Galaxies in Plasma Lab

Once upon a time, astronomers thought that the planets, the Sun, and the Moon all moved around the Earth in uniform circular motion. The heavens must be perfect, right? And what could be more perfect than a circle!

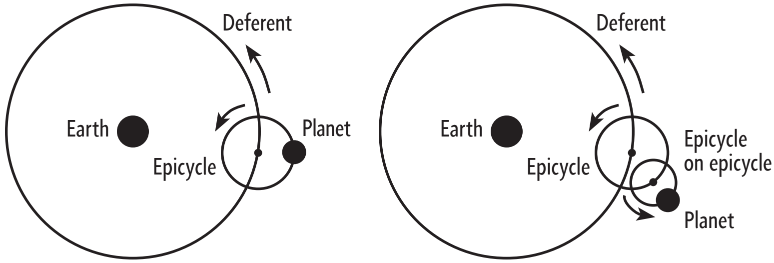
One problem: every now and then, planets reverse the direction of their visible motion across the sky, which would be impossible if they turned around the Earth on circular orbits. This so-called *retrograde motion* of planets forced the introduction of epicycles. An *epicycle* was a smaller circle on which a planet would turn around a certain point, which itself would turn on a circular orbit (a *deferent*) around the Earth.

If this sounds complex, you have seen nothing yet. Although retrograde motion now became possible, the calculations still didn't quite match the observations. Soon, epicycles on epicycles were invented, yet smaller circles on which the planets would turn around a certain point that would move along an epicycle that would move along a deferent around the Earth.

Where did all the original perfect simplicity go?

Unwilling to reconsider the basic assumption that the Earth was at the center, medieval astronomers kept shoring up the ailing geocentric system with *ad hoc* solutions.

This is a classic example of how science must not be done.



Some time in the 1930s, astronomers learned how to measure the velocities at which stars rotate around the centers of their galaxies, also known in the specialized scientific lingo as *rotation curves.* The results surprised them.

By the law of gravity, the stars closest to the center should rotate faster than those found farther away. This is how planets in the solar system rotate around the Sun. But the so-called rotation curves of galaxies were flat almost everywhere, meaning that the rotational velocities of stars around the center of the galaxy were just about equal, no matter what the distance from the center. The stars on the periphery were rotating way too fast. If the galaxy were held together only by the force of gravity, it should have long since fallen apart, ejecting the fast-rotating stars into the intergalactic space, like slingshots.

But this was the time when gravity was held in high esteem. For centuries since Newton, astronomy achieved many important results relying entirely on the law of gravity. And the General Relativity theory by Albert Einstein (1879–1955), only recently proposed and accepted, tickled scientists' minds and popular imagination. No one was about to suggest that anything but gravity ruled the universe at the galactic scale. Besides, there was no real alternative yet at that point in time.

Thus, *dark matter* was invented to shore up the gap discovered between theory and observation. No one was willing to suggest a new, unknown—or even an already known!—force other than gravity. But a new, unknown kind of matter that couldn't be made of any elementary particles known then (and even now), the kind of matter that neither absorbs nor emits electromagnetic radiation (like visible light, or radio, or infrared, etc.)—otherwise, it would have been detected by spectrography—and in general, doesn't affect the normal matter in any imaginable way but by exerting gravity? No problem! After all, the stars rotate so fast that there simply *must* be some additional mass lurking nearby.

Since then, dark matter was conveniently sprinkled anywhere it was needed to close yet another gap between theory and observation—and the number of such gaps kept mounting. New surprises, contradicting the generally accepted wisdom, were popping up like mushrooms almost anywhere one aimed a telescope. Naturally, the same kind of dark matter could not explain them all. So the variety kept growing. Soon we had cold dark matter, hot dark matter, warm dark matter, weakly interacting dark matter, strongly interacting dark matter, repulsive dark matter, self-annihilating dark matter, even fuzzy dark matter... none of which was ever observed, and not for the lack of trying. Moreover, the total amount of dark matter called upon dwarfed the visible matter many times over.

Every single so-called "proof" of dark matter's existence to date is just like that: dark matter must exist because there would have been a gap between theory and observation otherwise. Duh!

Somewhere along the way, scientists must have forgotten the venerable Occam's Razor principle: Do not invent new entities in vain!

Contrary to a common misconception, Occam's Razor principle does *not* say that a simpler explanation is more credible.

The world hadn't seen the like of it since the infamous epicycles.

Enter Hannes Alfvén (1908–1995). An experimentalist with incredibly strong intuition, he would have felt himself at home in the 19th century, the time of hands-on experimental science and passionate inventors. Instead, he lived and worked during the era when theory dominated over experiment in certain fields, the era of an increasing compartmentalization of science and the rise of scientific bureaucracy. One of the pioneers of plasma physics, he crossed into the space sciences with new ideas, going against the established wisdom. Even after he received the Nobel Prize in Physics in 1970, he continued to be ignored by the astrophysical establishment.

