

INTERGALACTIC MAGNETIC FIELDS

Unlike electromagnetic radiation from astrophysical sources, distant static magnetic fields are inherently difficult to detect. Nonetheless, recent measurements have begun to reveal that such fields exist at significant strengths, and on surprisingly large scales, in the extragalactic universe. These discoveries present us with an important, previously unrecognized component of energy and force in the cosmos.

Magnetic energy is released from individual galaxies. It appears to be captured within zones as large as typical intergalactic separations. Such surprising revelations invite us to understand the role that intergalactic magnetic fields have played in shaping the evolution of galaxies and large-scale groupings of galaxies. These fields doubtless also have an intimate connection with the flux of cosmic rays from outside the Milky Way, whose intergalactic energy density may be comparable to that of the magnetic fields. The acceleration process by which cosmic-ray particles from far away can reach energies as high as 10^{20} eV is still a mystery (see PHYSICS TODAY, October 1998, page 19).

Leaving aside the even more mysterious “dark matter” and cosmological vacuum energy that cosmologists have, in recent years, inferred from the motion of galaxies and from the apparent acceleration of the Hubble expansion, magnetic energy seems to be the last form of widespread conventional energy to be identified in the mature universe. (See PHYSICS TODAY, June 2001, page 17.)

Detecting astrophysical magnetic fields

The existence of a widespread, few-microgauss field in the Milky Way was ingeniously deduced more than 50 years ago by Arnulf Schlüter and Ludwig Biermann, and independently by both Hannes Alfvén and Enrico Fermi. Schlüter and Biermann confidently deduced the strength of this interstellar magnetic field to be 5 μG within a small uncertainty.¹ (One gauss, the customary unit, equals 10^{-4} tesla.) They invoked only a single astronomical observation—the thickness of the Milky Way’s disk—and related it to the then new discovery of cosmic rays.

In the previous decade, it had been established that these enigmatic visitors from space arrive at Earth isotropically, with energies up to 10^{16} eV. From the measured cosmic-ray energy spectrum, Schlüter and Biermann concluded that the average cosmic-ray energy density inside the Milky Way is about 0.6 eV/cm^3 . Such a high energy density, they argued, could not possibly apply to intergalactic space. But confinement of 10^{16} protons and

Magnetic fields that spread far beyond the galaxies that created them represent a significant, and only recently revealed, component of the cosmic energy budget.

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μG is close to the present consensus value for the Milky Way’s magnetic field, as measured with modern detection technologies.

Diffuse magnetic fields and cosmic rays are connected in several ways. In 1949, Fermi proposed a theory explaining how diffuse magnetic fields are responsible for accelerating cosmic rays within the Galaxy.² On wider scales, synchrotron radiation and the highest-energy cosmic rays offer us a way of detecting the otherwise elusive diffuse intergalactic magnetic fields. These ultrahigh-energy cosmic rays, above 10^{19} eV, almost certainly require some spectacular sort of magnetic field configuration for their acceleration.

Telltale synchrotron radiation

Around 1950, Julian Schwinger and Iosef Shklovskii recognized that the astrophysical electromagnetic radiation recently discovered at VHF frequencies is caused by the continuous acceleration of relativistic electrons in a magnetic field, similar to what one gets from a laboratory synchrotron. Radio-telescope imaging of synchrotron radiation at frequencies below about 40 GHz is the easiest way to detect the presence of magnetic fields within and beyond the boundaries of galaxies. That’s because the emissivity $\epsilon(\nu)$ of such an astrophysical synchrotron source increases logarithmically with decreasing frequency ν .

$$\epsilon(\nu) \propto n_r B^{(s+1)/2} \nu^{(1-s)/2}, \quad (1)$$

where B is the magnetic field strength and n_r is the density of relativistic electrons. The parameter s , which is the exponent of the power-law falloff of the relativistic electron energy spectrum, is typically near +2.7. Thus $\epsilon(\nu)$ typically falls off with increasing ν a little slower than $1/\nu$.

Synchrotron radiation can detect the intergalactic magnetic field. But, as we see from equation 1, it cannot give us B unless we already know the electron density. For a remote system like a radio galaxy, n_r is not, in general, independently measurable.

Extragalactic magnetic fields are most easily detected via their synchrotron radiation if radio telescopes are tuned to the lowest possible frequencies. How low can we go? In principle, all the way down to about 10 MHz. Below this, incoming radio waves begin to be scattered away or absorbed by Earth’s ionosphere. Figure 1 shows the voluminous synchrotron-emitting clouds from a giant radio galaxy. Their extent dramatically illustrates how the enormous magnetic energy necessary to explain this radiation

nuclei within the 2000-light-year thickness of the Milky Way’s disk and their isotropic bombardment of Earth implied that the Galaxy’s average magnetic field must be about 5 microgauss. These arguments are instructive, and they have stood the test of time. Five

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is somehow “injected” from a galaxy’s nucleus into a large volume of the surrounding intergalactic space—in this case, out to about 4 million light-years from the nucleus.

