Plasma Cosmology

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ISAAC ASIMOV'S "Nightfall" tells the story of a civilization on a planet with six suns, where night comes only once every 2,049 years. Scholars of that world have uncovered traces of at least nine previous cultures, all of which reached a height comparable to their own and then vanished suddenly.

Because of their viewing handicap, those scientists' cosmology is faulty. At their most creative, they can only imagine that their universe consists of perhaps a few dozen "stars" — mysterious lights that eccentric cultists are forever talking about. When night does fall and myriad stars shine forth, their cosmology, and indeed the philosophical basis of their society, crumbles.

Until recently our own view of the universe also was handicapped, limited to information derived from the narrow range of wavelengths that make up visible light. About the middle of this century our spectral window expanded to include infrared and radio radiation. Then, beginning in the 1960's, space research opened up the ultraviolet, X-ray, and gamma-ray regions of the spectrum as well. Today only very long-wavelength celestial radio waves remain unknown to us. They are blocked by the magnetosphere, a protective cocoon that envelops Earth.

Most of the radiation in the spectrum comes from something called *plasma*. This is a fourth state of matter, different from a solid, liquid, or gas, but most closely resembling the last. However, unlike a gas, whose component atoms or molecules are electrically neutral, a plasma is made up of charged particles.

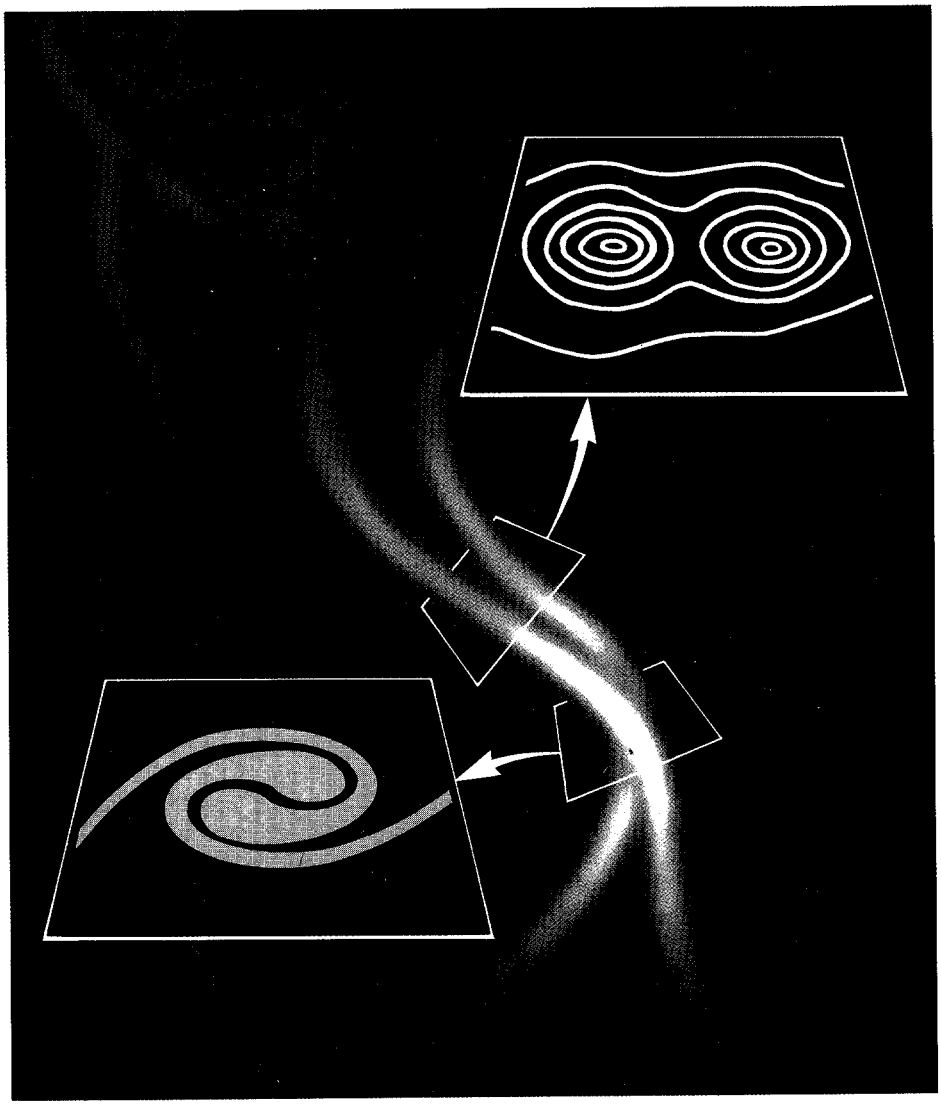
A plasma can form when a gas is heated to such a high temperature that collisions ionize it by tearing electrons from atoms. The result is a cloud of free, negatively charged electrons and positively charged ions, atomic nuclei with one or more of their attendant electrons missing.

The term plasma also includes ionized gas at a relatively low temperature, where only some of the atoms or molecules have lost electrons. This state of matter even exists inside a metal at room temperature. In this case the conducting electrons in the solid are free to wander through the rigid crystal lattice of metallic ions.

Because of its free electrons, a plasma is a good conductor of electricity, much better than copper, silver, or gold. Lightning offers one of the most dramatic manifestations of this property. As a thunderstorm develops, negative charges accumulate along the cloud base, causing positive charges to build up on the ground below. The resulting electrical field between the two concentrations becomes so strong that it ionizes the air. This creates a conducting path of free electrons and ions — a plasma — through which the lightning discharges.

A young engineer working for the General Electric Company gave plasma its name. In 1923 Irving Langmuir, who went on to win the Nobel prize in chemistry, was fascinated with the effect of electrical discharges on gases. He borrowed the term *plasma* from medicine because it fitted the unstable, almost lifelike behavior of the ionized material with which he experimented.

