Violently Active Galaxies: The Search for the Energy Machine

The energy source in these galaxies will be shown to be a black hole, I think, even though it may take 100 years before we have proven it.—MARTIN REES, at the Institute of Astronomy in Cambridge, England

I think it will take 1000 years and we may very well be on the wrong track. These [black hole] models are getting into the textbooks now, but there is never anything testable and people are working on smaller and smaller pieces of the problem.—GEOFFREY BURBIDGE, at the Univeristy of California, San Diego, and soon to assume the post of head of the Kitt Peak National Observatory in Tucson, Arizona

REES: *I agree, but I would argue that the way we are going about it is the most productive approach, even though the modelers may be getting the illusory satisfaction of a Ptolomean theorist who adds another epicycle.*

BURBRIDGE: *I'm glad to hear you say that, Martin. The trouble is that so many people take these things more seriously than you do.*

Many astronomers are indeed taking seriously the idea that black holes are at the center of galaxies.

Some of them have held the idea for over a decade. Harlan Smith, at the University of Texas, says that when he was studying quasars during the late 1960's he concluded that a black hole model was the only plausible approach. Others have adopted the view more recently. Roger Blandford, at Caltech, says that his personal policy on the subject is that black holes are the "least unattractive of the possibilities" for producing the prodigious amounts of energy from violently active galaxies such as quasars, but that the arguments are all theoretical ones and "hard evidence is hard to imagine." Rees, one of the most effective proponents of the case for black holes, characterizes it as a "best buy" theory of quasars—the most powerful and economical model that can be constructed within the framework of "conventional" physics.

Black holes, of course, are those mind-boggling regions where matter has become so dense that light rays can be sucked in just as easily as particles (or clouds of gas or stars), where gravitational forces can become even stronger than the forces within the atomic nucleus, and inside which the normal properties of time and space are thought to be reversed. The idea that black holes could exist in space was predicted in the late 1930's but lay dormant until revived in the late 1960's by theorists who proved that Einstein's equations of general relativity had a set of solutions that corresponded to the black hole prediction. Support for the idea came in the early 1970's when a modestly massive black hole was apparently found in the constellation Cygnus. Since then the idea of a black hole as one of the basic and common occurrences in the universe has gained credibility quickly. But the object in Cygnus, which has a mass not much greater than the sun, is a featherweight by comparison with the black holes that are posited to be at the centers of quasars and a whole range of energetic galaxies.

The Same Machine on Different Scales

The luminous power of quasars is so great that black holes with masses between 10^7 and 10^9 times the mass of the sun would be required to produce the energy that is emitted from them. Martin Rees's "best buy" theory of quasars, in more detail, is that they consist of black holes with a mass about 10^8 times the mass of the sun in the centers of giant galaxies, with fuel being supplied by the "capture of gas—or even entire stars—from their surroundings." (The brightest quasars are 100 times brighter than giant elliptical galaxies, which are the brightest "normal" galaxies in the universe.) Quasars were discovered in 1963.

Other very luminous objects, called BL Lacertae (*Science*, 2 June 1978), appear to be an extreme form of quasar and would require black holes just as massive as quasars would. Like quasars, BL Lacertae look much like stars upon first observation, and emit most of their energy as visible light. BL Lacertae were discovered in 1969.

Galaxies that produce most of their energy in the form of radio waves also require supermassive black holes to explain their output. So-called double radio galaxies, which have two huge lobes extending far into space beyond the visible galaxy, require 10^8 solar-mass cores. They were discovered in the 1940's.

Seyfert galaxies would also require supermassive black holes. Spiral galaxies which have extremely luminous nuclei and emit a large fraction of their energy as infrared radiation, Seyferts were discovered in 1946. N-galaxies, which are similar to Seyferts and quasars in many properties, are slightly weaker but also have active energy sources at their centers that produce bright blue light in an otherwise red (indicating cooler) galaxy.

In all of these unusually energetic galaxies, there is good evidence that the predominant source of energy is at the center. To emphasize this distinction, they are often called galaxies with active nuclei, and whatever it is that is active is presumed to be the same in each case. Martin Rees refers to it as the "prime mover." James Gunn, at Caltech, refers to it as the "monster," and Burbidge often refers to it as the "machine."