His sin was to maintain that the universe was made mostly not of dark matter but of plasma, a state of matter that contained charged particles (electrons and ions) instead of, or in addition to, neutral atoms—and consequently that the electromagnetic force played an equal or greater part than gravity at the galactic and supra-galactic scales.

Already in 1937, he predicted the existence of a galactic magnetic field. Before the space age, nothing seemed to portend such a discovery. Space was considered to be a vacuum, which obviously couldn't conduct electric currents, and so no magnetic field on such a scale was possible.

Of course, as soon as we went into space, we discovered that it was filled with plasma, electric currents, and magnetic fields. But even though the existence of electric currents in the solar system soon became common knowledge, galactic-scale electric currents continued to be denied.

The (in)famous Alfvén–Chapman controversy lasted for decades; it's symptomatic of the relationship between theory and experiment in the 20th century space sciences. The argument between Hannes Alfvén and Sydney Chapman (1888–1970) was about the nature of auroras. Chapman thought that the electric currents creating auroras existed entirely within the Earth's magnetosphere. Alfvén believed that there was an explicit Sun–Earth connection, continuing the tradition that began with Kristian Birkeland (1867–1917), a Norwegian scientist, inventor, and polar explorer, whose name Chapman had been systematically trying to erase from history of science.

Alfvén's is quoted in [9] on Chapman's approach to Birkeland's scientific legacy.

Chapman's theory was simple and mathematically elegant, while Alfvén's was the opposite. The matter couldn't be resolved before the space age, because the solution for the distribution of electric currents in space, based on the measurements on the surface of the Earth, was not unique; the measurements supported both models. But nearly as soon as we sent the first space probes, they literally flew into what's now called the *Birkeland filaments,* predicted by Birkeland and Alfvén.

So much for mathematical elegance.

Hannes Alfvén proposed the Plasma Universe paradigm, a radically new way of looking at the universe. It is based on two main principles:

- that the universe is made of plasma, for the most part; and
- that the fundamental properties of plasma are the same everywhere and at any scale.

Note that the well-known cosmological scenarios — the universe expanding from a singularity forever, or expanding first and then contracting, or vice versa — are born by the assumption that the universe is homogeneous. In a fractal universe, infinitely many different scenarios are possible.

The second one, the principle of scalability of plasma, is supported by direct measurements at the scales ranging from microscopic to the size of planetary systems. About the same number of degrees of magnitude separates the latter from superclusters of galaxies. It is not unreasonable to suppose that the principle of scalability of plasma holds at those scales as well. The Sloan Digital Sky Survey's discovery of a fractal structure (cf. [17]) suggests that this is indeed the case, for the fractal structure means self-similarity. The universe is made of filaments and cells ("great walls" of galaxies and empty voids), the structures typical of plasma's self-organization properties.

Perhaps the most fascinating thing about it is that astronomical events can be scaled down, in both space and time, to fit into a plasma lab. One can, for example, try to reproduce the formation and evolution of galaxies, however briefly!

This was done, successfully, by Anthony Peratt (b. 1940). His results were first published in 1986 in the IEEE Transactions on Plasma Science [25].

IEEE: the Institute of Electrical and Electronics Engineers.

A graduate student of Alfvén, Peratt is now a member of the Associate Directorate of Los Alamos National Laboratory. At that time, he was working with Blackjack V at Maxwell Laboratories. Back then, this was the most powerful electromagnetic pulse generator, capable of producing briefly several times the power generating capacity of the entire human civilization. Ultra-fast photography of high-energy plasma discharges captured what seemed like mini-galaxies, complete with spirals, the same radiation patterns, and a suggestive evolution.

See also [30] for an account of experiments that reproduced the Martian blueberries in plasma discharges.

Their rotation curves were flat.

Intrigued, Peratt developed a theory and a computer model to also take gravity into account and simulate the real galaxies, one by one, always backing his results by direct experiments. His theory withstood all tests to date, without requiring modifications. Briefly, it can be summarized as follows.

Unlike gravity that tends to form round bodies, the electromagnetic force tends to form filaments, thanks to the so-called *electromagnetic pinch* that forces charged particles to do turns around the magnetic field lines in spirals as tight as possible.

Filaments of plasma parallel to both the electric and magnetic fields (called *Birkeland filaments*) play a crucial part in auroras and are common to the solar system. According to Peratt, the universe is filled with galactic-sized Birkeland filaments of very low density and current, producing so little radiation that they are very hard to detect.

