tion thread by which they travel through the epidermal cells to the dividing cortical cells, which eventually give rise to the nodules.

Mutations in either the A, B, or C *nod* gene completely prevent nodule formation. Such mutants do not cause root-hair curling or form infection threads. Preliminary results from Long's laboratory indicate that the mutants also fail to elicit the early cortical cell divisions. Mutations that completely prevent D gene activity also prevent nodulation, although in *Rhizobium meliloti*, which has multiple D genes, a mutation in a single copy slows down the onset of nodulation but does not prevent it.

Work from Frank Dazzo's laboratory at Michigan State University suggests that some of the essential *nod* genes may participate in the synthesis of bacterial substances that are needed for interacting with legume roots. Dazzo and his colleagues had previously found that the specific recognition of clover roots by *R. trifolii* involves an interaction between a plant lectin, a glycoprotein that is found both on the root hairs and in clover root exudate, and polysaccharides on the bacterial surface. Dazzo hypothesizes that binding of the lectin, which is called trifoliin A, to the polysaccharide transmits to the bacteria a signal that triggers the responses necessary for successful infection of clover roots.

More recently, Dazzo's group, using mutant rhizobial strains prepared in Rolfe's laboratory, have found that mutations in the common *nod* genes A and D can not only prevent nodulation but may also decrease, by as much as 95 to 100 percent, the ability of *R. trifolii* bacteria to bind trifoliin A. Moreover, the investigators find the composition of the noncarbohydrate components of the lectin-binding polysaccharides to be altered in these mutants.

It seems somewhat surprising that mutations in the common *nod* genes could affect the synthesis of molecules involved in specific recognition. However, according to Dazzo, the evidence suggests that the genes do not code for the synthetic enzymes themselves but may produce products that help to regulate the highly complex pathways by which polysaccharides are synthesized. If that proves to be the case, then the products could have common functions in different rhizobial bacteria, even though the final products of the affected pathways might differ.

Not only can materials released by the plant affect expression of bacterial genes during the initiation of symbiosis, but materials released by the bacteria can also affect events in the legume root cells. The stimulation of the division of cortical cells is one example. Another was reported by Ton Bisseling of the Agricultural University in Wageningen in the Netherlands, who has been investigating the plant genes that are specifically expressed in the nodules. The activation of these genes follows a pattern in which one is turned on several days before the others. This early gene is a candidate to be a regulator of those that are expressed later.

According to Bisseling, the *nif* genes are not needed for the activation of the plant genes. The *nod* genes are, although they are not sufficient. Bisseling's experiments indicate that rhizobial chromosomal genes are also required to turn on the full complement of plant genes in the developing nodules.

All in all, the results described at the Nitrogen Fixation Symposium show that a great deal of progress has been made in the last year or two in identifying the genes that are needed to establish symbioses between rhizobial bacteria and their legume hosts. Although the picture is incomplete, it already shows that the interplay between the symbiotic partners is complex, requiring both to contribute to produce nitrogen-fixing nodules.

—JEAN L. MARX

The Core of the Milky Way

Our galaxy appears to be a miniature quasar; all the evidence now points to an enormous black hole at the center

At the core of the Milky Way there lies a turbulent agglomeration of stars, gas, and dust, arrayed around a compact energy source that resembles nothing else in our galaxy. Recent findings, including some observations announced only this year, have made the conclusion almost inescapable: this energy source is a miniature quasar powered by the accretion of matter into a huge black hole.

Admittedly, our galaxy is a pretty dim candle as quasars go, by a factor of many thousands. In the accretion process, matter spiraling into the black hole is compressed and heated so much that it converts most of its mass into radiant energy before finally falling in. Real quasars are thought to be galaxies containing black holes of roughly a billion solar masses; presumably our own black hole is only a few million solar masses. But in any case the Milky Way is hardly unique: dim quasar-like emissions have recently been detected in the cores of many other normal-looking galaxies (*1*); moreover, intermediate-sized black holes also seem to be responsible for the very luminous nuclei of "active" galaxies, such as the Seyferts and the BL Lacertae objects. Thus, the nucleus of the Milky Way offers astronomers their best chance for a close-up study of a phenomenon that is ubiquitous in the universe.