While all matter is subject to gravitational forces, the negatively charged elec-



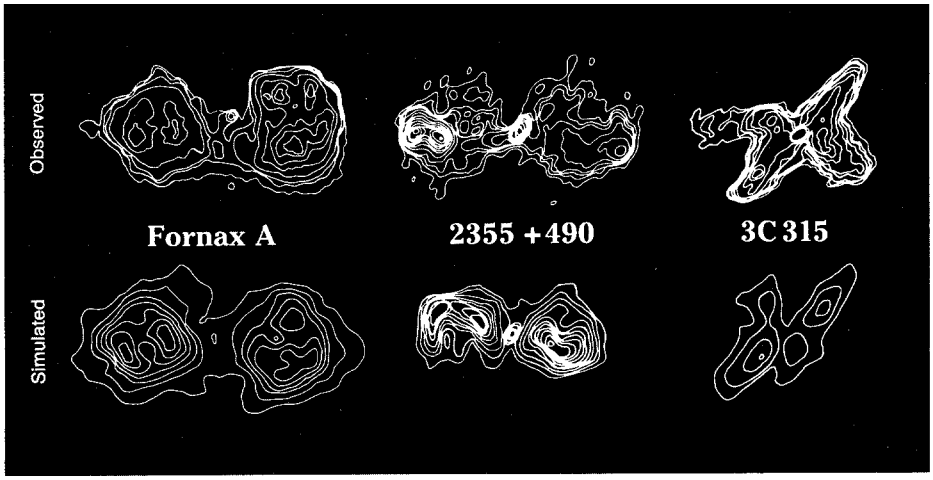
The plasma universe may be eternal and infinite, directly contradicting the Big Bang model. In this nonstandard picture, swirling streams of electrons and ions form filaments that span vast regions of space. Where pairs of these spaghettilike structures interact, the particles gain kinetic energy and at narrow "pinch" regions produce the entire range of galaxy types as well as the full spectrum of cosmic electromagnetic radiation. Thus galaxies must lie along filaments, much as they are observed to do on a large scale. The bulk of the filaments are invisible from a distance, much like the related Birkeland currents that circle Earth but are unobservable from its surface.

ons and positively charged ions in a asma also react to electric and magnetic rces that are 10^{36} times as strong. Beuse of these additional interactions, plasas display structures and motions that e far more complex than those found in eutral solids, liquids, or gases. Langmuir as among the first to note the separation f highly conducting plasma into charged-article sheaths or cellularlike walls. This ructure appears wherever samples with fferent densities, temperatures, or magetic-field strengths come into contact.

Like flashes of lightning, terrestrial plasas are by and large transient. Even in a eon or fluorescent bulb, the mixture of ee electrons and ions remains only as ng as the power is turned on. Extraterstrial plasmas are much more long-lived, ut until recently only a handful of scienists had speculated about the universal tent and character of such matter. Yet lmost all of the observable universe *is* lasma. Stars, for example, are gravitaonally bound plasmas, while all of interellar and intergalactic space is a plasma.

THE PLASMA UNIVERSE

Wherever plasmas exist, they produce rodigious amounts of electromagnetic raiation. In particular, X- and gamma rays om beyond the solar system are likely roduced by free electrons with energies rresponding to temperatures of more an 1 million degrees — the realm of hot, agnetized plasmas. We call the overall icture obtained from these energetic emisons the *plasma universe.*



Supercomputer simulations of interactions between a pair of galaxy-size plasma filaments can reproduce the shapes of cosmic radio sources. The brightness maps of actual double radio galaxies in the top row show bewildering variety. Those at bottom are all from different stages of *one* simulation. The left figure corresponds to some 20 million years after the interaction begins; time increases toward the right plot, which depicts the simulated interaction some 40 million years later. These calculations suggest that apparently unrelated radio galaxies may be part of the same family, but at different stages of development.

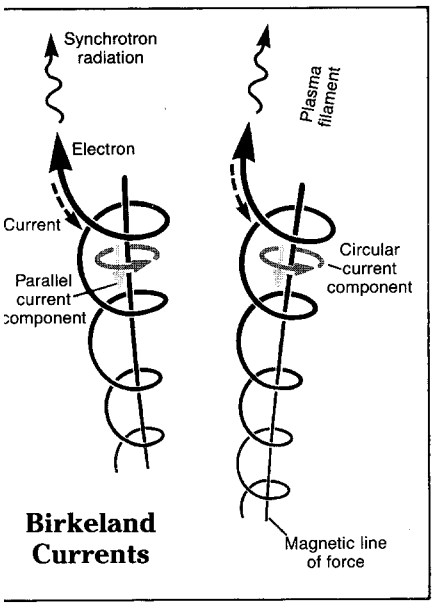
Hot plasmas also emit radiation of lower energy, such as visible and radio waves (we can both see lightning and hear it on a receiver). However, the emission does not always have a thermal origin. For example, unknowing humans have viewed synchrotron radiation (from electrons spiraling at nearly the speed of light in a magnetic field) from the Crab nebula for centuries.

