# Astrophysics: Discovery and the Ubiquity of Black Holes

It is generally understood that scientists are in the business of making discoveries. But discovery itself is unpredictable and often waits upon the right person to make the right leap in understanding at the right time. The process of building on a discovery, however, may be more susceptible to diligent hard work. Astrophysicists have seen many examples of both processes in the last decade or so. The record indicates that there is apparently no training that can ensure that a researcher will recognize a distinctly new phenomenon, but that a well-practiced group of researchers can do much to accelerate the ensuing exposition.

During the last 13 years, astrophysicists have come up with more than their share of revolutionary findings and ideas. They have discovered superbright quasars, pulsating radio sources or pulsars that are regular as clockwork, and objects so small and powerful that they emit x-rays rather than weaker forms of radiation. During the same period, their mathematically inclined colleagues have elucidated the properties of the black hole, and one or two of the transformed, ultradense stars have almost certainly been found. These developments have had a revolutionary impact on astronomy and they have collectively overturned the classical view that the universe is a world filled with quiescent galaxies and slowly evolving stars.

One place to assess the current status of astrophysics is the biennial meeting of the so-called Texas conference, which brings together theorists specializing in relativity, observationalists specializing in high-energy astronomical phenomena, and a keenly interested group of physicists who follow these subjects as an avocation. The latest meeting* not only presented important work in the field, but also highlighted the unique contributions of two key researchers, one theorist and one observer.

Among many dazzling concepts, black holes may be the most mind-boggling contribution of astrophysics. Being collapsed stars they have gravitational forces strong enough to warp nearby space and to swallow any light rays or particles passing close by. Because they absorb light, they would generally appear black. The same strong gravitational forces could also efficiently produce great amounts of energy. The final word has hardly been heard yet, but the growing consensus seems to be that the phenomena of interest in astrophysics—which are almost all highly energetic—are generally caused by interactions of gases with black holes or other similarly dense objects.

Black holes began to be taken quite seriously in the late 1960's when theoretical physicists first proved that Einstein's general equations describing relativity had certain "singular" solutions. Studying these solutions more carefully, the theorists found that inside a black hole matter lost most of its characteristic properties. Once trapped, neither matter nor light could escape. In fact, a black hole with the mass of the sun could grow more massive by sucking up gas and debris from nearby stars. There is apparently no limit to the growth of a black hole. Such views quickly became the common wisdom in the early 1970's, especially after the first American x-ray detecting satellite produced strong evidence that the x-ray source named Cygnus X-1 was a black hole (*Science*, 3 November 1972).

### Black Holes Are Not Really Black

The growth and vigor of the study of black holes is due to a considerable degree to the work of an unusual British theorist, Stephen F. Hawking of Cambridge University. Since helping to show that black holes could exist at all, along with Roger Penrose at Birbeck College and others, he has continued to play a prominent role in further developments, although he suffers from a degenerative disease of the nervous system. In spite of the disability he still travels and lectures widely, and his colleagues listen closely. "There's no doubt about" his reputation, according to Jeremiah Ostriker of Princeton University. "He has made more progress in relativity than anyone in 20 years and perhaps since Einstein."

The news about black holes that was stressed at the symposium is that they are not really black. Hawking has found that all black holes actually emit radiation when quantum effects are taken into account. The radiation emitted is insignificant for black holes of the sun's mass or greater, but for very small black holes with a mass of $10^{15}$ grams (about the mass of a meteoroid; such a black hole would have the size of a proton) the effect could cause an explosion that would produce a burst of gamma rays at the end of the black hole's life. Observation of such a burst of gamma rays would be a "tremendous vindication" of general relativity and quantum theory, according to Hawking. Such small black holes could have been formed in the early stages of the universe, and the telltale gamma rays could give information about that epoch, if they are found.

For black holes with the mass of the sun ($10^{33}$ grams), the Hawking dissipation process would be so slow as to be completely ineffectual and the black hole would either be static or grow from accretion of nearby matter. The work on black hole radiation was published in 1974.

Still more recently, Hawking has concluded that particles emitted from a black hole will have an "additional degree of randomness" or unpredictability over and above that normally associated with quantum mechanics. In ordinary quantum theory, either the position or the velocity of a particle can be predicted with certainty. In a black hole neither property can be predicted, and therefore certain information is "lost irretrievably down the black hole," according to Hawking.

The effect of the latest work on black holes is to demonstrate that there apparently exists a situation in which relativity, quantum mechanics, and thermodynamics must all be brought to bear on a problem, perhaps for the first time.

Whether gamma-ray bursts can be observed from exploding black holes is speculative, however. Hawking estimates that a black hole with a mass much less than $10^{15}$ grams would have radiated away already, and one with much more than $10^{15}$ grams would not finally explode until billions of years from now. So only a rather narrow range of possible black holes would be likely to be detectable from gamma-ray observations. The spectrum of possible sizes of black holes is, however, astronomical. The very small black holes that could radiate themselves away would have about $10^{-18}$ the mass of the sun, the black holes that cause x-ray phenomena are more typically the mass of the sun, and black holes invoked to explain quasars may have $10^{6}$ times the mass of the sun.

*The eighth Texas Symposium on Relativistic Astrophysics was held from 13 to 19 December 1976 in Boston, Massachusetts.

Fortunately for the relativists, just at the same time that the new theoretical justification for black holes was published, the key observation that marked astrophysics as undeniably different from classical astronomy was made.