Background probes

The largest gravitationally bound systems in the cosmos are clusters of galaxies. These huge systems also accrete a mass of diffuse, nonrelativistic (thermal) gas that actually constitutes 10 times the aggregate stellar mass of all the galaxies in the cluster. Although the typical density n_e of nonrelativistic intergalactic gas within clusters is only a few dozen atoms per m^3 , it is still hundreds of times greater than the density of the wider intergalactic medium into which the radio lobes of figure 1 extend.

The relatively high thermal-gas density within clusters permits a new combination of measurements, not yet possible elsewhere, that can more accurately measure intergalactic magnetic field strengths. Independent of any synchrotron-radiating relativistic electrons that might also permeate a galaxy cluster, the denser nonrelativistic gas, if it is permeated by a magnetic field, will rotate the polarization plane of the emission from a background radio source. This effect is known as Faraday rotation. The total rotation in traversing a foreground cluster on its way to us is given by the line integral

$$\lambda^2 \int n_e B_l dl, \quad (2)$$

where B_l is the line-of-sight component of the magnetic field, and λ is the wavelength of the radio emission whose Faraday rotation is being measured.

With the intracluster thermal gas, one can make additional measurements that provide an independent determination of n_e . Because the bulk of the gas is usually quite hot (typically 10^6 K), but not relativistic, it emits bremsstrahlung that is easily imaged by x-ray satellites such as Chandra and XMM Newton (see the news story on page 13). The x-ray images measure the line integral of n_e^2 over the path traversed by polarized photons from a radio source behind the cluster. Combining this information about the thermal electron density with the measured Faraday rotation, one gets an explicit estimate of the distance scale on which B reverses direction. Figure 2 illustrates this method of probing the intergalactic magnetic field that permeates a galaxy cluster. From an extended radio source embedded inside clusters, one can also measure the distance scale on which B reverses itself.

Thirteen years ago, x-ray emission and Faraday rotation from the Coma cluster of galaxies, some 200 million light-years from us, yielded the first credible estimate of the Coma’s intergalactic magnetic field strength. It was a surprise to learn that this nearest large cluster outside our own supercluster of galaxies is pervaded by magnetic fields at the level of a few microgauss.³ That’s similar to the field strength we find in the disk of the Milky Way, even though the density of Coma’s intergalactic gas is a hundred times rarer than the interstellar gas in our local precincts.

In retrospect, the substantial intergalactic magnetic fields found in the Coma cluster shouldn’t have been so surprising, given that the intracluster gas is very hot: 10^7

