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Black holes in the Milky Way Galaxy

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ABSTRACT   Extremely strong observational evidence has recently been found for the presence of black holes orbiting a few relatively normal stars in our Milky Way Galaxy and also at the centers of some galaxies. The former generally have masses of 4–16 times the mass of the sun, whereas the latter are "supermassive black holes" with millions to billions of solar masses. The evidence for a supermassive black hole in the center of our galaxy is especially strong.

Black holes are regions of space in which the gravitational field is so strong that nothing can escape, not even light (see ref. 1 for a thorough review). This condition requires matter to be compressed into such a small volume that the escape velocity reaches (or even exceeds) the speed of light. Specifically, a given mass M forms a black hole if its radius is decreased to a value no larger than the Schwarzschild radius, $R_S = 2GM/c^2$, where G is Newton's constant of gravitation and c is the speed of light. For example, $R_S \approx 3$ km for one solar mass ($1\ M_{Sun}$). In the case of a nonrotating black hole, the sphere having $r = R_S$ is called the "event horizon"—nothing can escape from it! According to classical general relativity, all matter inside a black hole gets crushed to a singularity, a point of infinite density at the center of the black hole. Light and matter are formally trapped by the extreme curvature of space–time, not by the Newtonian gravitational force given by $F = GMm/R^2$ (where R is the distance between masses M and m); indeed, in the case of light ($m = 0$), the Newtonian law is obviously false.

Stellar-mass black holes are believed to be the natural evolutionary endpoint for certain kinds of stars. A star that is initially larger than $10\ M_{Sun}$ becomes unstable at the end of its life: the core collapses, while the outer layers are ejected after rebounding from the core and being pushed by neutrinos. (The latter are nearly massless neutral particles emitted profusely during the first few seconds of the star's demise.) Normally, the collapsed core of such a supernova (exploding star) forms a neutron star—a sphere 10 to 15 km in radius with mass $1.4\ M_{Sun}$. However, in some cases the core may be too massive to support itself: the absolute theoretical maximum mass of a neutron star is $3\ M_{Sun}$, and the true maximum might be considerably smaller (1.5 to $2\ M_{Sun}$). Inexorable gravitational collapse then ensues, forming a black hole. Another possible scenario is the merging of two neutron stars: if the final mass exceeds the stability limit, a black hole forms.

A qualitatively different type of black hole can be produced by the gravitational collapse of gas in the central regions of galaxies, especially large ones like our Milky Way Galaxy. Such "supermassive black holes" have millions, or even billions, of solar masses. Their existence was postulated in the 1960s to explain the powerful quasars (see below). At the other end of the mass spectrum, tiny "primordial black holes" might have formed shortly after the birth of the Universe, but there is no evidence whatsoever for their existence.

Because light and matter are trapped inside, a black hole cannot be directly detected; instead, one measures its gravitational influence on surrounding material. The main celestial laboratories for such studies are binary star systems and galactic nuclei. If, for example, a visible star rapidly orbits a dark object whose minimum possible mass is found to exceed $3\ M_{Sun}$, the process of elimination suggests that the latter is a black hole. Similarly, if the motion of stars and gas near the nucleus of a galaxy indicates that an enormous mass is confined to a very small volume, a black hole is probably the culprit.

X-Ray Binary Stars. Occasionally, x-ray telescopes detect an outburst of high-energy radiation from certain parts of the sky. In many cases, further study shows that matter has been transferred from a relatively normal star (known as the "secondary star") to a compact object (the "primary") that is orbiting it (see ref. 2 for a review). The emitted radiation, whose origin is the release of gravitational potential energy, comes predominantly from a flattened accretion disk surrounding the primary. After a few months the accretion disk fades, making it possible to study the secondary. Specifically, measurements of its radial velocity (v_r) in a series of optical spectra sometimes reveal orbital motion: v_r varies sinusoidally with time. (In some cases, the secondary is sufficiently luminous to be measured even when the system is not in quiescence; light from the accretion disk does not dominate the system.)

Newton's laws of motion and gravitation can be used to derive the *mass function* of the primary, $f(M_1) = PK_2^3/2\pi G = M_1^3 \sin^3 i/(M_1 + M_2)^2$, where M_1 and M_2 are the masses of the primary and secondary (respectively), i is the system's orbital inclination ($90° =$ edge-on orbit), P is the orbital period, and K_2 is the half-amplitude of the sinusoid (e.g., 350 km/s, if the sinusoid varies from -350 km/s to $+350$ km/s). From the observed radial velocity curve, such as that shown in Fig. 1 for the x-ray binary GS 2000 + 25, P and K_2 are measured; hence, $f(M_1)$ is determined observationally. However, note that $M_1 \geq f(M_1)$, with the equality holding only if the orbit is edge-on ($i = 90°$) and the secondary is massless ($M_2 = 0$). Because $M_2 > 0$ (otherwise it would not be a binary system!), the measured value of $f(M_1)$ provides a strict *lower limit* to M_1. Therefore, if a particular x-ray binary has $f(M_1) > 3\ M_{Sun}$, and the primary is dark, it is a very good black-hole candidate; triple-star systems that mimic black holes, though not impossible, are difficult to form and would be short lived.