Probably the best way to understand the galactic nucleus is to start by relating it to the Milky Way as a whole. Beginning from the outside and working in:

• The disk and the spiral arms. In terms of its spiral structure and virtually everything else, the Milky Way seems utterly typical. From our vantage point on the edge of one of the spiral arms, about 10,000 parsecs out from the center, the galactic nucleus lies in the direction of the constellation of Sagittarius. (A parsec is 3.26 light-years.) Unfortunately for optical astronomers, however, the disk of the galaxy is lined with masses of interstellar gas and dust that block every vestige of visible light from the nucleus. The central regions are thus the domain of radio and infrared astronomers, who work at wavelengths where the clouds are relatively translucent. By the same token, the process of understanding the nucleus has largely been a story of ever improving radio and infrared instrumentation.

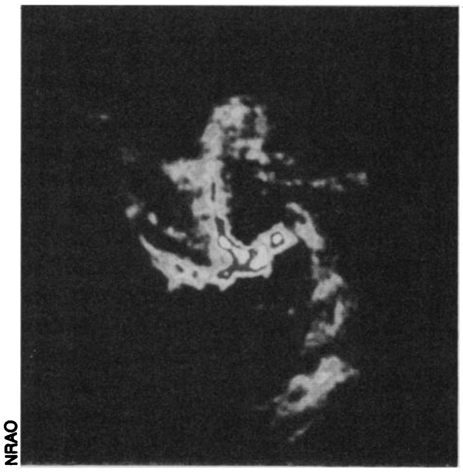
• The central bulge. One of the most prominent features of the Milky Way, this slightly flattened sphere of stars sits in the middle of the spiral disk like the yolk of a fried egg. It is about 5000 parsecs in radius and is composed primarily of old, reddish stars, with relatively little interstellar gas and dust and almost no formation of new stars.

• The 3-kiloparsec arm. The first evidence that the bulge is not entirely peaceful came in 1960. During their pioneering efforts to map the galaxy using the 21-centimeter line of neutral hydrogen, Jan H. Oort and G. W. Raugoor of the University of Leiden discovered a partial ring of material about 3000 parsecs from the center, expanding outward at roughly 100 kilometers per second. One obvious, although controversial, interpretation is that this "3-kiloparsec arm" represents a shock front expanding outward from an explosion at the center of the galaxy some 30 million years ago.

• The central star cluster. In 1968, as Eric Becklin of the University of Hawaii and Gerry Neugebauer of the California Institute of Technology were conducting their pioneering infrared survey of the Milky Way's nucleus, they detected what seemed to be a dense ball of stars occupying the inner 3 parsecs of the galaxy. Later observations have continued to support that interpretation: the infrared maps are freckled with hot spots that seem to correspond to red giant stars, and the overall density of stars in the central 3 parsecs appears to be roughly 10 million times the density in the solar neighborhood. In fact, the central cluster appears to have about the same size and density as the well-known globular clusters, which orbit the galaxy much farther out. An observer at the center of the galaxy would thus see more than a million stars as bright or brighter than Sirius, the brightest star in our own sky. A starlit night would be 200 times brighter than the full moon.

Thus far, except for the 3-kiloparsec arm, there is nothing particularly unusual about all this. (Central clusters have been observed in other galaxies, also.) However, evidence began to accumulate during the 1970's that those inner 3 parsecs hold something very strange indeed.

As early as 1974, for example, Charles H. Townes, John H. Lacy, and their colleagues at the University of California, Berkeley, observed the 12.8-micrometer emission line of singly ionized neon in the galactic nucleus in the course of a long-term program to develop improved infrared spectrometers. The emissions appeared to come from clouds of ionized gas and warm dust in the central regions; the Berkeley group eventually found 14 such clouds, many of them intermixed with the star cluster in the central 3 parsecs. However, the striking thing was that lines were quite broad, indicating that the emissions were being Doppler-shifted as the clouds moved through the nucleus at velocities of several hundred kilometers per second.



NRAO

The Inner 3 parsecs

In this radio image of the galactic core, produced by the Very Large Array at a resolution of 1 arcsecond, streamers of ionized gas form a striking spiral pattern. Actually, the spiral is a trick of perspective. Velocity measurements show that the south arm of the spiral (lower right) is arcing toward us and around to the north, where it may join up with the northern arm (top center) to form a complete ring. The horizontal arms are independent and appear to be falling inward to the center. An energetic point source, which lies at the precise center of the galaxy, has been deleted from this image for clarity; it lies just above the intersection of the northern and horizontal arms.