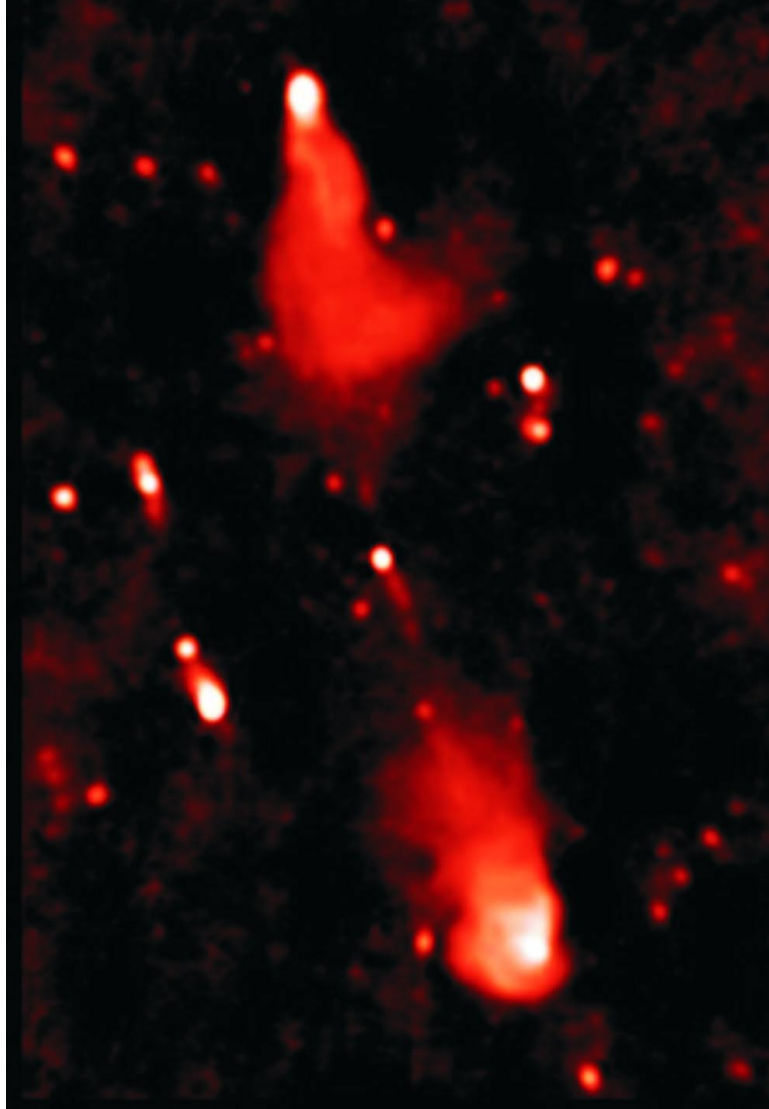


FIGURE 1. THE GIANT RADIO GALAXY 2147+816, imaged at 1.4 GHz by the Very Large Array of radio antennae. The galaxy’s two highly collimated radio lobes are shown here as red clouds, tipped in white at their far ends where the synchrotron radiation is most intense. They extend outward in opposite directions from the galaxy (the central white point) by more than 4 million light-years. The brightness of the radio lobes yields an estimate of the magnetic field in which spiraling electrons emit the synchrotron radiation.

to 10^8 K. Thus the *ratio* of magnetic energy density ($B^2/8\pi$) to thermal energy density ($n_e kT$) in the intergalactic medium of the distant cluster is not so different from that of the local interstellar medium.

Beyond clusters

To measure magnetic fields in even more rarified regions of intergalactic space, outside of galaxy clusters, we generally have only synchrotron radiation at our disposal, because the Faraday rotation or the column-integrated electron density is below the threshold of detectability. So we want to search for diffuse extragalactic synchrotron radiation at the lowest possible levels. In the late 1980s, my colleagues and I were able to detect such radiation beyond the confines of the Coma cluster by exploiting the capabilities of the new Westerbork Synthesis Radio Telescope in the Netherlands at the low frequency of 326 MHz.

Figure 3 shows our 326-MHz synchrotron-radiation

map of the Coma cluster and its environs.⁴ The extended radiation regions to the left and lower right of the cluster itself suggest magnetic fields of at least $0.1 \mu\text{G}$ in these diffuse extensions. This region of sky contains part of what is called the “Great Wall”—a roughly linear concentration of galaxies that stretches across the cosmos for perhaps a billion light-years. The Coma cluster is, in fact, the largest concentration of galaxies on the Great Wall. The results from our synchrotron radiation mapping raises an interesting question: Are all the overdense filaments and sheets of galaxies in the cosmos similarly permeated with magnetic fields of order 10^{-8} to 10^{-6} G? If so, that would represent an enormous amount of hidden magnetic energy in intergalactic space. And such fields should be detectable with the next generation of low-frequency radio telescopes. The international community’s planned Low Frequency Array for Radio Astronomy (LOFAR), whose site is yet to be chosen, will be able for the first time to explore these regions with unprecedented sensitivity to synchrotron radiation. Radio astronomers can regard the wider intergalactic space beyond the clusters as a new frontier.

How would such widespread magnetic fields have been started and then amplified? Before magnetic flux can be amplified, there must be some initial, nonzero seed field, which can arise in a plasma where the pressure and velocity gradients are locally different. That is the essence of the “battery” mechanism originally proposed by Biermann to explain how stars can seed their own magnetic fields. Subsequent amplification of a magnetic field can happen in many situations, all of which are a consequence of the magnetic induction equation for plasmas that can be straightforwardly derived from the Maxwell equations and Ohm’s law. In its basic simplified form, the equation reads

$$\partial \mathbf{B} / \partial t = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times \eta (\nabla \times \mathbf{B}), \quad (3)$$

where $\mathbf{v}$ is the velocity field of the plasma electrons and η is the diffusivity of the magnetic field, which can include a contribution from the plasma’s resistivity. One application of the induction equation is the so-called α - Ω galactic model dynamo proposed in the 1960s by Eugene Parker⁵ and by Fritz Krause and coworkers.⁶ They described how rotating galaxy disks could convert some of the kinetic energy of their organized gravitational motions into amplified galactic magnetic fields.

An important unsolved question is how magnetic fields can be destroyed by converting the field energy back into kinetic energy and heat. That can happen when antiparallel field lines are pressed together, which leads to magnetic reconnection. Reconnection is known to occur in the Sun’s atmosphere. Some of Earth’s auroral displays are believed to be caused by reconnection-accelerated particles that are injected into the upper atmosphere from the geomagnetic tail.

A major difficulty in understanding reconnection is that it happens much faster in nature, for example in the Sun, than our present physical models predict. Just how magnetic reconnection might proceed in intergalactic space is currently an interesting and challenging problem.

