PERSPECTIVES: ASTROPHYSICS

Shedding Light on Black Holes

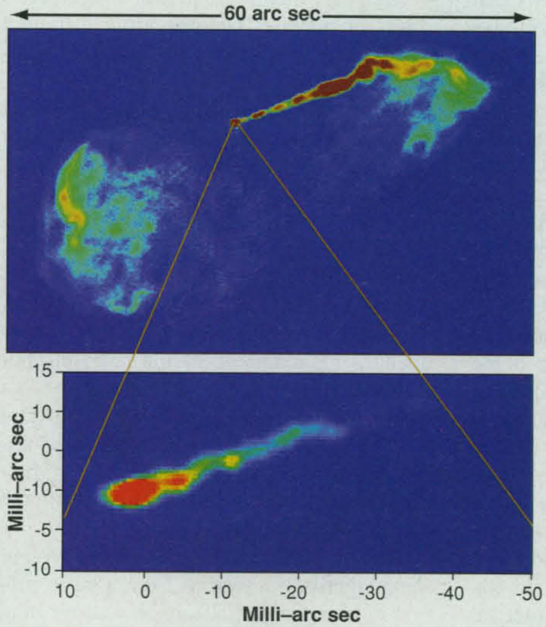
Mark Reid

The concept of a black hole, formed by the explosive collapse of a dying star, is difficult to grasp. Even more fantastic is the possibility that millions and even billions of stars can condense into a single massive black hole. Yet massive black holes almost surely exist and, in fact, are probably commonplace in the universe. How did we get to the point that most astronomers accept this assertion? The story starts with early results of radio astronomy and takes us to the present, with a new radio observatory in space that, as reported on page 1825 of this issue (*1*), is helping astronomers to better understand the bizarre world of massive black holes.

Early in the development of radio astronomy, very strong sources of radio waves were discovered (*2*) and given names like Cygnus A and Virgo A, where the "A" designates the strongest source in that constellation. Accurate positions of these sources revealed that they are often centered on distant, giant galaxies—usually the dominant galaxy at the center of a large cluster of galaxies. When radio interferometers (many telescopes linked together to achieve much finer resolution than a single telescope) were developed in England in the 1950s (*3*), they revealed a totally unexpected picture of these "radio galaxies." The radio waves did not come from the galaxy itself but from two giant "lobes" symmetrically placed about, but well separated from, the parent galaxy (see figure). These lobes can be among the largest structures in the universe—some exceeding distances of 1,000,000 light years apart, or nearly 100 times the size of our Milky Way galaxy.

How are immense radio lobes energized? Their symmetrical placement about giant galaxies suggested a galactic link. To see if the link was real, astronomers looked for the energy source—a "smoking gun." More sensitive radio interferometers, built in the Netherlands and the United States in the 1970s, confirmed the previously circumstantial case by detecting faint trails of radio emission from the lobes back toward the parent galaxy (*4*). This radio "smoke" often ends with a pointlike source at the center of the galaxy (see figure). Motivated by the desire to peer into these sources for some details of the smoking "gun," radio astronomers devised a way to link-up telescopes across the globe into an Earth-sized interferometer.

A radio interferometer takes advantage of coherent amplifiers to allow the signals from individual telescopes to be distributed and combined so that each telescope acts as a piece of a synthetic giant telescope. The angular resolution of such a synthetic telescope is inversely related to the maximum separation of the individual telescopes. Transmitting signals from each telescope to a central location originally involved cables or radio links, which limited telescopes to separations of hundreds of kilometers. However, by using magnetic tape and atomic clocks, the data could be recorded and precisely time-tagged for processing at a later time at any convenient location. Through this technological advance, telescopes in an interferometer could be anywhere on Earth. For operating wavelengths of centimeters, these Very Long Baseline Interferometers (VLBI) have achieved angular resolutions of about 0.001 arc sec, equivalent to the resolution necessary to read this magazine from a distance of a few thousand kilometers.



VSOP's tales. (Top) Radio image taken at the Very Large Array of M87 showing a bright pointlike core, two radio lobes, and a jetlike connection of the core with a lobe on the right side [adapted from (*6*)]. **(Bottom)** VSOP radio image of core. The scale is about 1000 times magnified relative to the top image.

