working at Ohio State University, noticed that the cylindrical field focuses the electron flow into a plasma beam. The process, which is called the pinch effect, causes the plasma to form multiple strands of conducting current. Furthermore, when magnetic and electric fields in a plasma are made to run parallel to each other, they create what is known as a magnetic field–aligned current: the current of free ions and plasma electrons actually spirals along the magnetic lines of force. Experiments conducted in 1952 indicated that if the magnetic field–aligned current of a plasma is bent into a closed loop, the plasma takes the shape of a torus, or doughnut. The torus geometry has proved highly useful for containing high-temperature fusion reactions.

Like the flickerings of lightning, Earth-bound plasmas are by and large a transient species. Even in a fluorescent bulb the mixture of ions and electrons remains charged only as long as the light is switched on; once the voltage is removed, the plasma reverts to an ordinary gas. In space, however, plasmas are a far more permanent form of matter. Yet before balloons and rockets probed the upper atmosphere, only a handful of scientists had speculated about the presence of extraterrestrial plasmas.

One of the most prescient was Kristian Birkeland, a Norwegian experimenter who built a remarkably accurate model of the aurora borealis, or northern lights, at the end of the nineteenth century. Birkeland constructed a copper sphere to represent the Earth, into which he placed an electromagnet to model the Earth's magnetic field. He then placed the sphere in a vacuum chamber and bombarded the model earth with electrons from a model sun (a set of cathodes). The electrons were captured by magnetic field–aligned currents surrounding the model earth, swept around the sphere and then spun downward in spirals toward its magnetic poles, just as they do in the electromagnetic region surrounding the real Earth. Such movement of plasma particles in an electromagnetic field is now called a Birkeland current.

Views such as Birkeland's, however, were in the minority. Until the space probes, most scientists, whose knowledge of the universe was confined primarily to the visible region of the electromagnetic spectrum, maintained that space is a perfect vacuum. But in recent decades investigators employing a wide array of sophisticated devices, including radio, ultraviolet and high-energy telescopes, particle counters and magnetic field probes, have shown that the cosmos is teeming with electrically charged subatomic particles. It is now estimated that 99.999 percent of the observable matter in the universe is made up of plasmas, which are crisscrossed by electromagnetic fields and Birkeland currents.

In our solar system the primary source of active plasma is the sun. Here temperatures are so high that atoms are stripped of their electrons. Concentric layers of plasma with differing densities—the photosphere, the chromosphere and the corona—form the sun and envelop it like the skin of an onion. At the same time electrons, protons and helium ions from the outer corona are expelled in a steady stream of plasma called the solar wind. Physicists such as Birkeland had predicted the existence of the solar wind, and in 1957 the Swedish physicist Hannes Alfvén, then at the Royal Institute of Technology in Stockholm, suggested that it might explain why comet tails always point away from the sun. Its presence was finally confirmed in 1959, when the Soviet probes *Luna 2* and *Luna 3* detected charged particles streaming away from the sun at three hundred miles a second. The solar wind blows across the entire solar system, buffeting the planets and eventually diffusing out into the plasma between the stars.

As the Earth rotates on its axis, it generates a magnetic field that traps and deflects the ionized particles of the solar wind. The trapped particles wrap the Earth in an envelope of plasma called the magnetosphere, which stretches out on the night side of the planet into a tail a thousand times as long as the radius of the Earth. The leading edge of the magnetosphere, compressed by the motion of the Earth, slows additional incoming particles to about sixty miles a second, deflecting most of them into the turbulent outermost region of the magnetosphere, known as the magnetosheath. Particles that slip past this first defense are trapped in two huge toroidal rings called the Van Allen radiation belts, after James A. Van Allen of the University of Iowa.

Also surrounding the Earth, as space probes verified in 1974, are magnetic field–aligned currents. These currents, as Birkeland had demonstrated experimentally, are responsible for the aurora. As the solar plasma sweeps past the magnetosphere, sheets of electrons are driven along the magnetic lines of force to the polar regions, generating an auroral "oval" above Scandinavia, Canada, Alaska and the USSR (in the case of the aurora borealis), and over Antarctica (in the aurora australis). The electrons collide with oxygen and nitrogen atoms in the upper atmosphere, and the atoms emit the waving curtains of light characteristic of this brilliant celestial display. Geophysicists expect particularly dramatic auroras beginning in March, when solar flares and sunspots peak in their cycle and blast extra charged particles into the magnetosphere.