To a first approximation the clouds appeared to be moving around the center in the same direction as the general galactic rotation. Unfortunately, they also seemed to be embroiled in quite a bit of chaotic, random motion, which made it difficult for the Berkeley astronomers to say for sure whether the clouds were actually in orbit around the center, or falling inwards toward the center, or just plain turbulent. But by assuming that the clouds *were* in orbit, and by invoking Kepler's third law, which describes how orbital velocity decreases with increasing orbital distance, the researchers were able to estimate the amount of mass concentrated at the center. The result: roughly 1 million solar masses, consistent with a galaxy-sized black hole.

Equally suggestive were the estimates of how much energy was being expended to ionize the gas clouds and heat the dust: somehow, the central parsec of the galaxy was shining at 10 million to 30 million times the luminosity of the sun—which happens to be consistent with models of accretion onto a million-solar-mass black hole. Furthermore, in 1978, 0.511-million-electron-volt gamma rays from the annihilation of electrons and positrons were observed coming from the direction of the galactic center, indicating that some very high energy processes were under way there.

Finally, radio astronomers have long had evidence of an energetic, compact source of some kind lying right at the center of the galaxy, with roughly the right properties to be an accreting black hole. In fact, just such a source was predicted in 1971 by Donald Lynden-Bell and Martin Rees of Cambridge University when they first suggested the idea of a black hole.

In sum, the evidence as of 1980 was intriguing but circumstantial. The picture of the inner 3 parsecs was just too fuzzy to say for sure what was there. Starting about then, however, the picture suddenly began to snap into focus.

The key technological advance was the Very Large Array (VLA), which went into operation near Socorro, New Mexico, in 1979, and which is capable of producing radio maps with a resolution of 0.1 arcsecond, equivalent to 0.005 parsec at the distance of the galactic center. Simultaneously, very long baseline interferometry techniques, which combine signals from radio telescopes scattered over most of the globe, have begun to make it possible to achieve still higher sensitivities.

One of the most obvious, and important, tasks has been to get an improved picture of that central compact source. Earlier this year, K. Y. Lo of the California Institute of Technology and his colleages published very long baseline data that gave the best upper limit yet on its size: less than 20 astronomical units, or smaller than the orbit of the planet Uranus (*2*). That size makes it almost impossible to support a non–black hole explanation of the source. If the emissions were coming from a grouping of hot, massive young stars, for example, as one model has it, at least 100 such stars, each more than a dozen times as massive as the sun, would have to be crammed into a space considerably smaller than the solar system. It seems dynamically impossible.

A second, and equally important, goal has been to clarify the diffuse blob of radio emission surrounding the compact source. Known from earlier studies as Sagittarius A West, it is presumably the radio image of the same ionized gas clouds observed by the Berkeley group in the infrared. It has also turned out to be perhaps the most striking and puzzling feature in the galactic nucleus.

In 1982, Ronald D. Ekers of the National Radio Astronomy Observatory and his colleagues obtained VLA maps of Sagittarius A West at 5-arcsecond resolution, the best up to that time, and found that the emissions were clearly resolved into a many-armed spiral (*3*). Moreover, the arms of this spiral appeared to contain many of the ionized clouds discovered by Townes and his colleagues.

The discovery of the spiral created considerable excitement within the astrophysical community. The most obvious and appealing interpretation was that the compact source at the center of Sagittarius A West was squirting out high-energy jets of material, and in the process wobbling just enough to throw the jets into a spiraling stream—rather like what happens when a child holds a garden hose and twirls the end. Jets are commonly found in active galaxies and quasars; the presumption is that accreting matter forms a disk around the black hole, and that superheated material from the immediate vicinity of the hole blasts out along the axis of the disk. Furthermore, some of these jets do seem to spiral; a notable small-scale example is a peculiar object in our own galaxy known as SS433, in which the central object is thought to be a neutron star pulling material from a more-or-less normal companion star.

The wobbling jets model would have fit in beautifully with the black hole model if it had been true. However, it quickly became apparent that the galactic nucleus is not so obliging. In 1983, Lo and his Caltech colleague Mark J. Claussen published new VLA maps of the spiral taken at 1-arcsecond resolution (*4*). Combining their maps with the Berkeley group's ionized-neon velocity data, Lo and Claussen showed that the spiral itself is an illusion: the "arms" are actually independent streamers of ionized gas that have been superposed on each other through a trick of perspective. Moreover, the streamers appear to be falling inward, not flowing outward: the velocities in a given streamer steadily increase as it approaches the center, Lo and Claussen pointed out, and at the same time the gas gets brighter, just as one would expect as it approaches the ionizing source. An interesting exception is the south arm, which appears to loop in front of the central source and then link up with the north arm to form a continuous inward spiral.