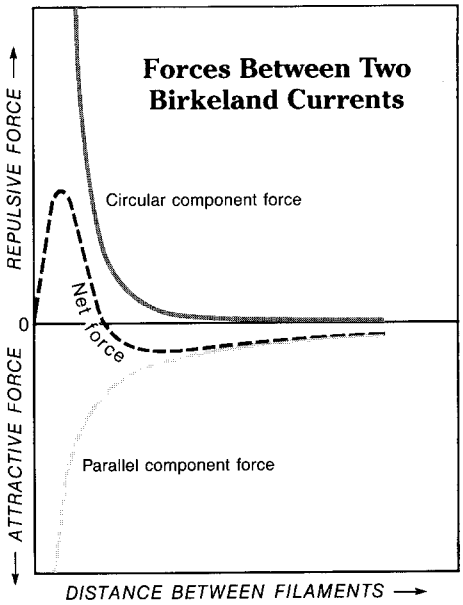
Synchrotron radiation is named after the particle accelerators developed in the 1930's and 1940's to produce high-energy electrons. In 1950 Hannes Alfvén, Nicolai Herlofson, and Karl Kiepenheuer brought this form of plasma radiation to astronomers' attention. Alfvén, who later won a Nobel prize in physics for his solar studies, proposed that streams of electrons move at nearly the speed of light along magnetic-field lines not only in Earth's magnetosphere and above the Sun, but also throughout the cosmos. If so, sheets and ropes of electric current should crisscross the universe in ever-increasing sizes. These currents, Alfvén thought, should give the universe a cellular and filamentary structure.

Astronomers accepted Alfvén's notion of widespread synchrotron radiation but refused to believe that electric currents give rise to the large-scale structure of the universe. In those days it was standard cosmological lore that the universe became smoother and smoother on larger and larger scales. Huge filaments, sheets, and walls of galaxies were unknown.

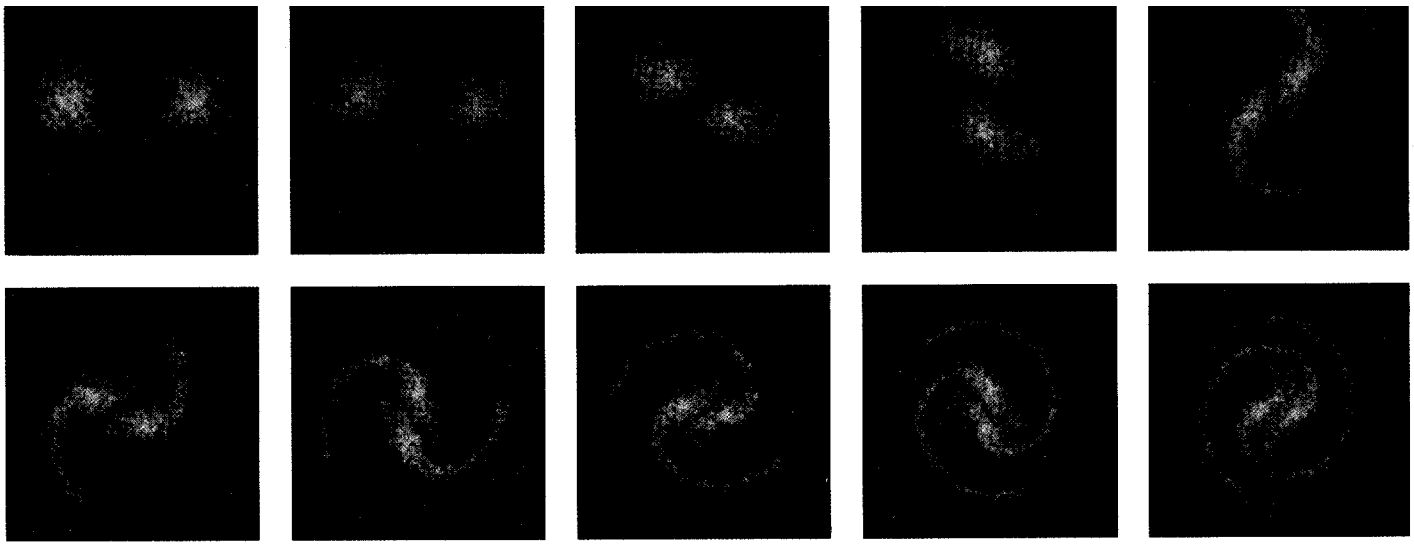
Modern plasma cosmologists have been heavily influenced by the earlier research of Norwegian scientist Kristian Birkeland (*S&T:* May, 1985, page 389). At the turn of the century he suggested that electrical currents due to "corpuscular rays" (plasma) from the Sun caused the aurora borealis. Such currents were considered impossible until they were discovered by an artificial satellite in 1974. Enormous Birkeland currents connecting Jupiter and its moon Io were recorded by the Voyager spacecraft in 1979.

In 1984 Farhad Yusef-Zadeh, Don Chance, and Mark Morris found an example of Birkeland currents on a galactic scale. Working with the Very Large Array





Complex forces between two Birkeland currents, which are electric currents aligned along magnetic-field lines created by electrons moving in helical orbits around and along the field lines. These currents have parallel components that exert a long-range attractive force and circular components that provide short-range repulsion. *Left:* The geometry used in computer simulations. If the electrons are moving near the speed of light they emit synchrotron radiation beamed along their magnetic-field line, so the emission nearly mirrors the magnetic-field pattern. *Right:* How the forces due to the Birkeland current components vary with separation, along with the behavior of the combined (net) force.



These images from a supercomputer simulation trace the development of spiral structure in two interacting plasma blobs over a span of nearly 1 billion years. At the start of the interaction at upper left the filaments are 260,000 light-years apart; all 10 panels are reproduced at the same scale. Simulations such as this can reproduce the full range of observed spiral-galaxy types using electromagnetic processes rather than gravitational ones. Unless otherwise noted, all illustrations are courtesy the author.