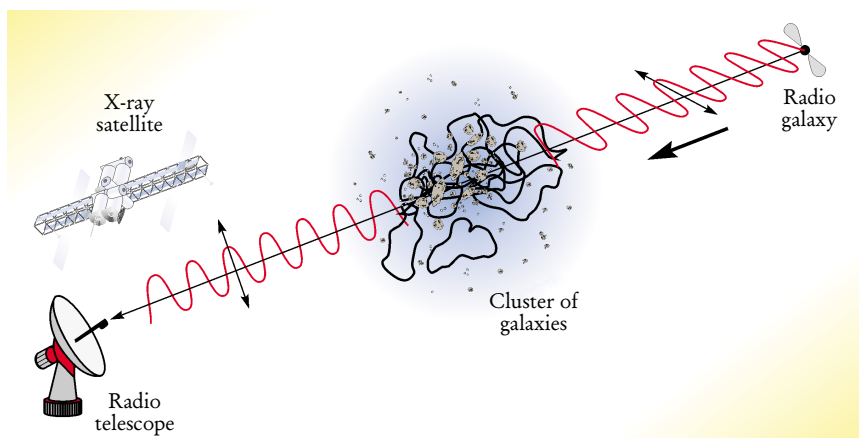


FIGURE 2. FARADAY ROTATION of the polarization plane of background radio emission as its path traverses the intergalactic hot gas within a foreground cluster of galaxies that is independently imaged in x rays. These combined observations measure the intergalactic magnetic field permeating the cluster.

It probably has important implications for understanding how extragalactic cosmic rays are accelerated.

Too strong too early

The first generations of galactic dynamo models were constructed on the assumption that the microgauss fields observed in the disks of spiral galaxies were weaker in the past than they are now, and that they were only amplified to current levels over dynamical lifetimes of at least 5 billion years by large-scale galactic dynamos. If that were the prime mechanism for generating magnetic fields in the universe, we would expect only very weak fields—much less than a microgauss—in galaxy systems at earlier cosmological epochs, and now in intergalactic space.

Within the past decade, however, magnetic field estimates have been made for a small number of extragalactic gaseous systems ranging in redshift z from 0.4 to about 2. These redshifts correspond to 35% and 75%, respectively, of the time back to first galaxy formation. Nonetheless, it turns out that these fields are in the range of a few microgauss. (One sees the wavelength of light emitted by a distant object at redshift z stretched by a factor $1 + z$.) Redshift serves cosmologists as a kind of nonlinear reverse clock. The larger the redshift, the earlier in cosmic history was the emission (see the red curve in figure 4).

More recently, synchrotron-loud quasars and galaxies have been imaged at redshifts up to 6. That’s about 95% of the look-back time to the Big Bang. And, sure enough, these very early galaxies appear to possess microgauss (or even stronger) magnetic fields. The elapsed time from the Big Bang to events at redshift 6 is about a billion years (see figure 4). And for much of that time, there were no large galaxies. So these new observations clearly contradict the supposition, from the standard galactic-dynamo models, that it takes several billion years to amplify galactic magnetic fields to their present strengths.

Observations of these early galaxy systems tell us that the amplification mechanisms for magnetic fields must be much faster than we had supposed. They also suggest that magnetic field creation may be a common process in astrophysical plasmas, and that this was also the case in the earlier universe. Taken in aggregate, the observations strongly hint that all astrophysical plasmas may develop

FIGURE 3. THE COMA CLUSTER OF GALAXIES and its vicinity, imaged in synchrotron radiation at 326 MHz with the Westerbork Synthesis Radio Telescope in the Netherlands. Shaded contours show the synchrotron glow both from the cluster itself (the core of most intense radiation slightly left of the map's center) and from extensions into the intergalactic space beyond the cluster. The extensions (left and lower right) strongly hint at a substantial magnetic field of at least 100 nG well beyond the Coma cluster. Grayer shading indicates higher intensity, except near maxima, where the gray scale saturates and shows up white. (Adapted from ref. 4.)

a kind of equilibrium in which the plasma's heat, its magnetic field, and its kinetic and turbulent motions all contribute comparable energy densities.

Could significant magnetic fields have been generated even before there were any stars or galaxies? In the early 1970s, Edward Harrison was the first to propose a mechanism for field generation in the plasma epoch that ended some 400 000 years after the Big Bang—when the cosmos was finally cool enough for neutral hydrogen atoms to survive.⁷ A variety of other field-seeding mechanisms concentrate on still earlier epochs: the first few seconds, or even the epoch of cosmic inflation in the first 10^{-34} s after the Big Bang. These early scenarios, however, are still poorly understood and, in any case, they generally predict very weak (subnanogauss) fields at the time when the first stars appear.

