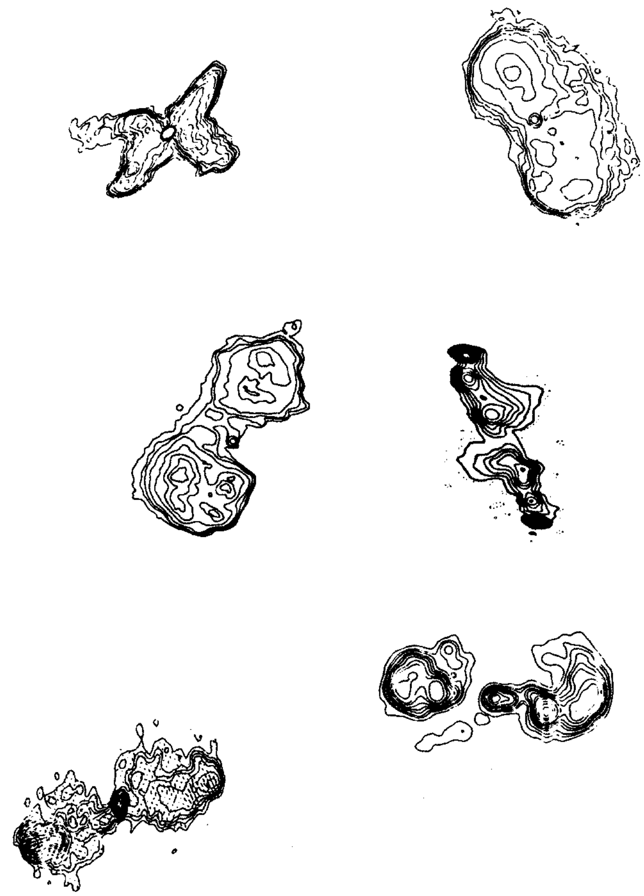

Figure 8. Synchrotron isophotes (various frequencies) of a random assortment of double radio galaxies and quasars.

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_{B_z} and ΔW_k are the differential beam magnetic and kinetic energies, respectively (Peratt, 1992a).* Thus, whether or not a current or beam is gravitationally balanced, electromagnetically balanced, or force-free, depends on the magnitude of the individual terms in Equation (7).

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,

$$\mathbf{F}_{21} = \int \mathbf{j}_2 \times \mathbf{B}_{21} d^3r \tag{8}$$

* When current rotation and transient phenomena are important, the *Generalized Bennett Condition* may be used in place of Equation (7) (Peratt, 1992a, chap. 2).

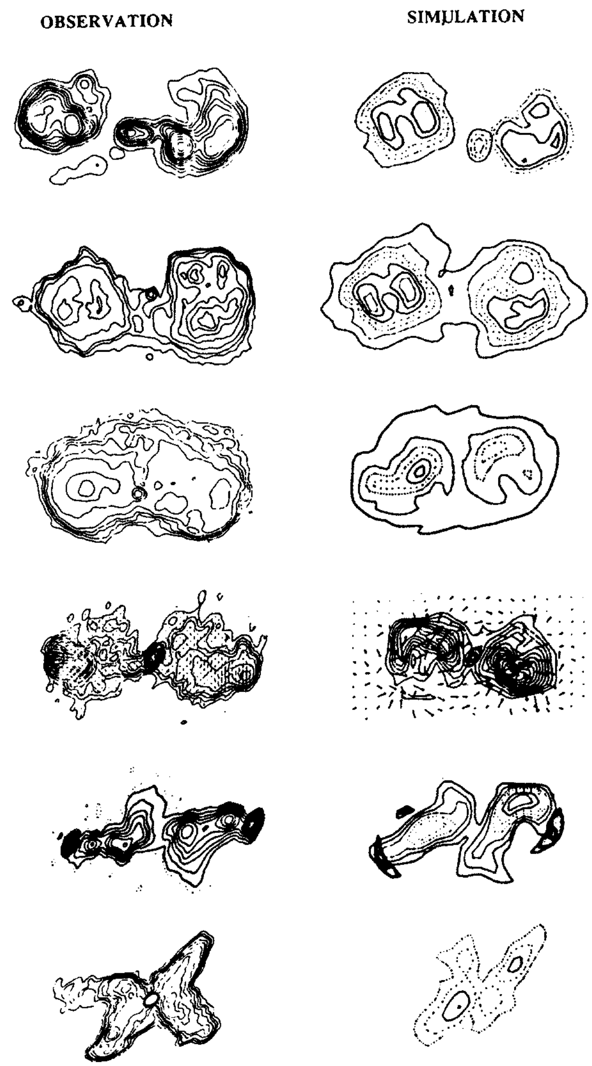

Figure 9. (a) Synchrotron isophotes (various frequencies) of double radio galaxies. (b) Simulation analogs at time 10.4 to 58.7 Myr. Time increases from top to bottom.