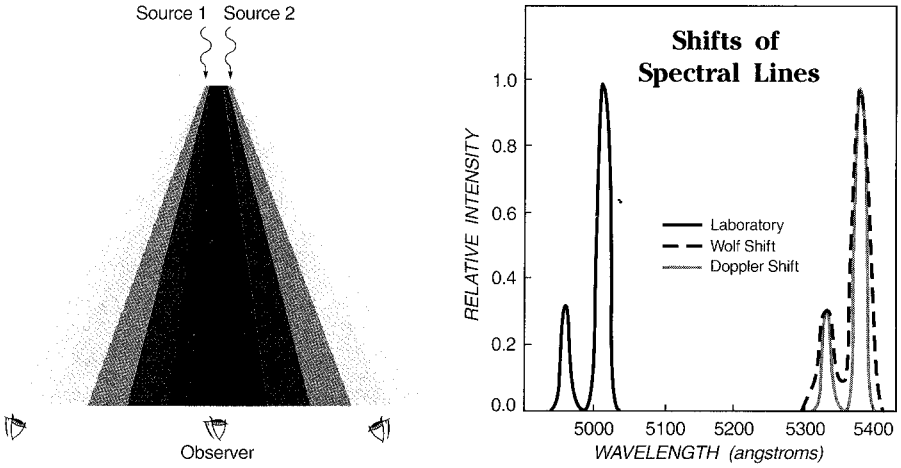
The Wolf Effect and Galaxy Redshifts

Spectral lines can be redshifted toward longer wavelengths or blueshifted toward shorter ones. The Doppler effect explains how these shifts occur because of relative motions of the source and the observer along the line of sight. Approach causes a blueward shift and recession a redward one.

Scientists have long believed that only the Doppler effect or gravity as described by Einstein could account for wavelength shifts in the spectrum of light as it travels through space. Where neither factor applies, scientists have always assumed *spectral invariance* — the spectrum remains the same no matter how far the light travels. This is the case with ordinary sources — called "Lambertian" after Johann Heinrich Lambert — such as the blackbody radiation from stellar surfaces.

In the past few years, however, experiments have shown that there is a third way to shift spectral lines. This mechanism involves non-Lambertian sources that emit beamed energy, such as lasers and devices producing synchrotron light. The discoverer of the new effect is physicist Emil Wolf, who, along with Max Born, wrote the definitive textbook *Principles of Optics*.

A mechanical analog to Wolf's discovery is a pair of tuning forks with nearly identical resonant frequencies (pitches). If these forks are connected together mechanically by, say, a sounding board, the coupling is strong and the resonant frequencies tend to get "dragged down" to lower ones. In other words, the wavelength is lengthened, or redshifted. This phenomenon has been verified experimentally with light waves and for sound waves from coupled speakers.

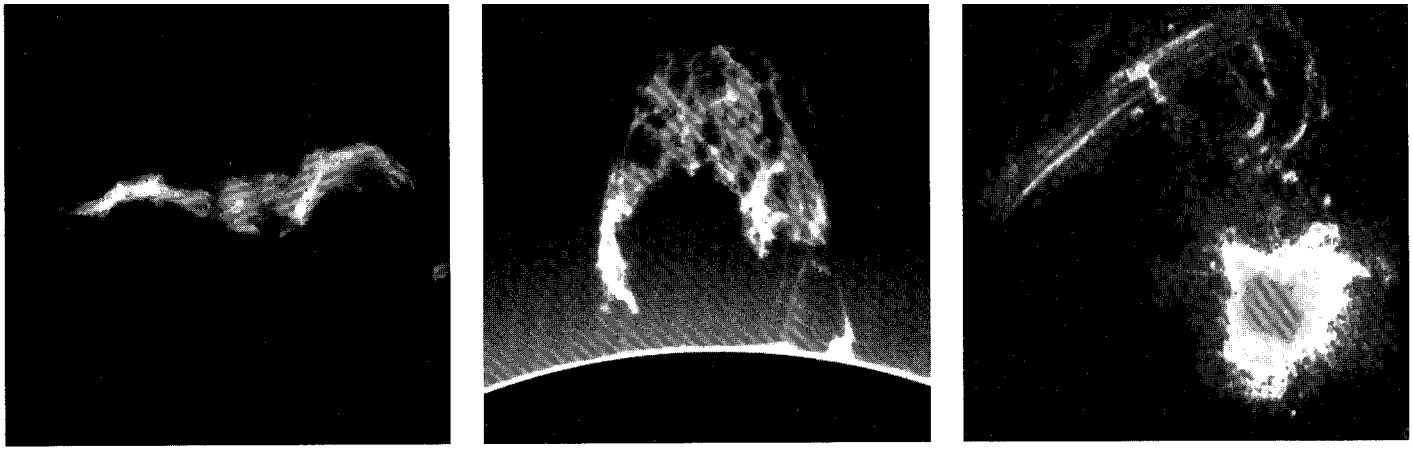


Left: Due to the Wolf effect beamed emission from two separate sources can interact and shift the wavelengths of lines in their spectra. The change can be redward or blueward by different amounts depending on the observer's point of view, but from "head-on" the shift is to the red. This is a distinctly different process than the more familiar Doppler effect. *Right:* Here the two mechanisms are compared for the case of oxygen lines with a redshift of 0.07. However, the light sources involved in the Wolf effect are *stationary*, not fleeing the observer at 84 kilometers per second.

The actual frequency shift due to the Wolf effect depends on the geometry. As the illustration above shows, whether an observer sees a redshift or a blueshift depends on his or her location with respect to the source.

This mechanism can be extended from the case of two radiating point sources to that of a whole collection of such objects, for example a plasma cloud. Wolf and his colleagues have shown that such a cloud can produce shifts that closely mimic the Doppler effect. The figure above shows an example.

Thus the assumption that quasars — beamed electromagnetic radiators with large redshifts — are part of the "Hubble flow" of an expanding universe could be wrong. Whether this also applies to normal galaxies remains unclear. This situation, coupled with the question of the origin of the cosmic background radiation, raises the possibility that there is really no need for the Big Bang.