Radio images made from VLBI observations revealed that the spatial extent of the "guns" at the centers of radio galaxies is incredibly small by astronomical standards—smaller than the distance between the sun and the nearest star (*5*). A simple calculation of the energy needed to keep giant radio lobes glowing is startling. The minimum energy for a powerful radio galaxy requires the total conversion of some 10 million stars into energy. Nuclear energy that powers the sun cannot convert even 1% of its mass to energy. Trying to explain a radio galaxy as a nuclear furnace would thus require channeling more than 1 billion stars like the sun through the tiny "gun" at its center. Because this energy calculation is only a lower limit on that required to power radio galaxies (it could be a lot more) and the size of the "gun" is still an upper limit (VLBI images show that it could be still smaller), nuclear reaction processes are too tame. Because of arguments like these, astronomers began considering more efficient and exotic energy sources—massive black holes.

Many important astrophysical problems associated with radiation from the environment of a massive black hole can best be investigated with greater-than-Earth-diameter telescope separations. In 1997, an 8-m-diameter radio telescope was put into orbit by the Japanese space agency. This telescope, the Highly Advanced Laboratory for Communications and Astronomy (HALCA), functions as part of the VLBI Space Observatory Programme (VSOP) and is used in conjunction with many ground-based radio telescopes and tracking facilities around the globe. VSOP allows astronomers to synthesize a telescope with a diameter of over 25,000 km and achieve about three times better angular resolution than from the ground for the VSOP frequency bands. Already many impressive results have been obtained (*1*), including a radio-frequency "image" of the nucleus of Virgo A (see figure). Such images reveal a complex jetlike structure with bends and wiggles, suggestive of magnetohydrodynamical instabilities or precessing motions associated with a spinning black hole (or both). Careful analysis of the jet structures can lead to estimates of the pressures inside and surrounding the jet or to the driving forces for a precessing beam emanating from a massive black hole.

Hopefully, the successes of the VSOP

The author is at the Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA. E-mail: reid@cfa.harvard.edu

mission will lead to more powerful space interferometers. Indeed, a bold mission to place a radio telescope in a 75,000-km orbit is being carried out in Russia (Radioastron), a second-generation Japanese telescope with higher frequency and higher sensitivity operation (VSOP-2) is being planned, and a much larger 25-m-diameter telescope project (ARISE) is being explored by NASA. Although we may never be able to see down to the very edge of the black hole, because of high opacity near the hole and instrumental limitations, VSOP and future space interferometers will certainly lead to great advances in our understanding of these amazing objects.

References

1. H. Hirabayashi *et al.*, *Science* **281**, 1825 (1998).
2. J. S. Hey, S. J. Parsons, J. W. Phillips, *Nature* **158**, 234 (1946).
3. R. C. Jennison and V. Latham, *Mon. Not. R. Astron. Soc.* **119**, 174 (1959).
4. R. A. Perley, J. W. Dreher, J. J. Cowen, *Astrophys. J.* **285**, L35 (1985).
5. M. Rowan-Robinson, *The Cosmological Distance Ladder* (Freeman, New York, 1985), pp. 30–35.
6. D. C. Hines, J. A. Eilek, F. N. Owen, *Astrophys. J.* **347**, 713 (1989).

PERSPECTIVES: PLASMA PHYSICS

Turbulence and Sheared Flow

Keith H. Burrell

In the quest for fusion energy, a continuing theme is the search for ways to improve energy confinement by eliminating the effects of plasma instabilities. Early workers in magnetic confinement fusion developed field configurations that eliminated gross, large-scale magnetohydrodynamic (MHD) instabilities. When present, these global MHD instabilities can typically tear apart in microseconds a plasma whose energy containment time can otherwise be several seconds. Even when gross instabilities are suppressed, most fusion plasmas still have small-scale turbulent eddies, so-called microturbulence, which dominate the loss of energy from the plasma.

One of the success stories of magnetic fusion research over the past decade is the intertwined development of techniques to reduce microturbulence-driven transport and the simultaneous development of what is called the $\mathbf{E} \times \mathbf{B}$ shear stabilization model (discussed below) to explain how those techniques work. The continuing interplay between experimental discovery and theoretical insight has guided this development. Some of the latest, most detailed numerical simulations in this area are reported on page 1835 of this issue (*1*). With these techniques, tokamak plasmas have been created with ion temperatures of 20 to 30 keV, the range relevant for fusion. Moreover, the energy loss through the plasma ions has been reduced by more than an order of magnitude—to the level caused simply by interparticle collisions. Indeed, in some cases, the measured loss rates are so low that the once-moribund field of collisional transport calculations is again active, as workers strive to determine whether even the collisional rates are too high to agree with experiment for the precise magnetic configuration used in the experiments.