In September 1967, a graduate student at Cambridge University noticed a peculiar radio source that turned on and off quite regularly with a period of a few seconds. Such a finding had been considered impossible because there were strong arguments that an object pulsing that quickly could not produce a radio signal strong enough to reach the earth. But there it was. The faculty members at Cambridge were dubious and even suggested for a while that the signal was the work of "little green men" in another solar system. Then the graduate student, Jocelyn Bell-Burnell, found three more signals in different parts of the sky. The 1974 Nobel prize in physics was awarded for the discovery, but the graduate student was not one of the recipients (*Science*, 1 August 1975).

Pulsars are now understood to be neutron stars spinning once every few seconds and producing radio signals from the plasma they drag around as they spin. Practically speaking, neutron stars are nearly as dense as black holes. They are so named because they are, in effect, made of neutrons packed as closely as matter in the nucleus of an atom.

**Recognizing the Pulsar**

Perhaps reflecting a general feeling that Jocelyn Bell-Burnell deserved more recognition than she had gotten for her discovery, the organizers of the Texas symposium invited her to be the featured after-dinner speaker at their banquet. Introducing her, Tom Gold of Cornell University credited her with "perhaps the greatest single discovery in astronomy in this century," and the standing ovation she was given after her speech seemed to indicate appreciation of the fact that many of the 400 astrophysicists in the audience would not have a field of work but for her discovery. Although she is an active scientist working on a project with a British x-ray satellite, she had not visited the United States before and would not have been able to attend the recent symposium except for the invitation to speak.

Expressing no bitterness at being left out by the Nobel committee, Bell-Burnell said it was proper that credit as well as blame for the results of a graduate student's thesis should rest with the supervisor. "Besides, it's no skin off my nose," she told the august audience, "look at the company I'm in."

At previous Texas symposia, a prime topic has been x-ray sources, and researchers seem to find new varieties of them each year. The latest x-ray phenomenon, referred to as an x-ray "burster," was the hottest topic of the symposium, although a number of well-regarded astrophysicists suggested that perhaps the subject was being overplayed.

The phenomenon is a quick pulse of x-radiation that is about 30 times stronger than that from a steady x-ray source but then fades away within about 10 seconds. It is not as reliably periodic as the x-ray emission from the class of sources known as x-ray binaries, many of which are driven by spinning neutron stars. The best x-ray candidates for black holes, such as Cygnus X-1, brighten up in a way similar to the bursters but also have steady x-ray emissions. Nevertheless, there are models of neutron stars and black holes interacting with normal stars that have been suggested to explain the bursters.

"There seems to be a great debate" over x-ray bursters, said one noted theorist, "but you have two types of problems in astrophysics: one in which there seems to be no postulate to fit the data and another in which there are many." "This," he observed, "is an example of the latter case."

Whether overplayed or not, it may set a record for the speedy development of a well-buttressed scientific debate. Since the discovery of x-ray sources in binary star systems (*Science*, 2 March 1973), x-ray observation has been the glamor field of high-energy astronomy. In the latest instance, it took only 10 months for them to find a new x-ray phenomenon, corroborate it, come up with more than 20 additional examples, develop several theories to explain it, and divide into two well-defined schools of thought on the subject. Thus the familiar process that usually takes years in many sciences has been completed in a matter of months.

The debate is being argued between the x-ray astronomers at the Center for Astrophysics at Harvard University on the one hand and those at the Massachusetts Institute of Technology (MIT) on the other, with prominent astrophysicists from other institutions joining in. Both groups have played key roles in managing the research carried out with U.S. x-ray satellites. The lines of the debate seem to divide fairly well between those inclined to black hole models and those who are not. More specifically, the two sides seem to disagree over the significance of the finding that some of the x-ray bursters are found in globular clusters—spherical groupings of $10^5$ very old stars that are thought to be plausible places for black holes to form and grow larger by absorbing star debris.

The first x-ray bursters known to American researchers were found in January 1975, but, in an ironical parallel to the account of the pulsar discoveries, an MIT undergraduate working on some old x-ray data during the previous summer had noticed some unusual blips on the data line. The summer intern pointed out the unusual features to several researchers, but for reasons that can only be guessed the blips were not considered worth pursuing.

Had the summer intern been taken seriously, the MIT group might have been the first to publish on the subject. As it was, a Russian paper published in 1975 and translated into English in January 1976 was the first publication. The MIT group subsequently made the fourth discovery of a burster.

Toward the end of the Texas symposium, the ubiquity of black holes was finally exemplified by the discussion of quasars. After quasars were discovered in 1963, a straightforward calculation of their intrinsic power gave such an enormous number that many astronomers attempted to explain it away. Quasars were considered an oddity, fundamentally different from other stars and galaxies, and some expressions of radically new physics were invented to reduce their apparent power.

Since the discovery of quasars, two other types of galaxies—Seyferts and N-types—have appeared to span the discontinuity between quasars and other objects. Thus quasars are now thought to be rather normal giant galaxies that happen to have an extraordinary powerhouse in the center.

What is the source of a quasar's energy? The "best-buy theory" is that the powerhouse is a gargantuan black hole, more than a million times the mass of the sun, that provides energy by capturing gas, according to Martin Rees of the Institute of Astronomy at Cambridge. After it passed a certain size, such a black hole could supplement its diet by swallowing whole stars. Many aspects of such a model are not yet worked out, but Rees emphasizes that there are multiple possibilities to explain each step in the production of energy and its conversion to radio and visible radiation.

Perhaps quasars were discovered too soon, Rees suggests. If they had been found later, he thinks that black hole models for quasars would have been considered just as natural as the numerous models that use black holes and neutron stars to explain x-ray data.

—WILLIAM D. METZ