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.*

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

* 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.

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

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, 1992b), it is useful to reproduce the evolutionary sequence in this paper. Figure 10 illustrates the cross-sections of the filaments over a 10^9 yr period.

3.3. Rotation Velocities

Rotational velocities of spiral galaxies are obtained by measuring the Doppler shift of the Hα line emitted by neutral hydrogen in the spiral arms. If the galaxy is at a cant towards earth, the emission-line in the arm moving away from earth is red-shifted while the line in the arm moving towards earth is blue-shifted. The first Doppler shift measurements of the radial velocities indicated that these were flat, rather than following the Keplerian law. If galaxies were gravitationally bound systems, their outer mass should follow Kepler's laws of motion and be slower than the inner mass. The flat rotation curves of galaxies has been cited as the strongest physical evidence for the existence of dark matter. In this scenario a massive halo of dark matter has been evoked to produce the flat rotation curves. However, the rotation curves are not really flat; they show appreciable structure representative of an instability mechanism within the arms. This instability precludes the existence on any external halo of matter around galaxies that, while making the rotation curves flat, would also dampen any instability growth.

Since E_z is out of the plane of the page, the column electrons spiral downward in counter-clockwise rotation while the column ions spiral upward in clockwise

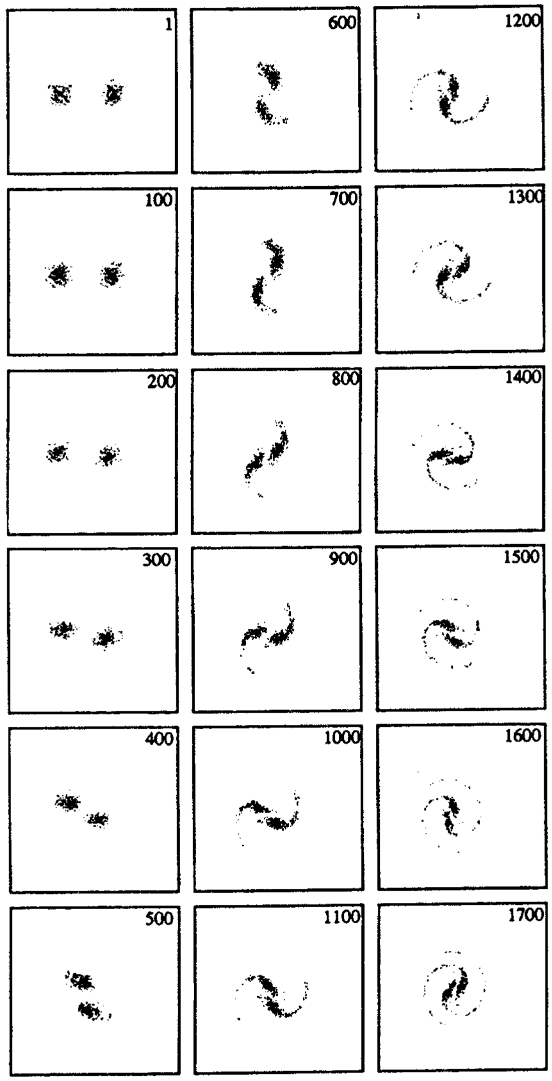

Figure 10. Single frame stills of plasma in the simulation of two adjacent Birkeland filaments: $\omega_c/\omega_p = 3.0$, $T_{e0} = T_{i0} = 32$ keV, $E_{z0} = 62$ mV/m. Total time elapsed: $\approx 10^9$ yr. The initial dimensions in frame 1 are: radius of filaments $r_{\text{filaments}} = 17.5$ kpc,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

rotation. A polarization induced charge separation also occurs in each arm, which, as it thins out, produces a radial electric field across the arm. Because of this field, the arm is susceptible to the diocotron instability (Peratt, 1992). This instability appears as a wave motion in each arm and is barely discernible in the single frame photographs in Figure 10 at late times. However, the instability is readily apparent in the simulation spiral rotational velocity curve (Figure 11).