The improvement due to $\mathbf{E} \times \mathbf{B}$ shear stabilization in magnetized plasmas is a fascinating basic physics result; it is not often that a turbulent system self-organizes to a higher energy state with reduced turbulence and transport when an additional source of free energy is applied to it. Usually, turbulent media like neutral fluids or plasmas become more turbulent and lose energy faster with increased heating or fueling. Although there are a few cases where neutral fluids exhibit velocity shear stabilization (*2*), the interplay of electric and magnetic fields in magnetized plasmas helps overcome the usually detrimental effect of increased velocity gradients in driving turbulence (*3*). In addition to its intrinsic physics interest, the transport decrease associated with $\mathbf{E} \times \mathbf{B}$ velocity shear has important practical consequences for magnetic fusion research. For example, the best fusion performance to date in the DIII-D (*4*), JT-60U (*5*), and TFTR (*6*) tokamaks has been obtained under conditions at which transport reduction through $\mathbf{E} \times \mathbf{B}$ stabilization is almost certainly taking place.

The "$\mathbf{E} \times \mathbf{B}$" in the name of this type of shear stabilization comes from a basic motion of charged particles in an electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$. In addition to the usual cyclotron motion around the magnetic field and motion parallel to it, a particle moves with a velocity $\mathbf{v}_D = \mathbf{E} \times \mathbf{B}/\mathbf{B}^2$. This velocity does not depend on the charge or the mass of the particle, so all particles share this component of their velocity. This common motion is one of the reasons why the $\mathbf{E} \times \mathbf{B}$ velocity shear is the most fundamental shear. Although shear in individual species' velocities or in turbulent wave propagation speeds can, in principle, affect the microturbulence, the ubiquitous character of sheared $\mathbf{E} \times \mathbf{B}$ flow makes it the most fundamental effect (*3*).

The basic physics involved in transport reduction is the effect of $\mathbf{E} \times \mathbf{B}$ velocity shear on the growth and size of turbulent eddies in the plasma. Although both nonlinear (*7*, *8*) and linear (*9*, *10*) effects have been considered, there is now a general consensus that the nonlinear effects must be included in the complete picture (*7*, *11*). [More complete references to the theory are given in (*3*)]. The basic shearing effect is the reduction in transport due to a decrease in the size of the turbulent eddies and due to a change in the relative phase between turbulent oscillations in the density, temperature, and electrostatic potential.

A greatly simplified illustration of the effect of $\mathbf{E} \times \mathbf{B}$ shear on turbulence and transport is given in the figure, which is based on work by Carreras (*12*). The colored ovals in panel B show the surfaces of constant turbulence-driven particle flux in a cylindrical plasma for the case of no $\mathbf{E} \times \mathbf{B}$ velocity shear, whereas the distorted ovals in panel D show how this quantity changes in the presence of the velocity shear. Panels A and C show how the particle flux varies with position across the middle of the turbulent eddies. Although this simplified model is for particle flux, similar effects hold for energy flux. A key point in the theory is that there must be a change in the $\mathbf{E} \times \mathbf{B}$ velocity with position (that is, a shear) to affect the turbulent transport. Notice that the twisting of the eddies caused by the spatially varying velocity makes them shrink in the radial direction, which is the direction of heat flow toward the wall of the container holding the plasma. In addition, although the peak particle flux in the two cases is the same, the total flux is greatly reduced by the $\mathbf{E} \times \mathbf{B}$ velocity shear. This total flux is given by the area under the curves in panels A and C. Much more elaborate numerical calculations (*13*), including those of Lin *et al.* (*1*), have shown the same qualitative features; indeed, the color plots in these two reports give wonderfully intuitive illustrations of the effects of $\mathbf{E} \times \mathbf{B}$ velocity shear on turbulence in the experimentally relevant toroidal geometry.

One of the strengths of the $\mathbf{E} \times \mathbf{B}$ shear stabilization idea is its ability to explain a wide range of results (*3*, *14*). Turbulence stabilization and associated transport reduction have been seen in a number of different magnetic configurations (tokamak, stellarator, and mirror machine) at a number of different locations in these plasmas. The source of this breadth of effects is the multitude of ways that the plasma transport and

The author is at General Atomics, P. O. Box 85608, San Diego, CA 92186–5608, USA. E-mail: burrell@gav.gat.com