Filamentation — the transformation of energetic, high-temperature material into current-carrying bundles — is characteristic of plasma at any scale. *Left:* In the laboratory filaments are produced when a pulse-power generator delivers 10 trillion watts to a plasma only a few centimeters long, heating it to a temperature of 8,000,000° Kelvin. *Center:* Similar structure is seen in solar prominences, but in this case the lengths are measured in hundreds of thousands of kilometers. Photograph by Benny Sundström. *Right:* Long, thin structures near the center of the Milky Way stretch out over roughly 120 light-years. Courtesy Farhad Yusef-Zadeh and Mark Morris. Another jump to a scale a few million times larger would bring us to the size of filaments that plasma cosmology needs to form galaxies. Thus the recent discovery of vast filaments and sheets of galaxies spanning hundreds of millions of light-years is good news for plasma cosmology. Standard cosmology assumes that the universe becomes smooth at very large scales.

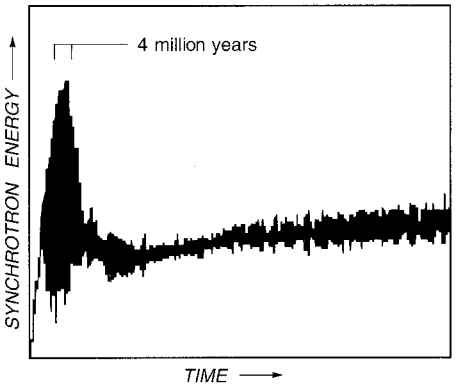
radio telescope, they discovered an arc of radio emission some 120 light-years long near the center of the Milky Way. The structure is made up of narrow filaments typically 3 light-years wide and running the full length of the arc (see the image above, right). The strength of the associated magnetic field is 100 times greater than previously thought possible on such a large scale, but the field is nearly identical in geometry and strength with simulations of Birkeland currents in studies of galaxy formation (*S&T:* August, 1984, page 118).

SUPERCOMPUTING THE COSMOS

The set of equations describing how a filamentary, electrically conducting, magnetized plasma evolves is a mathematician's nightmare! Because of this complexity, effective solutions had to wait for the advent of supercomputers.

Plasma theorists often use a method called *particle simulation.* Some tens of millions of "particles" are used to represent, say, a galaxy. But since a system similar to the Milky Way may contain 10^{65} free electrons and ions, each particle in the simulation actually represents a cloud of real ones. These "superparticles" are assumed to be in a magnetic field similar to that between the planets in the solar system, but much larger in size. The computer then calculates how the particles move according to the laws of electromagnetism.

The simplest simulation, whose geometry is pictured at the bottom of page 137, traces the interaction of two Birkeland filaments made up of fast-moving electrons (because of their greater mass, positively charged ions move more slowly and are usually ignored). No matter how many



When two magnetized plasma filaments of galactic dimensions interact, they emit an early burst of synchrotron radiation that lasts 4 million years or so.

filaments are present, the two closest to each other will always interact most strongly, because the net force between two like currents falls off in direct proportion to the distance between them (see the graph on page 137). This so-called Ampere's-law force is stronger and has a longer range than gravity, which falls off as the square of the distance.

Because electrons spiral around magnetic-field lines, each filament has a circular current component. Two such components repel each other and in so doing give off energy in the form of synchrotron radiation like the example illustrated above. In a typical case about 2×10^{51} joules are released over an interval of some 4 million years (1 joule will raise an apple 1 meter off the ground). Dividing the energy by the duration gives a radiated power of 10^{37} watts. Interestingly, this is close to the output of a strong extragalactic radio source like Cygnus A.

The two-current simulation was one of the first large-scale plasma calculations. Today's supercomputer networks are nearly 100 times more powerful than those of just a few years ago, and simulations can now involve as many as 50 million particles. The calculations provide information not only on sources' power levels and shapes but also on their polarizations. All of these properties can be compared with results from radio telescopes.

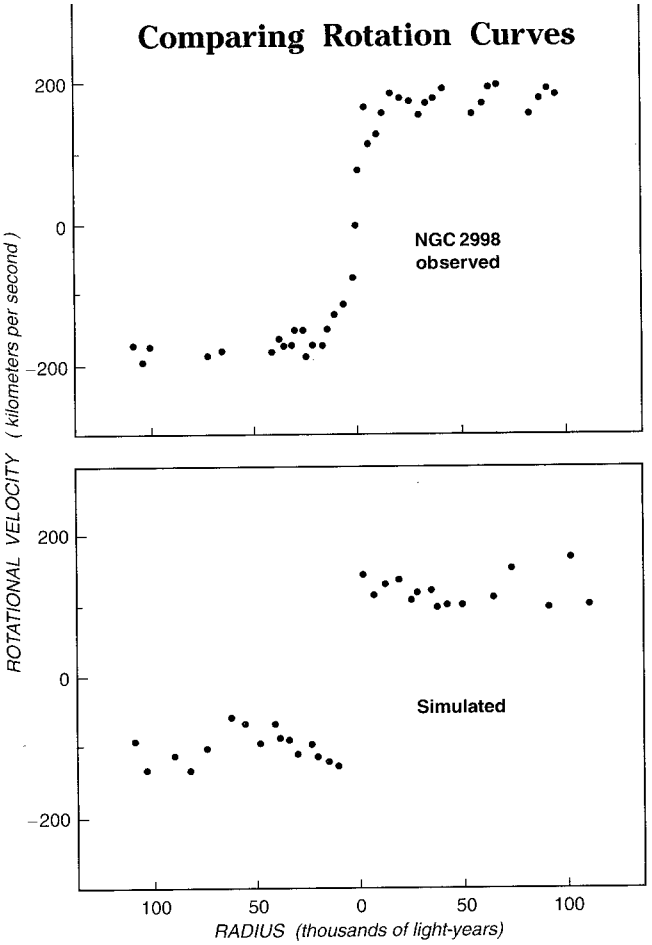
One result of this improved performance is the ability to sort out the evolution of "double" radio sources that until now seemed unrelated. The top diagram on page 137 suggests that double radio galaxies evolve from filamentary plasma, announcing their birth through a double-beam pattern of radiation that they retain through the era of synchrotron radiation.