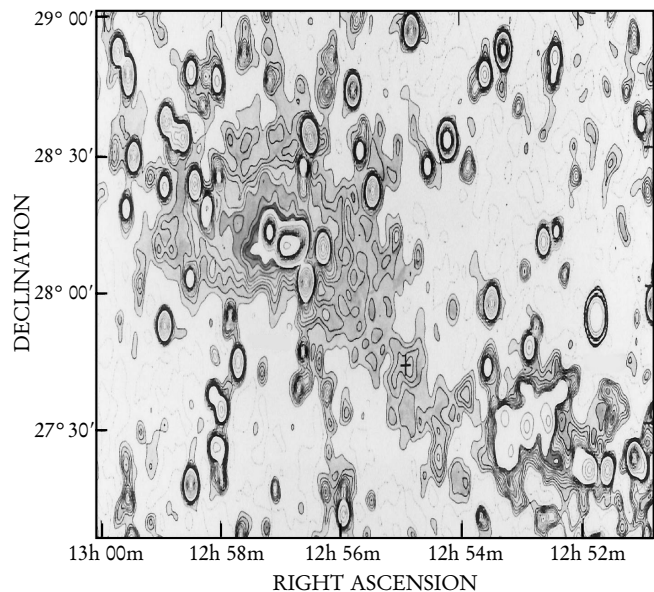
Intergalactic fields from stars

Recent observations show galaxy systems generating magnetic fields and expelling them into intergalactic space on cosmologically short time scales. Prime candidates for such phenomena, as illustrated in figure 1, are supermassive black holes at the centers of galaxies, associated with radio source lobes that extend far beyond the galaxies.^{8,9}

Another leading candidate is star-formation sites in galaxies.^{10,11} Interesting systems in this category are nearby “exploding” starburst galaxies and the many now gasless dwarf galaxies that populate our local corner of the universe. The implication for these gasless dwarfs is that they blew out their magnetized interstellar gas at some earlier stage. The energy for such a collective explosive process would have come from supernovae and the most massive stars in these galaxies. In such a brief, early outburst phase, the galaxy would sporadically have spewed out magnetized hot gas into a large supragalactic halo.

An example of such a galactic explosion, caught *in flagrante* in the present epoch, is the nearby galaxy Messier 82. This galaxy can be seen ejecting relativistic cosmic rays, ionized hot gas (10^7 K), and cooler neutral gas into a large halo that is found to harbor surprisingly strong (greater than $10\ \mu\text{G}$) and partially ordered magnetic fields. In a galaxy's starburst phase, large numbers of the hottest, most massive stars race through their life cycle in less than 10 million years. The resulting outflow typically fills a 30 000 light-year-radius zone with magnetic flux, cosmic rays, and hot gas.

Intergalactic space could have become largely filled by this kind of outflow in the much more crowded early universe, densely packed with starbursting dwarf galaxies. In that epoch the smallest dwarfs, presumably very numerous, would have been particularly effective in ejecting magnetized gas into the intergalactic medium, partly be-



cause their smaller masses imposed lower escape velocities on the ejecta. So we can imagine that the intergalactic medium was then easier to fill with magnetic fields and gas enriched with heavy elements. Figure 4 shows the results of model calculations of the fraction of available intergalactic space that would have been filled with starburst-driven magnetic fields over the time since the first galaxies formed, about a billion years after the Big Bang.

The expansion of cosmic volume, which grows like $(1+z)^3$, and the progression of cosmic time are such that, from $z = 10$ to 7, the most numerous galaxies (dwarfs) would have largely done their job of filling the cosmos with magnetic fields. (See figure 4.) This redshift interval range corresponds to a comparatively short interval in cosmic history, as indicated by the flattening of the red curve in the figure that translates redshift into cosmic time, assuming that the universe is about 13 billion years old. The

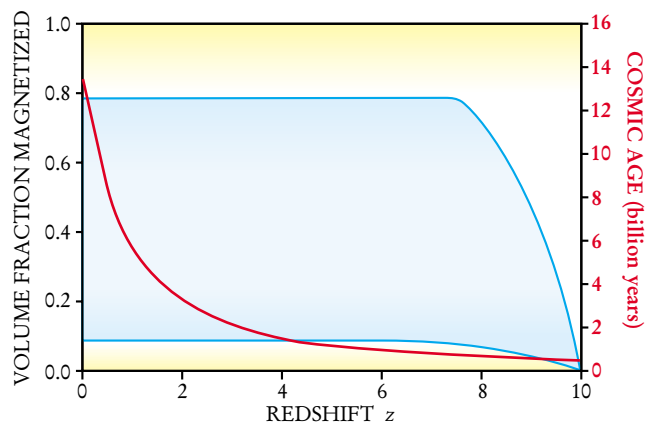


FIGURE 4. CALCULATED FILLING OF INTERGALACTIC SPACE with magnetic fields ejected from galaxies is expressed as a fraction of the total available intergalactic volume (left scale) and plotted against redshift z , a measure of time since the Big Bang. The height of the shaded zone indicates the range of estimates from different model input assumptions. In all cases, the filling is assumed to begin with primeval dwarf galaxies at redshift 10. The red curve and right-hand scale translate the observed redshift of a distant galaxy into the age of the universe at the time its light was emitted.