While there is vigorous debate over the nature of the machine, there is virtually unanimous consensus that the same machine is at the heart of all the active galaxies and many other less-active galaxies. "Presumably even our own galaxy has a source of the same type at the center, which is in continuity with the others, although admittedly very much less luminous," says George Field, director of the Center for Astrophysics in Cambridge, Massachusetts. The source at the center of our galaxy is a weak and compact radio wave emitter with a diameter no more than ten times that of the solar system. J. H. Oort, at the Leiden Observatory, finds that its mass is about 10^6 solar masses, so it is not nearly so weighty as the sources presumed for quasars.

Although skeptical about black holes, Geoffrey Burbidge is one of the strongest proponents of the idea that the same machine, at different scales, produces the great variety of phenomena in galactic nuclei. Taking into account the difference between the luminosities of the very faint nucleus of the Milky Way and the luminosity of the brightest quasars and BL Lacertae, the machine therefore has a range of energies differing by more than 1 million.

It is difficult to tell how astronomers would vote if a scientific Gallup pole were taken on the validity of black hole models for galactic nuclei today. All the interest spurred by developments in the past 5 years has improved their standing, but the majority of astronomers may be uncommitted. "There has been a subtle shift as more people favor black holes," says one astrophysicist, while another observes that "Only people working ac-

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tively on the models seem to favor black holes." There are certainly a large number of skeptics, some of whom are highly critical. "Black holes are being oversold on unconvincing evidence," says I. Shapiro, a prominent radio astronomer at MIT, "and a lot of people feel the same way I do. The black hole may be the best bet without having a high probability of success." The appeal of the black hole, however, is that it has—in principle—three attributes that seem to be precisely what is needed.

First, black holes can produce the enormous power required. Near a black hole, it is generally assumed that matter does not fall in directly, but forms a disk around it (an accretion disk) which feeds the black hole. The gravitational forces on the inner parts of this disk are so great that a black hole can convert to energy 10 percent or more of the mass falling into it. Fusion (the reaction that occurs in stars) can convert only about 0.4 percent of matter into energy and fission only about 0.1 percent.

The size of galactic nuclei is another key characteristic that coincides well with black holes. The most highly resolved radio measurements show that galactic nuclei are less than 30 light-years across. The rapid fluctuations in the output of active galaxies, particularly BL Lacertae and the most violent quasars, indicate the size may be light-months or -days across. The nuclei are therefore 1 millionth or less the size of a giant elliptical galaxy. Black holes, being the most compressed form of matter known, would be appropriately small.

Third, the stability of galactic nuclei to rotations is another—the newest—requisite that black holes seem to fulfill quite well. The huge lobes in double radio sources are presumed to be shot out from the center of the galaxy. High resolution measurements (*Science*, 27 June 1975), showing that young double clouds visible only on a small scale are being ejected on exactly the same line as the much larger (and presumably older) clouds, indicate that the energetic core of a galaxy can preserve a memory of its orientation in space for 1 to 100 million years. The direction of the radio structure does not necessarily coincide with the axis of rotation of the galaxy as a whole. Because the radio structure does not rotate with the rest of the galaxy, the energy machine must be massive enough to resist this motion. It is thought that the preferred direction in space is provided by the axis of a spinning black hole. (Only in the simplest models does the black hole not rotate.)

There don't happen to be any quasars or BL Lacertae close enough to us that their central regions can be studied with large telescopes. Only one double radio source, Centaurus A, is nearby, but it must be viewed from the Southern Hemisphere which is badly lacking in radio observing capability. Several astronomers are now suggesting that the energy machine will most likely be solved by looking at giant elliptical galaxies that are nearby and have compact radio sources in their centers, such as M 81 and M 87. Rees, in particular, argues that these may be old quasars that are now defunct. (Our galaxy, with a central core of only 10^6 solar masses, could never have been a quasar, Rees says, although some think it may have once been a Seyfert galaxy.)

Circumstantial Evidence for a Black Hole

Some of the most impressive evidence accumulated to date comes from M 87, which was examined by two teams of optical astronomers over the past 2 years.