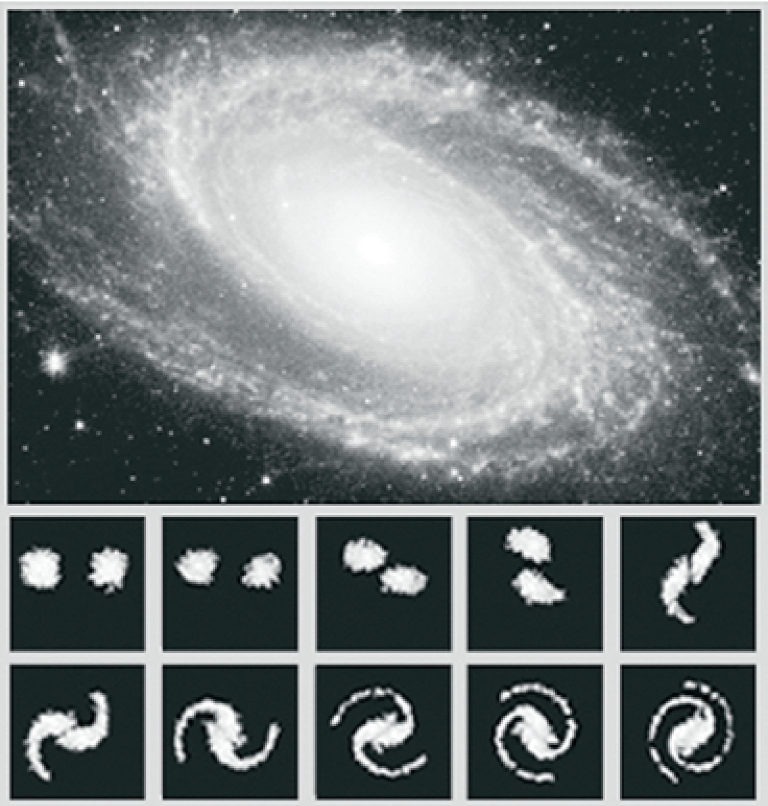
Plasma is an excellent conductor, although not a perfect one. Thus, voltage can exist in plasma but primarily within narrow layers of charged particles, called double layers. Everywhere else, plasma is locally quasi-neutral, which means that the electrostatic force—the like charges repel, the unlike charges attract—can be ignored.

As plasma physics tells us, double layers form in narrow cross-sections along the filaments. This is where most of the voltage is squeezed into. More voltage means higher resistance. Therefore, matter accumulates within the double layers, where the galactic disks eventually form, like beads along a string.

Three major forces act on Birkeland filaments:

- The $1/r$ attractive electromagnetic force.

  The electric current in each filament creates a magnetic field that exerts force on the other filament. Parallel electric currents of the same direction attract, while those of the opposite direction repel. In our case, this force is attractive and proportional to the product of current in the filaments.



Top: The spiral galaxy M81. NASA/JPL–Caltech/S. Willner, Harvard–Smithsonian Center for Astrophysics. **Bottom:** Galaxy formation stages from a simulation run by Anthony L. Peratt, Los Alamos National Laboratory. Copyright © 1986 Institute of Electrical and Electronics Engineers.

It depends on the distance *r* between them as $1/r$, if the filaments' lengths are much greater than *r*. This is because the current is the same along the entire length of each filament. This force is often called the Biot–Savart force.

- The $1/r^2$ force of gravity.

This force is proportional to the product of mass in the filaments. If plasma density were uniform along the filaments, this force would also have been $1/r$. But matter accumulates only in the relatively narrow cross-sections where double layers form. Elsewhere, mass is negligible, and therefore the force of gravity between the filaments is $1/r^2$.

◑ The $1/r^4$ repulsive electromagnetic force.

Positively charged and negatively charged particles spiral around the magnetic field lines in opposite directions. This adds a circular (properly called *azimuthal*) component to the total electric current in the filaments. Azimuthal currents of the same orientation repel; of the opposite, attract. In our case, they repel. The cumulative force is proportional to the product of magnetic momenta of the filaments and behaves as $1/r^4$. Importantly, the interaction of these azimuthal currents also produces a torque that eventually makes the filaments turn around each other, like a hurricane.

Because it's $1/r$, the attractive electromagnetic force is dominant at the long range, but the $1/r^4$ repulsive force overtakes it at the close range. Simulations show that gravity does not make much impact at the galactic scale.

Because the attractive force is $1/r$, the plasma filaments usually form pairs, occasionally triples. The number of filaments determines the number of spiral arms to form. But one-armed galaxies are possible as well, if one of the filaments is too weak to produce stars.