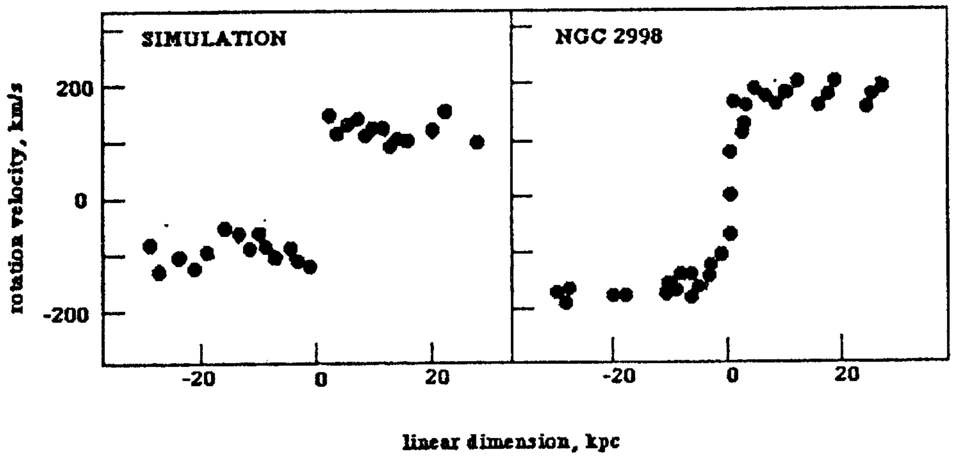

Figure 11. Spiral galaxy rotational velocity curves. Note the well–defined structure on the 'flat' portions of the curves.

The velocity consists essentially of a linearly increasing component due to a central body undergoing rigid rotation, with two 'flat' components on either side of $r = 0$ due to the trailing arms. The diocotron instability modulates the 'flat' components at the strong-magnetic-field, low-density instability wavelength $\lambda \approx 2.5\Delta r$, where Δr is the width of an arm.

3.4. The Association of Neutral Hydrogen with Galactic Magnetic Fields

Neutral hydrogen distributions are characteristic of spiral galaxies but not pre-spiral galaxy forms. Because the rotation velocities of spiral galaxies are determined by the motion of neutral hydrogen, it is desirable to know the process for neutral hydrogen accumulation in late-time galaxies.

In the plasma universe model, spiral galaxies form from the interaction of current-carrying filaments at regions where electric fields exist. The individual filaments are defined by the *Carlqvist Condition* that specifies the relationship between gravitational and electromagnetic constraining forces (Verschuur, 1995). In this model, whether or not neutral hydrogen and other neutral gases form from hydrogenic plasma depends of the efficiency of convection of plasma into the filament.

When an electric field is present in a plasma and has a component perpendicular to a magnetic field, inward convection of the charged particles occurs. Both electrons and ions drift with velocity

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

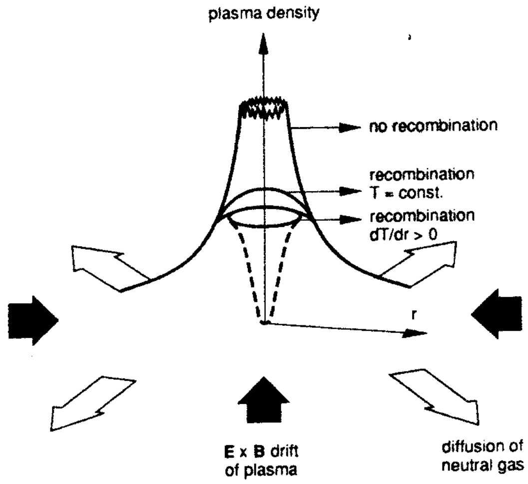

Figure 12. Plasma density profile as a function of radius shown qualitatively for three cases: No recombination, recombination with temperature T = constant, and recombination with a lower central temperature.

so that the plasma as a whole moves radially inwards. The material thus forms as magnetic ropes around magnetic flux tubes. Magnetic ropes thus contain material filaments that have a higher density than the surrounding plasma.

