Plasma Physics Primer: The Electromagnetic Toolkit of Cosmology

universe-physics.com — Electrodynamic Cosmology Series

Abstract

More than 99.99% of the observable universe is plasma — ionised gas dominated by electromagnetic forces. This primer introduces the fundamental plasma phenomena that structure the cosmos: Birkeland currents (the wires of space), z-pinches (nature's compression engine), double layers (nature's particle accelerators), and plasma instabilities (the pattern generators). These phenomena are scale-invariant, operating identically from laboratory devices to the cosmic web. Understanding them is essential for the electrodynamic cosmology presented throughout this site.

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1. The Plasma Universe

Plasma is ionised gas in which electrons and ions move freely and electromagnetic forces dominate. Stars, nebulae, the interstellar medium, the intergalactic medium, and the solar wind are all plasmas. Standard cosmology ignores this, treating electromagnetic effects as minor perturbations on gravitational dynamics.

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2. Birkeland Currents

Named after Kristian Birkeland (1908), these are current-carrying plasma filaments self-confined by their own magnetic field. Key properties:

- **Self-confining:** The current's own magnetic field provides the confining pressure
- **Scale-free:** The same physics operates from millimetre to megaparsec scale
- **Filamentary:** Naturally form long, thin filaments — explaining the filamentary cosmic web
- **Attracting in pairs:** Parallel currents attract (Ampère's law) — filaments pair up, rotate, and merge

Birkeland currents have been observed at every scale: Earth's magnetosphere, the Sun, stellar jets, planetary nebulae, galaxy filaments, and the intergalactic medium.

3. The z-Pinch

A z-pinch occurs when the magnetic pressure from an axial current exceeds the plasma's thermal and kinetic pressure. The Bennett relation (1934) gives the equilibrium condition:

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I² = 8πNk_B(T_e + T_i) / μ■
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The z-pinch operates at every scale:

Scale	z-Pinch Product	Size
Cosmological	Galaxy clusters	~1–10 Mpc
Galactic	Galaxies	~10–100 kpc
Stellar	Stars	~0.01–1 pc
Planetary	Planets	~AU
Nuclear	Plasmoids (quasars)	~AU–pc
Laboratory	Plasma focus devices	~mm–cm

4. Double Layers

A double layer (DL) is a thin region where two oppositely charged layers create a strong electric field, accelerating particles to high energies across short distances. Alfvén (1986): "A DL acts as a voltage generator… the most efficient particle accelerator known."

Applications: solar flares (DL discharges in the corona), auroral acceleration (directly observed), cosmic ray acceleration (galactic-scale DLs provide the voltages for ~10^{2}■ eV particles).

5. Plasma Instabilities

Plasmas are inherently unstable — perturbations grow into structures:

Sausage instability (m=0): Axisymmetric constrictions forming “beads on a string.” Creates periodic node spacing — galaxies along filaments, stars in clouds, planets in discs.

Kink instability (m=1, 2, …): Helical displacements producing spiral and barred structures. The m=2 mode creates two-armed spirals in galaxies.

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6. Scaling Laws

Plasma equations are scale-invariant. Alfvén and Fälthammar’s scaling relations:

Quantity	Scales As	Implication
Length	L	Directly proportional
Time	L/v_A	Set by Alfvén velocity
Magnetic field	B	Independent of size
Current	B·L	Proportional to size
Voltage	v_A·B·L	Larger = higher voltages
Power	$v_A \cdot B^2 \cdot L^2$	Quadratic with size

This is why laboratory PIC simulations reproduce galaxy morphology — identical physics at different parameters.

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7. Circuits, Not Islands

Astrophysical objects are nodes in a cosmic electrical circuit. The Sun connects to the galaxy via Birkeland currents. The galaxy connects to neighbours via intergalactic filaments. At every level, current flows, energy is transported, and structure is maintained by the circuit.

References

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