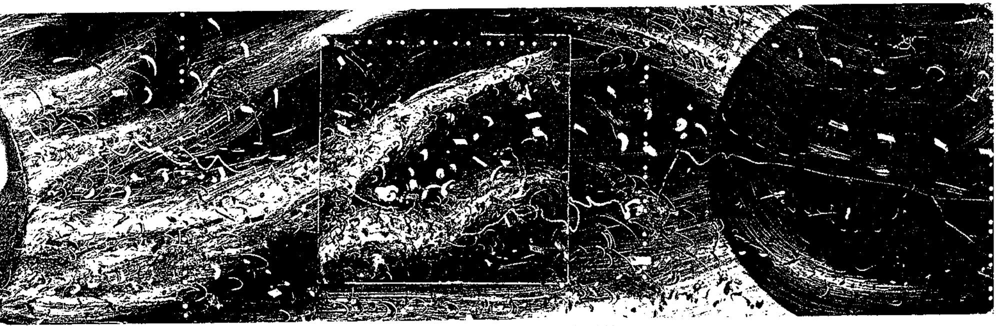
Space probes have shown that plasmas affect many of our planetary neighbors in ways reminiscent of those on Earth—as well as in plenty of ways that are radically different. Mercury, Jupiter, Saturn, Uranus and Neptune all have magnetospheres, and X-ray telescopes indicate that all except perhaps Mercury produce auroras. Unlike

Earth's moon, however, the moons of the giant planets orbit entirely within the magnetosphere of their parent. (Our moon passes through the Earth's magnetosphere only when it briefly crosses its tail.) As a result the planetary moons are subject to a hostile charged-particle environment. The surfaces of Jupiter's seven inner moons, for instance, are eroding under the constant bombardment of high-energy particles.

In 1979 the *Voyager 1* spacecraft discovered that the magnetic field lines of Jupiter pass directly through Io, its innermost moon. Connecting the two is a tube of Birkeland current that carries seventy times the electric power capable of being generated by all the nations on Earth. Threading the tube of current and forming a ring around Jupiter is a gigantic torus of sulfur ions thought to have been ejected from Io. Another huge torus of plasma surrounds Saturn and its ring system, extending to twenty-five times the radius of the planet. Fusion experimenters have tried for decades to replicate these configurations in the laboratory but have met with only fleeting success.

All laboratory simulations incorporate a model of plasma filament interaction, based on observations of many space plasmas such as the aurora, solar prominences and the Jupiter–Io flux tube. Whenever an intense Birkeland current is flowing, instabilities develop along its length; at these points small electric fields appear. The electric fields accelerate electrons to high energies, thereby producing a current that pinches the plasma into small whirlpools. Adjacent filaments tend to be pulled together at these points, and where they cross, the individual whirlpools combine into larger spirals. Hence plasma spirals periodically dot the length of long laboratory filaments.

At their crossing points plasma filaments in the laboratory also emit synchrotron radiation, which is simply electromagnetic radiation caused by the rapid circular motion of charged particles in a magnetic field. This finding turned out to be an important clue to the plasma universe, because synchrotron radiation is also released from many natural cosmic sources.



Robert Siegelman, Untitled, *1989*

Thirty years of space research has revealed the solar system to be a veritable sea of plasma, invisible to optical telescopes yet traversed by complex, interacting electric and magnetic fields. Do plasma phenomena abruptly cease at the threshold of the solar system? Alfvén, who won the 1970 Nobel Prize in physics for his work on plasmas, argues to the contrary. He has suggested that Birkeland currents of unlimited size might be found throughout the universe. After all, why should plasma physics operate any differently at the far end of the cosmos, ten billion light-years away, than it does in the Earth's magnetosphere or in laboratories on the Earth's surface?

STILL, only in the past ten years have the dynamics of the plasma universe begun to be understood and appreciated. With supercomputers, physicists have for the first time been able to simulate the interaction of plasma currents. In the simulations galaxylike plasma structures have been generated that closely match the shapes of all known kinds of galaxies. The computer simulations, supported by recent observations of intergalactic plasmas, give strong evidence that plasmas do indeed play a primary role in the formation of the cosmos.