When a plasma is only partly ionized, the electromagnetic forces act on the non-ionized components only indirectly through the viscosity between the ionized and non-ionized constituents. For a filament, the inward radial velocity drift is

$$v_r = E_z / B_\phi$$

for the case of an axial electric field and azimuthal magnetic field (induced by the axial current I_z). Hence, at a large radial distance r, the rate of accumulation of matter into a filament is

$$\frac{dM}{dt} = 2\pi r v_r \rho_m = (2\pi r)^2 \rho_m \frac{E_z}{\mu_0 I_z} \,. \tag{9}$$

Marklund (1979) found a stationary state when the inward convections of ions and electrons toward the axis of a filament was matched by recombination and outward diffusion of the neutralized plasma (Figure 12). The equilibrium density of the ionized component normally has a maximum at the axis. However, because of the radiated loss of energy, the filament cools and a temperature gradient is associated with the plasma. Because of this hollow cylinders, or modifications of hollow cylinders of matter, will form about the flux tubes.

Because the radial transport depends on the ionization potential of the element, elements with the lowest ionization potentials are brought closest to axis. The most abundant elements of cosmical plasma can be divided into groups of roughly equal ionization potentials: He (24 eV); H, O, N (13 eV); C, S (11 eV); and Fe, Si,

Mg (8 eV). These elements can be expected to form hollow cylinders whose radii increase with ionization potential. Helium will make up the most widely distributed outer layer; hydrogen, oxygen, and nitrogen should form the middle layers, while iron, silicon, and magnesium will make up the inner layers. Interlap between the layers can be expected and, for the case of galaxies, the metal-to-hydrogen ratio should be maximum near the center and decrease outwardly. Both the convection process and luminosity increase with the field E_z.

For the case of a fully ionized hydrogenic plasma, the ions drift inwards until they reach a radius where the temperature is well below the ionization potential and the rate of recombination of the hydrogen plasma is considerable. Because of this 'ion pump' action, hydrogenic plasma will be evacuated from the surroundings and neutral hydrogen will be most heavily deposited in regions of strong magnetic field.

3.5. Axisymmetric and Bisymmetric Magnetic Field Patterns in Spiral Galaxies

When the ion pump-magnetic field action was discovered in the laboratory, there existed some debate as to whether galaxies possessed magnetic fields at all. Today, it is known that large-scale magnetic fields do exist in spiral galaxies. For example, the Effelsberg radio telescope has collected polarization data from about a dozen spiral galaxies at 6 to 49 cm wavelengths (Beck, 1986, 1990). Rotation measures show two different large-scale structures of the interstellar fields: Axisymmetric-spiral and bisymmetric-spiral patterns (Krause et al., 1989), as shown in Figure 13.

The orientation of the field lines is mostly along the optical spiral arms. However, the uniform field is often strongest outside the optical spiral arms. For example, in the case of galaxy IC 342, two filamentary structures were found in the map of polarized intensity (Figure 14). Their degree of polarization of $\approx 30\%$ indicates a high degree of uniformity of the magnetic field on the scale of the resolution (≈ 700 pc). These filaments extend over a length of ≈ 30 kpc and hence are the most prominent magnetic-field features detected in normal spiral galaxies so far.

A detailed analysis of the rotation measure distribution in a spiral arm southwest of the center of the Andromeda galaxy M31 (Beck et al., 1990) shows that the magnetic field and a huge HI cloud complex are anchored together (Figure 15). The magnetic field then inflates out of the plane outside the cloud. The tendency for the magnetic field to follow the HI distribution has been noted in several recent observations. Circumstantial evidence has accumulated which suggests that there is a close connection between rings of CO and Hα seen rotating in some galaxies and the magnetic fields in the nuclear regions. This is particularly apparent in observations of spiral galaxies viewed edge-on. This scenario has also been invoked for our Galaxy (Wielebinski, 1989).

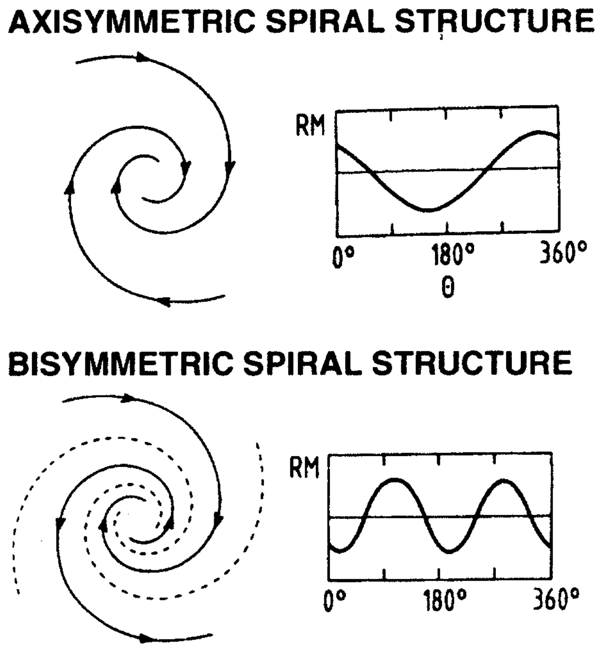

Figure 13. Definition of Axisymmetric-spiral and bisymmetric-spiral patterns.