The radiation patterns grow more complex as they fade. The plasma does not disappear, however, and the illustrations at the top of the facing page show how double radio galaxies and quasars might change first into peculiar and Seyfert galaxies, then into normal and barred spirals. Filamentary plasma on supergalactic scales can produce a wide variety of galaxy shapes.

Calculations are now good enough that we can compare their detailed predictions with observations of how a galaxy's rotational velocity varies with distance from its center (see the illustrations on the next page). Simulations involving plasma can match the data well and do not require a large amount of "dark matter" (whatever that is) to do so.

COSMIC BACKGROUND

In one view, the radio sky is peppered with sources that chance to beam their energy toward Earth. If so, what happens



Here the observed change of rotational velocity with radius in a spiral galaxy's disk is compared with the results of a supercomputer simulation of a spinning object composed of two interacting plasma filaments. NGC 2998 is a 13th magnitude spiral in Ursa Major. The mass used in the supercomputer calculations was typical of the *observable* mass of a galaxy — its luminous stars and gas. The plasma universe needs no dark matter to reproduce such rotation curves because the electromagnetic forces acting on plasma are so much stronger than gravity.

limit? How large can filaments really get?

We observe tiny plasma filaments in the laboratory and ever-larger examples in the aurora, solar coronal loops, the galactic center, and perhaps the lobes of double radio galaxies and even clusters of galaxies. Could there be even bigger examples containing superclusters of galaxies or even greater aggregations? If so, enormous cell walls and filaments might explain the surprisingly nonuniform, very-large-scale structure of the universe.

Plasma cosmology offers other interesting alternative views of the universe. One example, described in the box below, involves Olbers' paradox. Another, summarized in the box on page 138, explains the redshifts of galaxies without resorting to cosmic expansion, thus getting rid of the need for the Big Bang.

The plasma vision of the universe is at odds with how most cosmologists have viewed our universe for several generations. It probably will be proved or disproved in the coming century. Either way, we are in for some exciting and interesting times now that we have reached "nightfall" and can explore the universe at almost all wavelengths.

Anthony Peratt is an associate editor of the Institute of Electrical and Electronics Engineers' journal Transactions on Plasma Science *and author of* Physics of the Plasma Universe *(Springer-Verlag, 1991).*

to the energy haphazardly radiated in other directions?

Plasma cosmologists William Peter and Eric Lerner asked just that question. The two were intrigued by the parallels between the cosmic microwave background radiation and the radiation produced by very energetic plasma generators in the laboratory.

In both cases the spectrum is that of a blackbody, a perfect absorber and emitter of energy. However, this is so in the laboratory version only because filamentary insulation is placed around the generator to protect the environment. Could gigantic filaments of cosmic plasma act like that shielding and give the "wasted" radiation a blackbody spectrum that would fill the sky? Indeed they could.

Then what would the energy density be? The answer is a minuscule 5×10^{-14} joule per cubic meter. Interestingly, this corresponds to a blackbody temperature of 2.87° Kelvin, in close agreement with the 2.73° K measured by the Cosmic Background Explorer satellite.

MORE ANSWERS FROM PLASMAS?

Except for weakly ionized gases, all plasma is cellular, having regions with different properties separated by transition zones. Does this honeycomb structure occur at increasingly larger scales without

No Paradox in the Plasma Universe

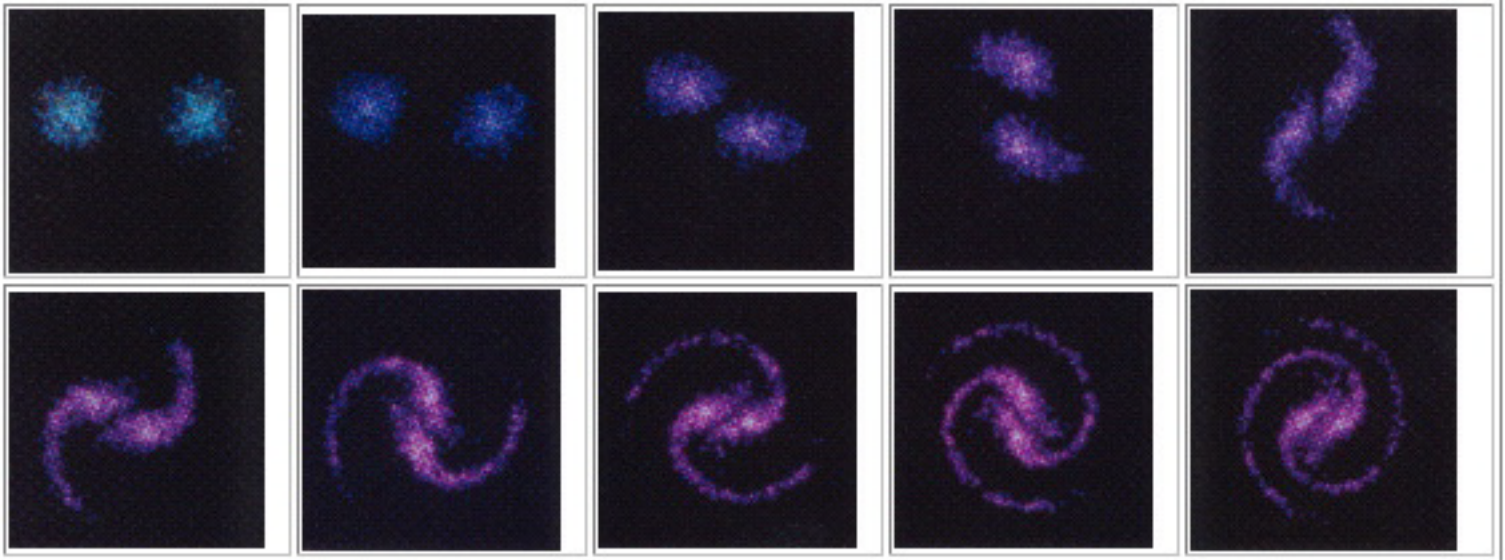
Olbers' paradox, which dates back at least to Edmond Halley, exemplifies the bias of a purely "visual" cosmos. If the universe is an infinite set of stars, why is the sky dark at night? Sooner or later *every* line of sight should intercept the surface of a star, and the entire sky should blaze as brightly as the Sun.