To determine what was at the heart of M 87, the two teams examined the amount of light and the average star motions there. (At a distance of 50 million light-years from earth, individual stars in M87 cannot be resolved.) A team working with the 200-inch telescope at the Hale Observatories on Mount Palomar scanned the distribution of light and found a bright spike only 1 arc second in diameter that coincided with the center of the galaxy almost exactly. According to Jerome Kristian, of the Mount Palomar team, such a spike is not observed in "normal" galaxies of the same type as M 87 that occur nearby. The measurement indicates that the bright region is less than 300 light-years in diameter, which is considered to be near the limit of resolution of ground-based astronomy. The other team, working with the 4-meter telescope at the Kitt Peak National Observatory, examined the width of the spectral lines (monochromatic atomic emissions) from stars moving around the center of M 87 and found that the stars had anomalously high velocities. Stars with such large velocities could only be held captive by an extremely large mass at the core of the galaxy, and an analysis by Wallace Sargent and Roger Lynds at Kitt Peak showed it to be 6×10^9 solar masses. With both the mass and the luminosity of the core of M 87 determined, it was possible to determine whether the core was brighter or darker than a dense cloud of stars. Kristian and Paul Young at Caltech found that the mass-to-light ratio was ten times greater than in the rest of the galaxy.

The M 87 observations, published in April of this year, showed that the core is indeed supermassive, that it is very small on the scale of the rest of the galaxy (which is 300,000 light-years in diameter), and is unusually dark. Although a population of low-mass red dwarf stars could match the mass-to-light finding, they would not match the color of the central bright cusp, which is bluish. "One is not driven to a black hole on theoretical grounds," says Kristian. "The evidence is in fact circumstantial," he says, "but it does have an impact because it demonstrates the existence of a large, invisible mass in the nucleus." Thus, the modus operandi of a black hole seems to be well borne out, particularly in the direct determination of a value for the mass that closely coincides with what the theorists said would be required.

What would be required to go beyond circumstantial evidence and prove that the object in the center of M 87 is (or is not) a black hole is a more difficult question. As the dialogue between Rees and Burbidge illustrates, there is a wide range of opinion on the subject. The most optimistic observers, perhaps typified by Harlan Smith, think that more data will make the case more plausible, and that the black hole hypothesis will be "pretty well accepted" in the 1980's. But the present models are rather general and seldom predict anything testable, as Burbidge observes. Whether they will soon give definitive predictions that would make it possible to decide between particular models is a question of interest to many astronomers, including the model-builders themselves. At a meeting on BL Lacertae in mid-1978 there was practically a standing ovation when it appeared that one theorist, faced with a report of conflicting data, would withdraw his model. "You are about—for the first time—to see a model die," he told the cheering audience.

If the theory will not tell observers what to look for, then they can make the decision themselves. Smith casts his vote with the Space Telescope, a 2.4-meter telescope due to be launched in 1982. By eliminating atmospheric effects, it should improve upon the resolution of earthbound optical telescopes by a factor of 10. He also has high hopes for spaceborne x-ray and gamma-ray observatories. (M 87 and certain other active galaxies emit x-rays as well as radio waves from their centers.) Kristian is also hopeful for the Space Telescope, which he says should be able to measure whether the bright spot on M 87 is as small as 30 light-years across. Radio techniques in which two radio telescopes are connected by a very long (several thousand mile) baseline, can already resolve structures milliseconds in size and drastic improvement may not be possible. But Valtonen thinks that the present radio techniques should be capable of giving data at least five times better for M 87 and Centaurus A. Field suggests that a new long-baseline infrared instrument would allow optical astronomers to approach the resolution achieved by radio astronomers and might permit "imaging the accretion disk itself—something mind-blowing but possible."

At this point the alternative to black hole models are rather limited. One possibility is that the core of active galaxies has a dense cluster of stars providing that requisite energy through frequent supernova reactions, but a number of astronomers think the 100-million-year memory observed in the double radio galaxies is inconsistent with a source powered by numerous small flickering explosions. Another possibility is that the machine could be an object that has not quite collapsed to the characteristic diameter of a black hole. Such objects are usually called spinars or magnetoids, because it is postulated that rotating internal magnetic fields would stop their further contraction. But most astronomers believe that spinars would subsequently collapse into black holes, perhaps within only about 1 million years. Thus they might be more accurately understood as way stations leading to a black hole.