FIGURE 5. TOTAL ENERGY CONTENT of magnetic fields and cosmic rays in strong extragalactic radio sources is plotted against projected linear size for two different classes: galaxies (green points) embedded within rich clusters, and freestanding giant radio galaxies larger than 2.2 million light-years (blue points). For the latter class, which includes the source shown in figure 1, the energies approach 10^{61} ergs, about 10% of the gravitational infall energy (red line) of a 10^8 -solar-mass black hole. (Adapted from ref. 12.)

original energy source for the starburst-driven fields in this model is mostly from the thermonuclear energy of stars in the dwarf galaxies.

Supermassive black holes

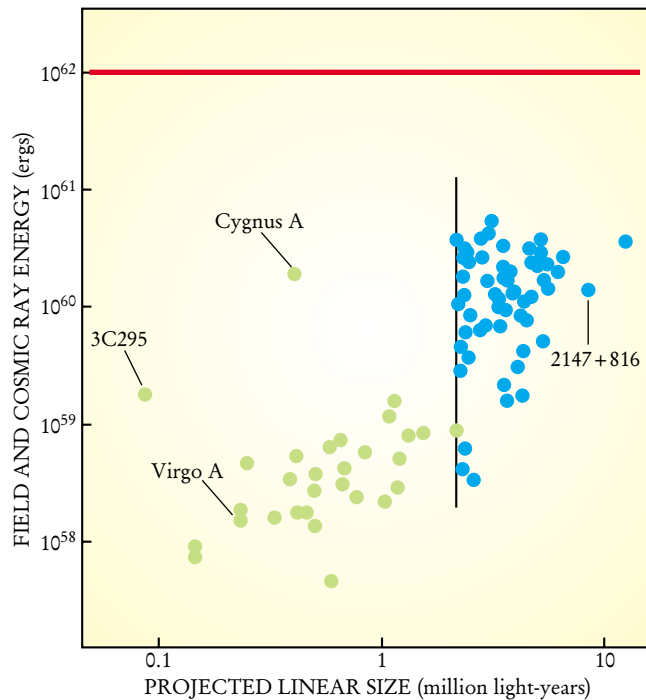
Although these star- and supernova-driven outflows can plausibly fill a substantial fraction of intergalactic space with magnetized dilute gas, the aggregate stellar thermonuclear energy from all the stars would not be enough to explain all the energy that appears to be stored up in the extragalactic magnetic fields we are detecting. Indeed, the thermonuclear energy from the large radio galaxy in figure 1 is insufficient to explain the total energy content of its very large lobes, filled with cosmic ray particles and relatively strong magnetic fields.

So we are led to consider an even greater energy source. The solution lies in the recent discovery that most, if not all, large galaxies in the mature universe harbor a supermassive black hole at their centers. And the gravitational infall energy liberated as these black holes accrete surrounding matter and grow to millions of solar masses is very large indeed.

The infall energy of a large host galaxy's central black hole is of order about 10^{62} or 10^{63} ergs, and much of that is converted to rotational energy. Furthermore, this gravitational energy is all captured within a dimension comparable to our solar system! It would seem that such spinning central objects are what powers quasars and radio galaxies. Avi Loeb and Steven Furlanetto have recently calculated how such active galactic black holes would have contributed to the filling of the intergalactic medium.⁸ They and others doing similar calculations estimate the fraction of the intergalactic volume that would have been filled by magnetized gas and cosmic rays powered by galactic black holes to be between 5% and 20%. That's comparable to the fraction attributed to star-powered filling by early dwarf galaxies. But, at least locally, the total magnetic energy from black-hole radio sources is greater than what stellar thermonuclear processes can generate.

A recent quantitative analysis of energies supplied by galaxy and quasar radio sources, by Stirling Colgate, Hui Li, Quentin Dufton, and me, compares the energy content of magnetic fields and cosmic rays in free-standing giant radio sources (larger than 2.2 million light-years) with that of smaller radio galaxy sources embedded in clusters.¹² Figure 5 illustrates the observation that, for giant radio sources, the upper limit of the field and cosmic-ray energy approaches 10^{61} ergs. These giants occur in relatively rarified intergalactic environments in the mature (low redshift) universe. Unhindered by the higher pressure of the ambient intergalactic gas one would find in a cluster, their radio lobes expand out to typical intergalactic distances outside of crowded clusters.

The enormous energy stored in these lobes is about



equally shared between cosmic rays and magnetic fields. The proximity of these energies to the gravitational infall energy of a supermassive black hole means that such giant radio galaxies are, for now, the best calorimeters we have for the energy that the accreting black holes are recycling back into the intergalactic medium. The efficiency of this energy conversion from gravitational potential to magnetic fields and cosmic rays would appear to be about 10%.