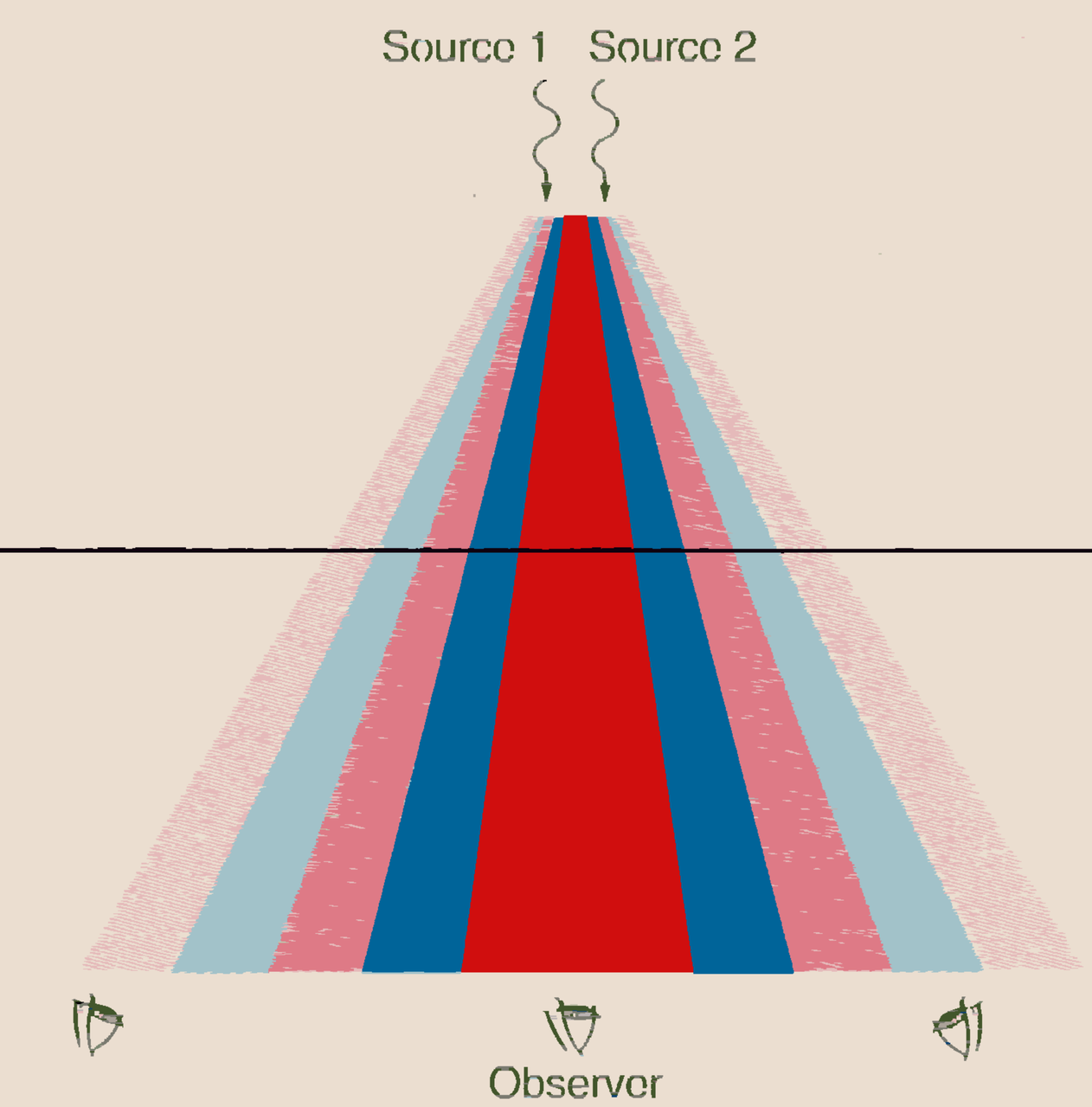
Olbers thought that the solution lay in light-absorbing interstellar matter. We now know that this couldn't work because the dust would just heat up until it vaporized. Sir John Herschel believed in a "hierarchical" universe in which stars form galaxies, galaxies form clusters, clusters form superclusters, and so on without end, so that stars are *not* distributed uniformly.

Some modern cosmologists say the sky is dark because the expansion of the universe redshifts and dims light. Others say the reason is that the cosmos is young — there hasn't been enough time for light from very distant objects to have reached us yet. Still others cite both of these explanations (*S&T:* June, 1989, page 594).

From the viewpoint of plasma cosmology, the original question starts from an incorrect assumption. The universe may be neither filled with an infinite number of stars nor finite and uniformly filled. According to plasma physicists Per Carlqvist, Hannes Alfvén, and Boris Meierovich, stars condense out of plasma only when the electric current passing through the material exceeds a certain threshold. Then the plasma is "pinched" and compressed to the point where gravitational collapse ensues. This threshold is exceeded only when galaxies evolve from quasars into normal spirals (stars are not resolved in quasars, but emission lines from plasmas are observed).