The other major alternative is that "new physics" will be required for the final explanation. Burbidge, Halton Arp at the Hale Observatories, and a few other American astronomers hold this view, which has been criticized as, in fact, a false alternative. "New physics," says Ed Spiegel, at Columbia, "is a non-idea." Burbidge, however, argues that if black holes had really been formed in the middle of large galaxies by the evolution of stars into superstars and then black holes, thermal energy should be produced that we do not see. Rees, for his part, agrees, but argues that black holes are capable of qualitatively and quantitatively accounting for the phenomena that we do see.

So the problem of ascertaining the validity of the black hole hypothesis is as much a problem in the sociology of science as anything else. In spite of the vocal opponents and sharp skeptics, as well as the phalanx of uncommitted voters, it must be considered the leading explanation for the most cataclysmic events we see in the universe.

—WILLIAM D. METZ

UPDATE

Function of the *src* Gene Product

Avian sarcoma virus (ASV) is an RNA-containing virus that causes sarcomas in birds. The virus, which is also known as Rous sarcoma virus, carries a gene—the *src* (for sarcoma) gene—coding for a protein that must be produced in order for the virus to transform normal cells to malignant ones. Several months ago, Raymond Erikson and his colleagues at the University of Colorado Medical Center reported that they had identified the *src* gene product as a protein with a molecular weight of 60,000, an identification that was subsequently confirmed by two other groups of investigators (*Science*, 13 January, p. 161).

The researchers were excited by this development because they thought it might lead to the achievement of a long-sought goal—the identification, at least in the ASV system, of the specific biochemical event or events causing the malignant state. But at the time the 60,000-dalton protein was discovered no function could be ascribed to it. Now, newly acquired evidence shows it to be an enzyme, specifically a kinase that transfers the terminal phosphate group from adenosine triphosphate (ATP) to an acceptor protein. Other kinase enzymes are known to be involved in the regulation of a wide variety of cellular activities. Therefore, participation of a kinase in the events producing transformation, including as it does many changes in cell properties, is an attractive idea.

The experiments indicating that the *src* gene product is a kinase are basically of two types. One type was described in the April issue of the *Proceedings of the National Academy of Sciences* by Erikson and Marc Collett, also at Colorado, and more recently by Arthur Levinson, J. Michael Bishop, and Harold Varmus of the University of California at San Francisco. These investigators detected the kinase activity in protein precipitated from extracts of transformed cells by treatment of the extracts with antibody specifically directed against the *src* gene product.

Kinase Activity Not a Contaminant

Although there was always the chance that the kinase activity in the precipitate belonged not to the *src* gene product, but rather to a contaminant that had precipitated with it, the results of the second type of experiment, performed in the laboratories mentioned above, militate against this possibility. Here, purified segments of the RNA genome of ASV containing the *src* gene were used to direct protein synthesis in the test tube. The synthetic protein also has kinase activity. Other investigators, including Karen Beemon and Tony Hunter of the Salk Institute, have obtained similar results with both types of experiments, and there now seems to be general agreement that the kinase is a *src* gene product.

The identity of the cell protein naturally phosphorylated by the kinase is unknown, however. The investigators doing the work think that locating this protein could be very difficult, but they also agree that the cell skeleton is a good place to start their search. The cell skeleton consists of a network of tubules and filaments thought by many investigators to be involved in the control of cell division. This network usually disperses in cells that have undergone transformation initiated by a variety of agents, including ASV. The hypothesis is that dispersion of the cell skeleton disrupts the normal signals controlling cell division and thus leads to uncontrolled proliferation and the other changes characteristic of transformation. Erikson has speculated that the kinase product of the *src* gene may distrupt the cell skeleton by phosphorylating one of the proteins forming it.

Bishop sounds a note of caution, however. He points out that there is now no evidence that the cell skeleton is the immediate target of the *src* gene product or even that dispersal of the cell skeleton is the initial event of transformation. Moreover, transformation involves a large number of changes, many of which may not be produced directly by the kinase. It is also possible that the *src* gene encodes additional, as yet undetected, functions. Thus, although investigators are enthused about the latest advance toward unraveling transformation, the problem is not yet solved.—J.L.M.

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