One of the brightest synchrotron sources in the sky is Cygnus A, a double radio galaxy thought to be hundreds of millions of light-years away. Through a radio telescope Cygnus A appears as two C-shaped lobes of intense synchrotron radiation, about 250,000 light-years apart and each measuring about 100,000 light-years across (about the diameter of our galaxy). Each lobe, moreover, emits a hot spot of radiation near the end of one arm.

Why double radio galaxies are structured this way has long been a mystery in astrophysics. The standard explanation is that a black hole emits electron beams, which in turn generate the synchrotron radiation. But that explanation is thrown into doubt by the laboratory demonstrations of synchrotron radiation arising from interactions of plasma filaments. Even more impressive, the computer simulations of the laboratory experiments generate synchrotron radiation in a pattern nearly identical with the one observed in double radio galaxies—including the distinctive hot spots.

Confident that simulated plasmas mimic phenomena observed in distant space, physicists have run further computer simulations to study how galaxies might form from plasma currents. From 1979 until 1986 James C.

Green of Stanford University and I used supercomputers to simulate the long-term effects of plasma forces on a double radio galaxy with the characteristics of Cygnus A. To verify the method, the lobe structures generated in the computer simulation were compared frame by frame and in fine detail with the lobe structure of numerous double radio galaxies, peculiar galaxies and ordinary galaxies mapped by telescope. Our results were stunning. The simulation showed how a double radio galaxy 250,000 light-years wide can evolve, in a billion years, through recognizable stages into a barred-spiral galaxy 100,000 light-years wide. Galactic astronomers believe that barred spirals breed new stars and further evolve into the spirals and ellipticals that complete the catalogue of galaxies. In other words, radio galaxies seem to be the precursors of all other galaxies. Even double radio galaxies that vary widely in appearance may be merely at different stages on similar evolutionary paths, separated in age by a few million years. In fact, nearly all cosmological objects in the near and far universe, from quasars to spiral galaxies, appear to belong to a single family, differing only in age.

SUPPORT FOR THIS MODEL of interacting plasma currents has grown rapidly in the past five years as a number of its predictions have been confirmed. In laboratory models a rotating "galaxy" generates two magnetic fields: one toroidal—an enormous ring around the galaxy in the galactic plane—and the other vertical, looping out of the galactic center above and below the plane of the galaxy. The two fields appear even if no magnetic field is initially present. The natural prediction of the model was that like-structured plasma filaments should be found at the center of our own galaxy.

In 1984 three radio astronomers, Farhad Yusef-Zadeh and Don Chance of Columbia University and Mark Morris of the University of California at Los Angeles, found a textbook example of galactic currents. Working at the Very Large Array radio telescope in New Mexico, they discovered an arc some 120 light-years long at the center of the Milky Way. The arc is a system of narrow filaments, typically three light-years wide and each running the length of the arc. Spiraling helixes formed the outer layer of the tube, and an inner layer of nearly straight filaments threaded the core of the helixes; around the entire tube were both vertical and toroidal magnetic fields. Although the strength of the field was a hundred times what astrophysicists thought possible on such a large scale, it was nearly identical with the values from our simulation, published barely a month earlier.

The discovery of a large-scale magnetized plasma was a good sign that highly ordered magnetic fields can indeed be found within galaxies, which can stretch across tens of thousands of light-years. Meanwhile early in 1984 we realized that the fields in the simulations were strong enough to collect vast amounts of ionized hydrogen around the field lines. The shapes of the fields in the simulations closely matched regions of nearly neutral hydrogen that had been mapped previously by A. Bosma of the University of Groningen in the Netherlands. In both, hydrogen was distributed in a horseshoe pattern with distinct north and south magnetic poles. Final confirmation of large-scale magnetic fields came a year later. Radio astronomers Rainer Beck, Richard Wielebinski, Marita Krause, R. Gräve and E. Hummel of the Max Planck Institute for Radio Astronomy in Bonn, West Germany, have now shown conclusively that ordered magnetic fields do exist in galaxies and that weakly ionized hydrogen is distributed along these fields in the characteristic horseshoe pattern.

The interacting current model has also led to an even more telling discovery. In the laboratory the width of a synchrotron-emitting filament is about a ten-thousandth of its length. If what astronomers perceive as a double radio galaxy is actually the cross section of interacting plasma filaments, then double radio galaxies—and ultimately all galaxies—should be part of filamentary structures stretching across 10,000 times 100,000 light-years, or a billion light-years of space.