Neutral hydrogen is detected from galaxies via the van de Hulst radio-emission line at 21.11 cm (1.420 GHz). High-resolution observation of neutral hydrogen in irregular and spiral galaxies usually reveal extended HI distributions. Contour maps of the HI typically show a relative lack of HI in the cores of spiral galaxies but high HI content in the surrounding region, usually in the shape of a 'horseshoe'. This region is not uniform but may have two or more peaks in neutral hydrogen content. Figure 16 (right) shows an example of the HI distribution in a spiral galaxy.

Figure 16 (left) shows the plasma spiral formed in this simulation overlayed on its magnetic field line (squared) isobars. The diameter of the spiral is about 50 kpc with a mass of 10^{41} kg, i.e., a size and mass of that observed from spiral galaxies. A direct comparison to observations is made by superimposing the HI distribution in NGC 4151 on its optical photograph. The observation shows two peaks in neutral hydrogen surrounding a void. The void is orientated towards one of the arms. The simulation allows the two peaks to be traced back to their origin. Both are found to be the remnants of the originally extended components, i.e., cross-sections of the original Birkeland filaments. The hydrogen deficient center is the remnant of an elliptical galaxy formed midway between the filaments, in the magnetic null.

Figure 17 shows the magnetic field orientations of the vertical (or 'parallel' to the line-of-sight) and the circumferential magnetic fields in an Sc type galaxy. Because of the acute reversals of the circumferential magnetic field, whether or not an observer sees axisymmetric or bisymmetric patterns in the synchrotron radiation

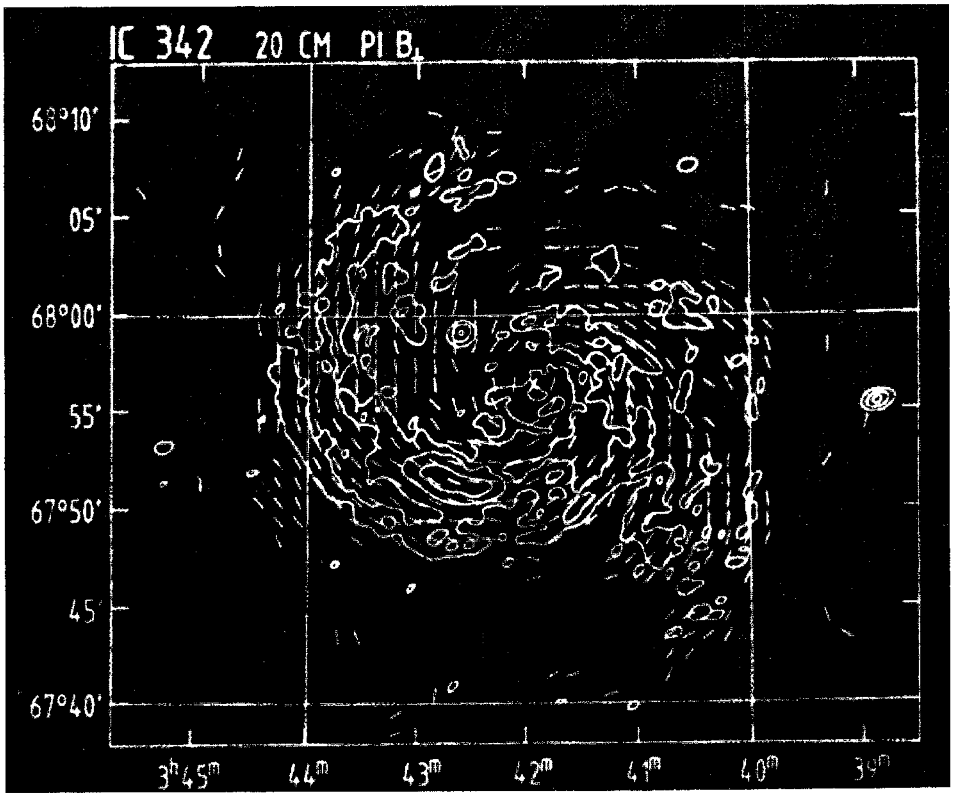

Figure 14. Contour map of the linearly polarized intensity at 1.4 GHz. The HPBW is 45″. Contour levels are 0.06, 0.12, 0.24, 0.48, 0.96 mJy/b.a. and the rms noise is 0.03 mJy/b.a. The vectors represent the orientation of the observed E-vectors and the degree of linear polarization.