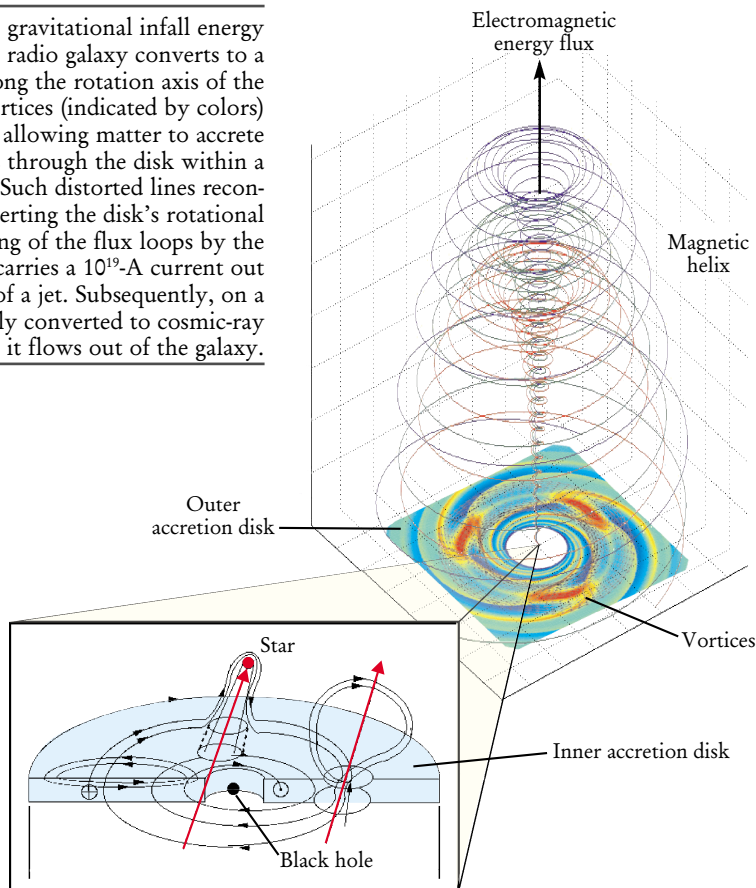
The number of known radio sources whose extension (projected on the celestial sphere) exceeds 2 million light-years has grown from a handful in the 1970s and 1980s to more than 100 now. As we see in figure 5, galactic radio lobes embedded in clusters, where the ambient intergalactic gas is much denser, store strikingly less magnetic and cosmic-ray energy—by an order of magnitude. The apparent reason for this discrepancy is that much of the original black-hole energy in galaxies deeply embedded in clusters goes into other forms, such as expansion work on the hot intracluster gas or its buoyant removal from the inner cluster.¹³

All of the currently visible extragalactic radio sources will no longer be synchrotron-visible after a few hundred million years. But radio galaxies powered by black holes have been produced over more than a billion years. Therefore, the objects we now see injecting magnetic fields and cosmic rays into intergalactic space represent less than 10% of the total energy injected into the intergalactic medium by black holes.

Generators and accelerators

It is important to understand how the angular momentum of the nearby material spiraling into the black hole over distances comparable to the size of the Solar System is transferred outward. Achieving that understanding is a major agenda for current astrophysical research. It is a prerequisite for understanding any subsequent conversion of energy into a form that can be collimated and then thrust out into intergalactic space to a distance of millions of light years from the central black hole. Somewhere in that chain of processes, probably quite early on, the energy

FIGURE 6. INTERCONNECTED MODELS of how the gravitational infall energy onto the supermassive black hole at the heart of a radio galaxy converts to a collimated outward electromagnetic energy flow along the rotation axis of the black hole's accretion disk.¹⁵⁻¹⁷ In the outer disk, vortices (indicated by colors) transport the disk's angular momentum outward, allowing matter to accrete into the central region (inset). Here, a star punches through the disk within a light-hour of the black hole, stretching field lines. Such distorted lines reconnect to form flux loops that act as a dynamo, converting the disk's rotational energy to magnetic field energy. Continuous shearing of the flux loops by the spinning disk creates the helical magnetic field that carries a 10^{19} -A current out along the rotation axis, forming the beginnings of a jet. Subsequently, on a larger scale, the magnetic energy is partly converted to cosmic-ray energy as it flows out of the galaxy.



must be converted efficiently into magnetic fields. And then finally, we must understand how the cosmic-ray particles are accelerated to the relativistic energies that produce the synchrotron-emitting radio lobes.

Answers are beginning to emerge for some, though not yet all, of these questions. Even the most ambitious models and simulations we have at present will likely be superseded as the complex plasma-physics phenomena at work become better understood.