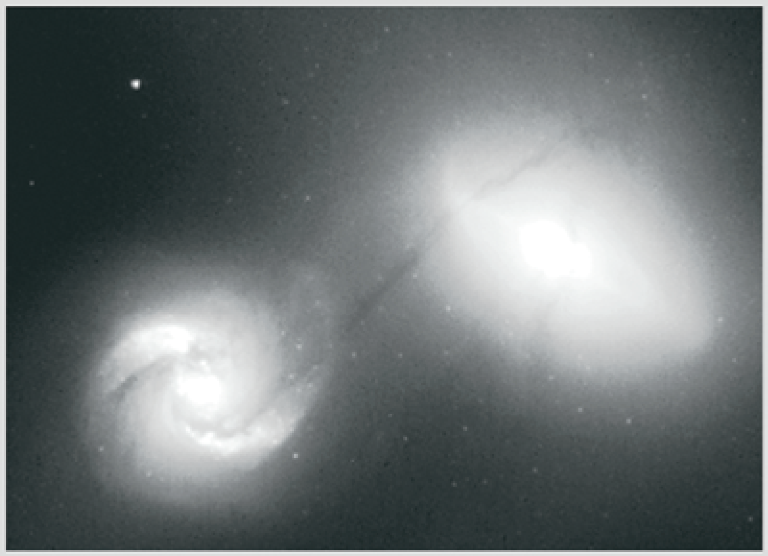
Double radio galaxy is the first stage. The cross-sections of each filament emit the so-called *synchrotron radiation* in the radio range, a kind of electromagnetic radiation with a specific, recognizable spectrum, which can only be produced by relativistic electrons accelerating in an electric field.

QUASAR: a quasi-stellar radio source. Usually thought to be extremely far away, they may be actually much closer to us.

As the filaments are drawn toward each other, the plasma in the center is squeezed by the converging magnetic mirrors, producing a plasmoid that behaves like a quasar.

Eventually, the plasma in the center is compressed so much that stars begin to form in the elliptical sump, where the magnetic field is lower.

By this time, the short-range repulsive force is already felt, and the filaments begin to turn around each other, trailing plasma in the spiral arms, along which electric currents start to flow.



A portion of the plasma filament connecting the galaxies NGC 1409 (right) and NGC 1410 (left) may have captured some dust and therefore turned visible. NASA / William C. Keel, University of Alabama.

The electromagnetic pinch in those currents compresses plasma such that, reaching a certain threshold, stars begin to form throughout the entire spiral arm at nearly the same time. This phenomenon is called *starburst*.

In fact, the condition for gravity to take over—and thus for round bodies, like stars, to form from filaments—is that the density divided by the electric current density must be greater than a certain constant. If the current is almost the same everywhere, this leads to the de Vaucouleurs relation that has been vexing our astronomers: for most of the stars in our galaxy, the mass divided by the radius is nearly the same.

This brief account doesn't go into many technical details and is far from rigorous. I must at this point refer the reader to the original article [25], as well as the monograph [26] and the popular science book [18].

PLASMA IS AN AMAZING STATE OF MATTER. IT DOES NOT behave like gas, especially when it's of low density (collisionless). The electromagnetic forces between moving particles make its behavior very complex, almost life-like. Plasma even got its name from a similarity with blood plasma, which coagulates around foreign bodies. Electromagnetic plasma forms double layers around solid bodies immersed in it, shielding them from electrostatic interaction (which is why it's very hard to determine if planets have significant non-zero electric charge). Double layers also form at the boundaries between plasmas with different physical characterstics (like temperature, chemical composition, etc.).

Plasma does not stay still. It writhes and bucks as if alive, behaving in ways difficult to predict by theory, as the fusion scientists have learned to their chagrin. Even Alfvén's intuition sometimes failed to anticipate plasma's behavior.

Formation of filaments and development of cellular structure are characteristic properties of plasma. At the large scale, the universe is made of "great walls" of galaxies separated by enormous voids. Within these walls, galaxies are strung along gigantic Birkeland filaments like beads on a string. So are stars within the galaxies.

During his controversy with Chapman, Alfvén fought against the tendency to consider the Earth as an isolated system. Not only is there the Sun–Earth plasma connection, but there also must be the Sun–Galaxy plasma connection, and so on to the ever larger scales.

In order to sustain complexity and to continue self-organization, a system must keep exchanging energy and entropy with its environment. Had the Sun been isolated from our Milky Way galaxy (except for the gravitational interaction), or had the Earth been likewise separated from the Sun, they would have long since succumbed to the "heat death" or, at the very least, would not have been able to keep the evolutionary spiral going. The galactic currents connected to the Sun's polar jets, the solar wind continuously engaged in complex interactions with the Earth's magnetosphere, the auroral currents influencing the atmospheric processes—all of this complexity may have allowed life to blossom on the Earth.