depends on the location of the parallel electric fields in the radiating plasma with respect to the circumferential magnetic field.

4. Conclusions

Based on optical observations of astrophysical objects, early models of the universe were founded solely on the assumption that the mass found throughout the universe was the same as that found on the crustal regions of the planets and satellites of the solar system. Not until the 1980s was it clear that most of the observable universe as seen over large portions of the electromagnetic spectrum consisted of matter in the fourth, or fundamental state; *plasma*. However, without the computational resources to simulate astrophysical and cosmic plasmas in three dimensions and the experimental facilities to produce plasmas of similar properties with diagnostics sufficient to benchmark them to the simulations, the field languished in favor of simpler models developed in the 1920s.

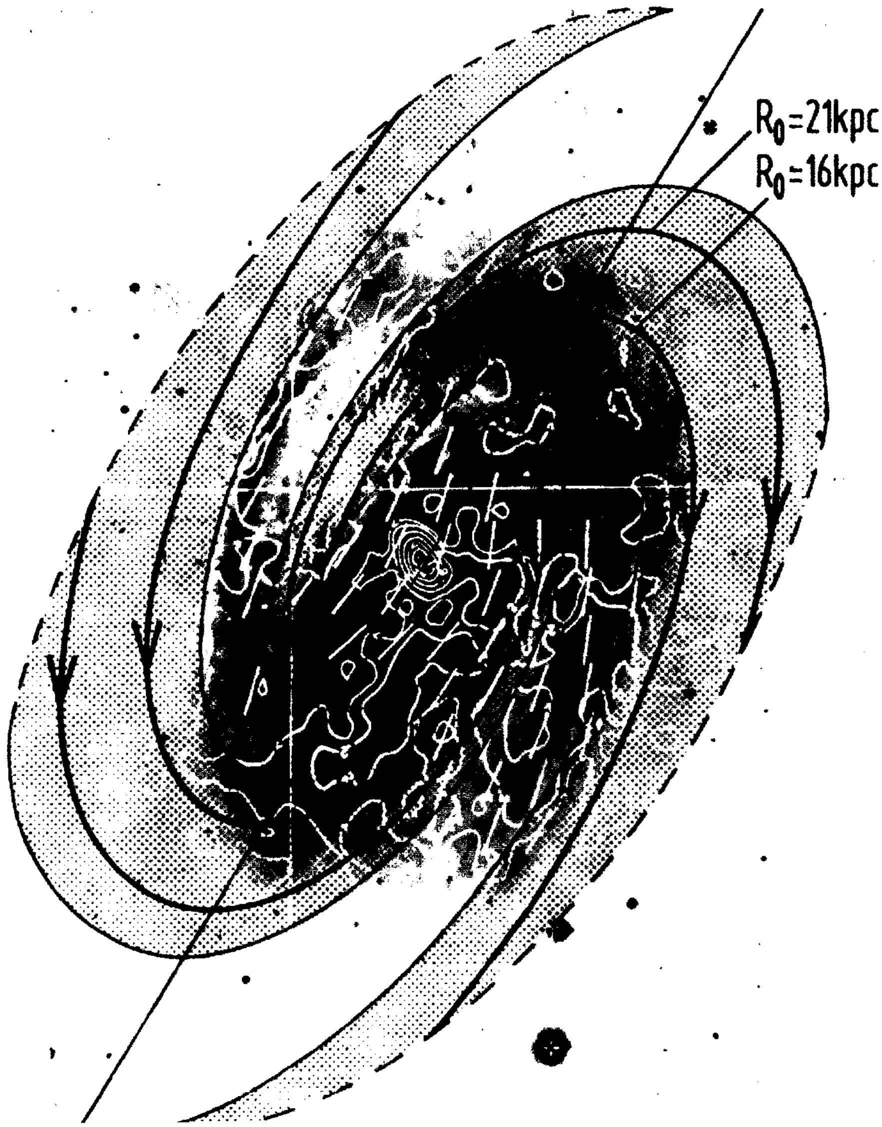

Figure 15. Magnetic field spirals between 3 kpc $< R <$ 12 kpc calculated from the observed rotation measure distributions of both rings. The dotted area sketches the overlapping regions of uncertainty concerning the locations of the spirals. The magnetic field direction is indicated by the arrows. Note that the neutral lines are located in between the dotted areas, namely in the interarm areas.