Lo and Claussen's streamer picture nicely explains the chaotic velocity fields found in the Berkeley infrared observations: the ionized clouds lie on the streamers, and the streamers are all moving in different directions. However, it should be said that the picture is still a bit controversial. Townes and his colleagues have recently published a variant interpretation in which the south arm is not part of an inward spiral but is part of an orbiting ring. The northern arm, meanwhile, is said to be a separate streamer in a parabolic orbit (*5*).

This is clearly the sort of thing that specialists can argue about for hours. But the Berkeley model does allow for a fresh calculation of the central mass. The answer depends to an extent on what assumptions are made about the central star cluster—it is worth remembering that all these streamers of gas are moving *through* the cluster—but the most plausible interpretation gives 4 million solar masses, which is still very much in keeping with the massive black hole model.

Our picture of the galactic nucleus has taken on remarkable clarity and detail in recent years.

Lo, for one, hopes that within a few years it will be possible to resolve any lingering controversy about the streamers with a measurement of the proper, or side-to-side, motions of the gas. The Doppler-shift measurements only give radial velocities along the line of sight. However, Lo points out that the streamers are moving at a few hundred kilometers per second, which means that individual features will move across the sky at the rate of a few milliarcseconds every year. Not too many years from now he expects to be able to detect such displacements, thus giving astronomers both radial and side-to-side velocities, and a full three-dimensional picture of the activity at the center.

Whatever the details of the streamer motion, there still remains the question of where they came from. The answer appears to lie with another intriguing feature of the nucleus, a fat ring of gas and dust that surrounds the nucleus from about 2 parsecs outward.

There is nothing extraordinary about the presence of the ring per se. The material appears to be the standard mix of interstellar gas and dust, which is plentiful in the galaxy. And it shares the general rotation of the galaxy, which means that, for dynamical reasons, one would expect it to form into a relatively flat disk.

However, what is striking about the ring is that it shows signs of recent disturbance. The ring itself is asymmetric, and the gas is turbulent. Yet turbulence tends to damp out fairly quickly. Furthermore, the gap in the middle—the hole in the donut—is really quite dramatic. The streamers represent very dense material falling through a nearly gas-free hollow (and, of course, stars). Yet one would expect the gas to quickly drift inward and fill the gap.

Finally, if the streamers did originate in the ring—it is difficult to see where else they might have come from—and if they are indeed falling toward the center, then they must have started falling only about 10,000 years ago. (Actually the south arm and perhaps even the north arm may simply be the inner boundary of the ring, where the gas is ionized by radiation from the middle. But the other streamers cannot be explained so easily.)

Clearly, something dramatic happened in the nucleus almost yesterday, as things go on a cosmic time scale. One intriguing possibility is that some kind of explosion occurred around the central black hole, creating a shock wave that cleared out a 2-parsec hollow in the surrounding gas. Now, clumps of material are beginning to fall back in.

This picture does have an appealing consistency: a dense clump of material falling into the black hole might very plausibly produce an explosive burst of energy—thereby clearing out the central hollow again and setting the stage for more clumps to fall in. Perhaps the nucleus goes through an endless cycle of explosive events, and we are just now seeing it in between, preparing for the next. (It should be said, however, that no such explosion would have anywhere near enough energy to produce the 3-kiloparsec arm. Theorists will have to look elsewhere for explanations of that feature.)

In summary, there is still a lot of sorting out to do before anyone completely understands the galactic nucleus. And, admittedly, much of the evidence is still circumstantial. But our picture has taken on a remarkable clarity and detail in recent years. It has become virtually impossible to explain the data with anything but the massive black hole model. And it seems more certain than ever that the Milky Way possesses an active galactic nucleus that differs only in mass and luminosity from that of a quasar or a Seyfert galaxy.—**M. MITCHELL WALDROP**

References

1. M. M. Waldrop, *Science* **228**, 1185 (1985).
2. K. Y. Lo, D. C. Backer, R. D. Ekers, K. I. Kellermann, M. Reid, J. M. Moran, *Nature (London)* **315**, 124 (1985).
3. R. D. Ekers, J. H. van Gorkom, U. J. Schwarz, W. M. Goss, *Astron. Astrophys.* **122**, 143 (1983).
4. K. Y. Lo and M. J. Claussen, *Nature (London)* **306**, 647 (1983).
5. M. K. Crawford *et al.*, *ibid.* **315**, 407 (1985).