Energy outflow models involving coherent electromagnetic energy flow have been discussed since the 1970s by Colgate, Martin Rees, Richard Lovelace, Roger Blandford, Max Camenzind, Donald Lynden-Bell, Harald Lesch, and others. Particle-beam jets have also been widely considered, but I focus here on the electromagnetic black-hole-jet models, because they have made the most impressive recent progress, especially with the help of supercomputer simulations. An example is the recent black-hole-jet simulations undertaken by Shinji Koide and coworkers in Japan and the US.¹⁴ The simulations model how the rotational energy is extracted from deep within the complex, rotationally distorted (Kerr metric) space-time very close to the massive galactic black hole.

A quite different class of black-hole-jet models, combining dynamo, hydrodynamic, and electromagnetic processes, has recently been proposed by Colgate and coworkers at Los Alamos. Such models attempt to explain the various stages of the progression from the spiraling of material in toward the galactic black hole to the ultimate emergence of the great synchrotron-radiating lobes.

Figure 6 illustrates elements of a set of such models that address this progression up to the conversion of the infalling energy into magnetic fields. The accretion disk around the galactic black hole is shown in false color in a nonlinear hydrodynamic calculation of angular-momentum transfer outward via the so-called Rossby vortex mechanism.¹⁵

The subsequent conversion of infalling energy into a form that can be collimated is modeled with the plausible assumption of a naturally magnetized accretion disk that is regularly punctured by a densely packed "bee swarm" of thousands of stars orbiting near the black hole.¹⁶ The stellar speeds are of order 20 000 km/s. The shock from each stellar puncture of the 30-kilogauss magnetized accretion disk drags a loop of magnetic field vertically out

of the rapidly rotating disk. That sets up an α - Ω dynamo analogous to the large-scale galactic dynamo originally proposed to explain the fields found in differentially rotating spiral galaxy disks. This powerful dynamo would generate a rapidly rotating helical field tied to the rotating accretion disk (see the inset in figure 6). Under certain plausible assumptions, such a magnetic field would be self-collimating, and it would propagate away as illustrated in the figure.

A system of this kind could aptly be called Nature's ultimate electricity generator. In the initial phases illustrated in the figure, the energy is carried away almost entirely by magnetic fields and electric currents. The current along the inner jet axis in figure 6 is of order 10^{19} amperes and, near the axis, it flows mostly parallel to the local magnetic field.¹⁷ The outward coupling of the rotational energy occurs in the black-hole accretion disk at distances beyond the inner zone in which the Kerr-metric space-time distortions dominate.

Details of the final step—conversion of the magnetic energy into the energy of cosmic-ray particles—are not yet understood even well enough to warrant an illustrative cartoon. The process, which probably involves a combination of magnetic reconnection and shock acceleration, occurs much farther out on the jet axis, beyond the scale of the figure. Magnetic reconnection (which also operates at the base of the helix in the figure) is an active area of research in plasma physics, relevant also for problems in very different fields of physics and engineering.

Captured energy and cosmic history

The lesson of the giant radio sources—gravitational energy converted with high efficiency into ejected mag-

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netic fields and energetic particles—leads us to imagine some further consequences at even larger scales. The ejected energy in fields and cosmic rays is comparable to the total energy that a quasar releases as electromagnetic radiation energy in all wavebands from radio to gammas. The radiation escapes at the velocity of light, once the absorption around the quasar becomes small. But the magnetostatic and cosmic-ray energy is captured and deposited on scales of order a few million light-years, for at least 100 million years, the visible lifetime of radio sources like the one shown in figure 1.

All this implies that, if the first galactic black holes formed early in cosmic history, their aggregate energizing of the intergalactic medium happened before many subsequent generations of galaxies and stars were formed. Therefore, those fields will subsequently collapse out of the intergalactic medium, which had been pre-permeated by magnetic fields. Those early fields may have been strong enough to influence the subsequent evolution of individual galaxies or structures on even larger scales. The challenge is to incorporate these effects into cosmological theory.

Colgate's bee-swarm-helix model¹⁶ was partly inspired by a major difficulty that occurs in the confinement of fusion plasmas in the laboratory. Energy escape by magnetic instabilities is a very serious problem that would destroy plasma confinement in a fusion reactor. But in galactic radio jets, instabilities perhaps involving a similar magnetic field configuration may provide precisely the explanation of how the black-hole energy escapes in such a highly collimated fashion. So the two phenomena, on vastly different scales, may in fact be more closely related than we had imagined. The scalability of some plasma physics processes over 20 orders of magnitude lets us hope that solving astrophysical puzzles might yield important breakthroughs in fusion technology and solar-system physics. Such communality of scalable problems is a good illustration of the intertwining of scientific missions between laboratory physics and the latest astrophysical detectors of radio emission, γ bursts, ultrahigh-energy protons, and even neutrinos from distant realms.

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