In 1987 radio astronomers discovered immense galactic structures with remarkably similar dimensions. R. Brent Tully of the University of Hawaii found that nearby galaxy clusters are grouped into a supercluster complex a billion light-years long, 130 million light-years thick and 325 million light-years wide. Inside the complex, which includes the Milky Way, galaxies are packed more than twenty times as densely as they are outside. Peter A. Shaver of the European Southern Observatory in West Germany found similar clustering in the distribution of quasars within eight billion light-years of the Earth. Even on this scale, which is half the radius of the observable universe, Shaver found that the quasars seem to be arrayed in a structure 2.5 billion light-years long and 1.25 billion light-years wide. Although the width-to-length ratio of this structure is not as small as that of a full-fledged filament, its shape is consistent with that of a laboratory plasma in an early stage of evolution.

On the basis of these findings, a number of physicists have adopted the view advocated by Birkeland and Alfvén: not only is the universe permeated by plasmas and plasma currents, but its dynamics are dominated by electromagnetic, not gravitational, forces. According to plasma cosmology, the universe has been and remains a veritable sea of charged particles interlaced with complex magnetic fields and electric currents. To develop this view, we modified the initial conditions in our interacting current model and ran the supercomputer from some hypothetical time when there were no stars, no galaxies, no quasars or superclusters. In so doing we are able to tell a new story about how the universe might have been born.

Our model presupposes an indefinitely large space of magnetic fields, where plasma is distributed uniformly in all directions. (A uniform distribution of plasma is not required in the simulations, but it does simplify the setup for the study of plasma filamentation.) If any other kind of nonuniformity is present, such as variations in electron temperature, vast and swirling electromagnetic fields develop that pinch the plasma into filaments. The filaments grow to the size of Tully's superclusters, billions of light-years long. The plasma within these clusters is further pinched into smaller, galaxy-size filaments, which interact for billions of years; eventually they collect and neutralize so much mass that gravity becomes a factor in the continued evolution. Thus is formed the full range of galaxy species. Like predawn mist beading on a spiderweb, the observable cosmos condenses out of the plasma background in progressively smaller steps, eventually forming stars, planets and moons. There is no expansion, and there need not be any final crunch. Unlike the universe envisioned in the big bang model, the plasma universe evolves without beginning and without end: it is indefinitely ancient and has an indefinite lifetime in store.

ALTHOUGH BIG BANG THEORISTS are well aware of the predominance of plasmas in the universe, there is little plasma physics deployed in their model. For example, though the fireball at the beginning of the big bang must have been a plasma, theorists argue that plasma forces persisted for only a few hundred thousand years. Thereafter, they maintain, the universe has been dominated by matter and gravity. As support for the plasma model has grown, however, the evidence for the big bang theory has become much less compelling.

One criticism of the big bang, delivered from outside the plasma physics community, challenges the idea that the observed pattern of red shifts is evidence for the expansion of the universe. If the universe is expanding, a higher red shift should indicate a greater distance from the Earth. But Halton C. Arp of the Max Planck Institute for Astrophysics in Garching, West Germany, has noted numerous objects in the past two decades whose red shifts do not seem to correlate with distance.

Quasars, for instance, have such large red shifts that they would seem to be the most distant objects in the universe. But Arp and an independent observer, Jack W. Sulentic of the University of Alabama, have found that some quasars appear in the vicinity of nearby galaxies with

Robert Siegelman, Untitled, *1986*

much smaller red shifts. If quasars and the nearby galaxies are connected, the two objects could not be moving at greatly different speeds; more likely their red shifts—and possibly all red shifts—result from something other than a rapid retreat from the Earth. One possibility is that the quasars are shrinking: red shifts can be caused not only by receding objects but also by contracting or pinched ones. A third mechanism, proposed in 1987 by Emil Wolf of the University of Rochester and confirmed in laboratory experiments, is that certain forms of coherent light can shift as the light propagates through space. Perhaps that shift could account for the red shift seen in quasars. Although these ideas continue to be debated among astrophysicists, one thing is clear: if the red shifts cannot be traced to cosmic causes, the evidence in favor of the big bang is seriously attenuated.