With the advent of multi-teraflop computational resources reaching towards petaflop speeds and the emergence of facilities capable of producing high-energy density plasmas that can be adequately diagnosed, the capability now exists for studying the evolution of the universe by including the most abundant state of matter observed, that of plasma. With this resource, replication of many of the fine

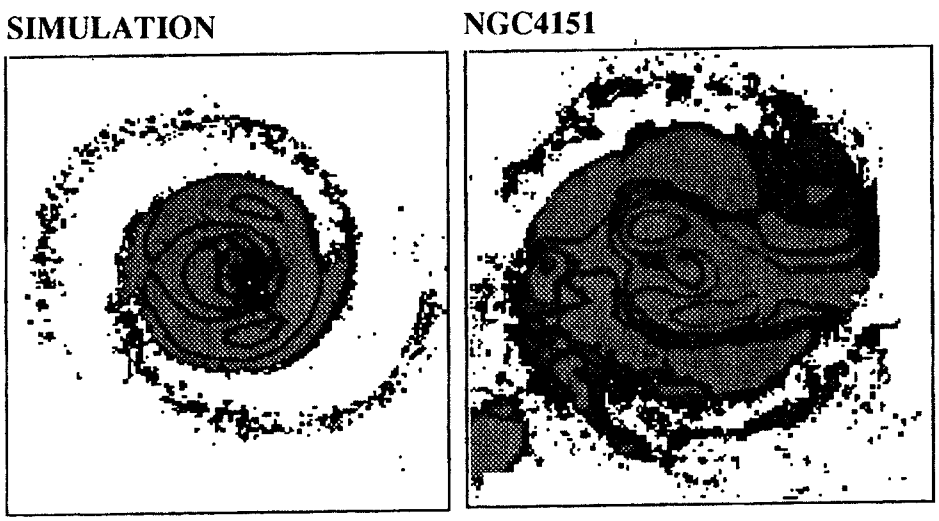

Figure 16. Left: Simulation magnetic energy density superimposed on simulation galaxy. In both cases a 'horseshoe' shaped cusp, opening towards a spiral arm, surrounds a magnetic field/HI minima core. Within the cusp, two magnetic field/HI peaks are observed. Right: HI distribution superimposed on an optical photograph of NGC 4151.

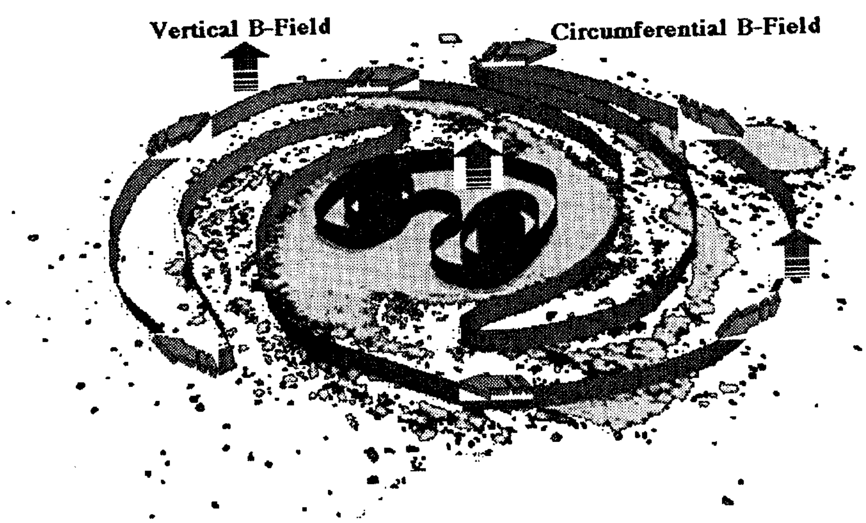

Figure 17. Simulated magnetic fields in an Sc type galaxy.

detail features observed from cosmic objects appears feasible leading to a better understanding of the nature of our infinitely evolving universe.

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