Olbers' paradox exists only if we are limited to observing the universe in visible light. Then we miss entirely the hot, magnetized plasma that may be the predominant form of matter. No paradox exists in the plasma universe because the evolving stars are not assumed to occupy all of space. Understanding their evolution requires use of the full electromagnetic spectrum — that is, the stars' radiation before they "ignite" and begin to shine in visible light and after they disappear from sight.

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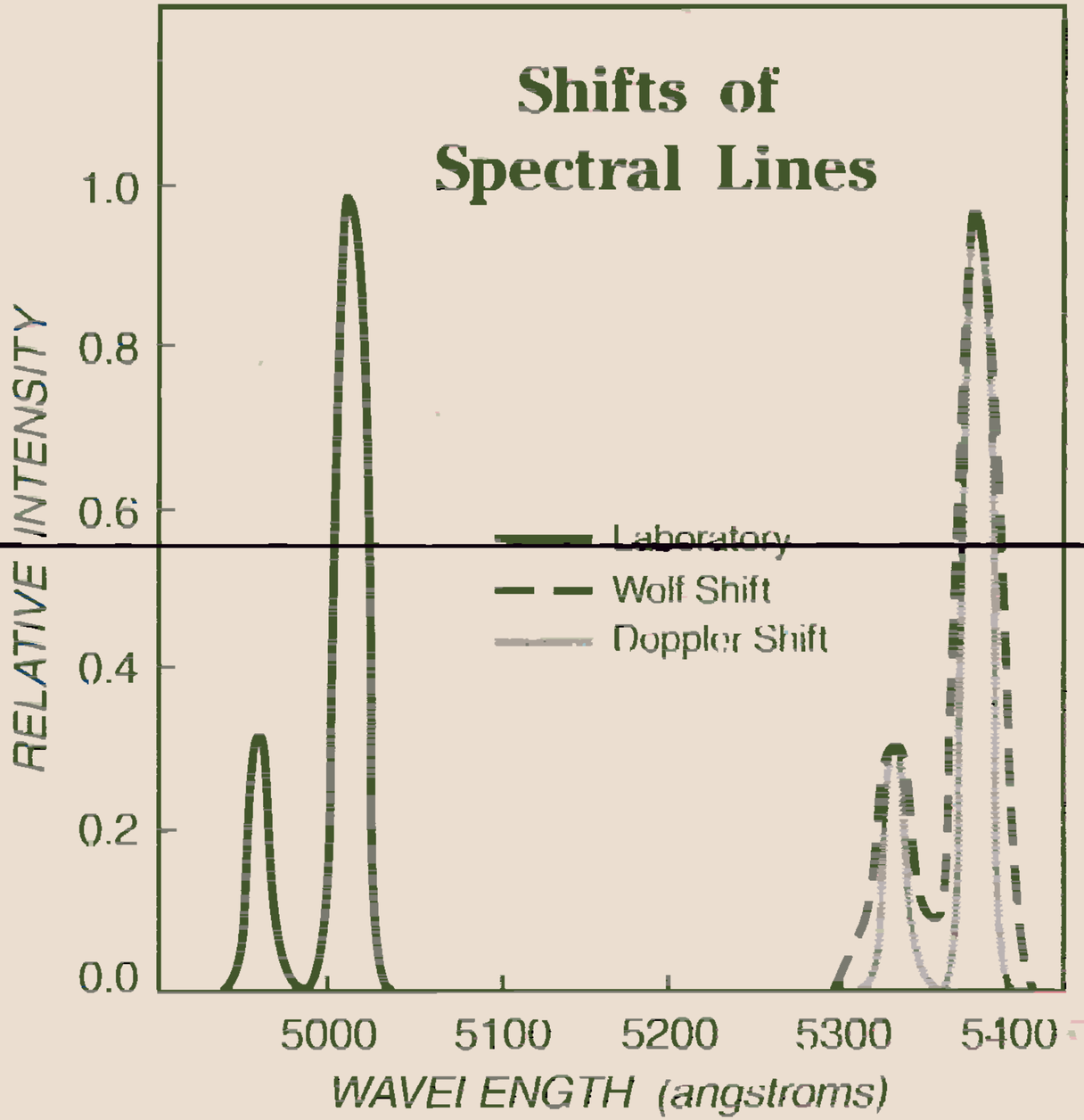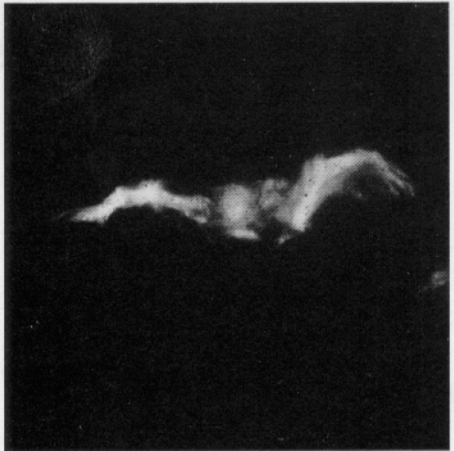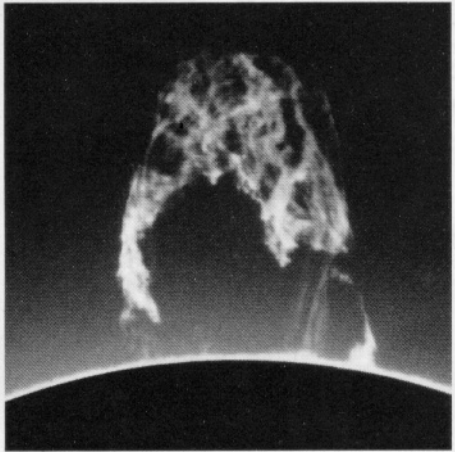
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