The strongest evidence big bang proponents adduce in support of their model is the cosmic microwave background radiation. Observations of the background, spanning a range of wavelengths from about one millimeter to twelve centimeters, suggests its intensity corresponds to a temperature of 2.78 degrees above absolute zero. But in 1987 a collaboration between experimenters led by Toshio Matsumoto at Nagoya University in Tokyo and by Paul L. Richards at the University of California at Berkeley recorded excess background radiation at wavelengths around a tenth of a millimeter. The excess radiation was nearly ten times more intense than would be expected at 2.78 degrees above absolute zero, and strongly indicates that the spectrum of radiation does not follow the smooth temperature curve predicted by the big bang.

The most plausible way to reconcile the original prediction of the big bang with this new Japanese–American observation is to assume that an early generation of massive stars heated dust in the universe. The dust might then have emitted the excess radiation at the observed submillimeter wavelengths. But this explanation introduces another problem. If massive stars had indeed generated the extra heat, they would have formed an enormous amount of helium. When this extra helium is added to the amount predicted by the big bang model, the total helium is nearly twice the observed amount. In short, at least one of the predictions of the big bang is wrong: either the spectrum of background radiation or the cosmic abundance of helium.

The cosmic microwave background raises other troubling questions for the big bang. To radio observers the radiation appears as a hiss of static arriving from all directions in space, with almost no variation in intensity. The smooth radiation suggests that the primordial explosion also spread matter evenly throughout the universe. As I noted above, however, if the cosmos were shaped mainly by gravity, there must have been some fluctuations of matter in the primal soup on which the force could act. Shouldn't these fluctuations show up as nonuniformities in the cosmic background? In a plasma universe no such initial fluctuations are required.

MEANWHILE simulations of a plasma universe indicate that its fields and currents can give rise to a cosmic microwave background, uniform in all directions. As laboratory experiments have shown, all filamentary plasmas generate microwaves. Simulations of the mechanisms that generate microwaves in the laboratory, when scaled up to galactic dimensions, generate microwave radiation at a temperature of 2.0 degrees above absolute zero, which compares favorably with the observed radiation at 2.78 degrees. To put this result in perspective, the energy of the predicted radiation is somewhat less than a third of the energy of the observed radiation (because energy decreases rapidly with decreasing temperature). On the other hand, it is much closer to the real value than were the estimates made by the big bang model before the 1965 discovery and measurement of the background.

Less than two years ago William F. Peter, now at the University of California at Irvine, showed how the microwave background can be smooth, even though matter is distributed unevenly in the universe. Peter's calculations indicate that the plasma filaments encompassing the billions of galaxies scattered through space could absorb and reemit such radiation repeatedly. The process would ultimately scramble the radiations into the uniform sea we now observe.

A plasma-dominated dynamics can also account for the formations of galaxies, clusters of galaxies and superclusters that are highly problematic for the big bang. For example, dark matter has been discussed for years as a possible way to account for the rotation of spiral galaxies. The laws of motion assert that the visible matter in a galaxy should spin rapidly at its center, where gravitational forces are strongest, and more slowly at its outer edges. Actually, spiral galaxies tend to spin more like Frisbees, as if, say the big bang theorists, some missing mass were holding them together. As our computer simulations indicated in 1984, however, a plasma cosmology can account for galaxy rotation without resorting to such ad hoc explanations. Incorporating the observable mass of a typical galaxy (about 100 billion suns), the interacting plasma current model replicated the rotation of galaxies in exquisite detail, right down to the formation of spiral arms.

It is still too early to tell whether the big bang has outlived its usefulness as a theory and whether plasma cosmology can successfully replace it. The *Cosmic Background Explorer* satellite, scheduled for launch as this magazine goes to press in November, is designed to determine the true nature of the microwave background radiation. Proponents of the big bang, meanwhile, steadfastly deny that their model has reached a crisis point: the "missing mass" and the massive stars that generated the extra burst of microwave radiation early in the history of the universe are not ad hoc assumptions, they say, but merely predictions awaiting future verification. There comes a time in the life of almost every model, though, when it stretches the limits of patience and credibility, a time at which, as Mr. Palomar observed while musing on his failures, "if the model does not succeed in transforming reality, reality must succeed in transforming the model." Many physicists believe the time is fast approaching when the big bang must prove its worth anew or step out of the limelight. And perhaps these physicists can afford to be patient; according to the plasma universe clock, they have all the time there is. ●

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