The approximate mass of the secondary can sometimes be deduced from its spectrum. Moreover, the mass ratio ($q = M_2/M_1$) can be found from rotational broadening of the absorption lines in the spectrum of the secondary, which is locked into synchronous rotation (i.e., it rotates about its axis in a time equal to its orbital period). Further constraints on q and i are obtained from the light curve (brightness vs. time) of the secondary in quiescence: because of the secondary's tidal distortion (the degree of which depends on q), its apparent cross-sectional area

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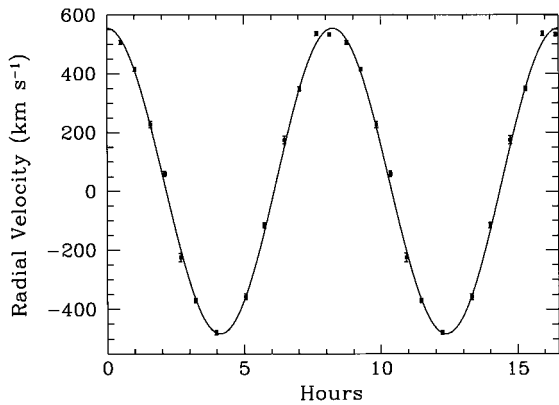[†]To whom reprint requests should be addressed. E-mail: alex@astro.berkeley.edu.

FIG. 1. Radial-velocity curve of the secondary star in the x-ray binary GS 2000 + 25 (adapted from ref. 3). Two cycles are shown for clarity.

varies as a function of position in its orbit, unless $i = 0°$. Also, if i is close to $90°$, mutual eclipses of the accretion disk and the secondary produce dips in the light curve.

By 1994, the mass functions (and the probable masses, in some cases) of five strong black-hole candidates had been measured (2). Because of the relatively small size of existing optical telescopes, these studies were limited to the brightest objects. With the completion of the two 10-m Keck telescopes, however, fainter systems could be investigated. The author's group, in particular, measured $f(M_1) = 5.0 \pm 0.1\ M_{Sun}$ for *GS 2000 + 25* (Fig. 1, adapted from ref. 3), the second-highest mass function known (after *GS 2023 + 338*, with $6.08 \pm 0.06\ M_{Sun}$). They also found $f(M_1) = 4.7 \pm 0.2\ M_{Sun}$ for *Nova Oph 1977*, the third-highest known. By late 1998, there were nine convincing black holes known in binary systems.

One may reasonably ask whether there is any more direct evidence that the dark primaries in these x-ray binary systems are black holes, rather than strange neutron stars whose mass somehow defies the expected upper limit of $3\ M_{Sun}$. Intriguing, but still somewhat controversial, evidence has recently been provided by a comparison of x-ray and optical brightness in quiescence (4). For a given optical brightness (determined by the mass transfer rate in the outer parts of the accretion disk), the x-ray brightness (from matter close to the primary) is much *lower* in the candidate black-hole systems than in those whose primary is known to be a neutron star. This suggests that in the former, the accreting matter is not hitting a stellar surface, and that the gravitational energy released in the disk is carried past the event horizon rather than radiated away.

The Center of the Milky Way Galaxy. Some galaxies are known to have very "active" central regions from which enormous amounts of energy are emitted each second. These *active galactic nuclei* are probably powered by accretion of matter into a supermassive black hole (10^6–$10^9\ M_{Sun}$; see ref. 5 for a review). The gravitational potential energy is converted into radiation through frictional forces in an accretion disk surrounding the black hole, a process that can be over 10 times more efficient than fusion of hydrogen into helium (which is what occurs in normal stars). Quasars, generally seen at large distances (and hence when the universe was young) are the most powerful examples of active galactic nuclei. As the available fuel in the central region was consumed with time, they faded to become less active objects, perhaps eventually becoming relatively normal galaxies such as our own.

Indeed, the center of our Milky Way Galaxy exhibits mild activity, especially at radio wavelengths: "nonthermal radiation" characteristic of high-energy electrons spiraling in magnetic fields is emitted by a compact object known as Sagittarius A*. Might it harbor a supermassive black hole? One way to find out is to see whether stars in the central region are moving very

rapidly, as would be expected if a large mass were present. More specifically, if a single supermassive black hole dominates the mass in the central region, the typical speeds v of stars at distance R from the nucleus should be proportional to $1/R^{1/2}$: at progressively *smaller* radii, v continues to grow. This would not be the case if the central region contained a spatially extended cluster of stars; for example, in the case of a uniform density of stars, we expect $v \propto R$.

During the past 5 years, two teams have obtained high-resolution images of our galactic center, each on several occasions so that temporal changes in the *positions* of stars could be detected (6, 7). The observations were conducted at infrared wavelengths, which penetrate the gas and dust between Earth and the galactic center [a distance of about 25,000 light years (ly)] much more readily than optical light. A special technique called *speckle imaging* was used to dramatically improve the clarity of the images: with exposures of a few tenths of a second, the diffraction limit of a telescope can be approached, because the atmospheric turbulence tends to smear the light rays over significantly longer time scales. By using the 10-m Keck-I telescope in Hawaii, the resulting angular resolution is about 0.05 arc second at $\lambda = 2.2$ μm, corresponding to a spatial scale of 0.007 ly at the Galactic center. The data are in excellent agreement with the $1/R^{1/2}$ curve at $R < 0.4$ ly; hence, the central region's gravitational potential is dominated by a single object! Its derived mass is $(2.6 \pm 0.2) \times 10^6$ M_{Sun}, and the mass density within a radius of 0.05 ly is at least $6 \times 10^9\ M_{Sun}/ly^3$, effectively eliminating all possibilities other than a black hole.

Although our galaxy provides the most convincing case for the existence of supermassive black holes, observations of the centers of a few other galaxies bolster the conclusion. Very precise measurements of some "masers" (like lasers, but with microwave radiation) in a disk surrounding the nucleus of NGC 4258, for example, reveal that $v \propto 1/R^{1/2}$ within a radius of 1 light year from the center (8). The derived mass of the compact object is $3.6 \times 10^7\ M_{Sun}$. On somewhat larger scales, spectra obtained with the Hubble Space Telescope show gas and stars rapidly moving in a manner consistent with the presence of a supermassive black hole (9); the most massive existing case, that of the giant elliptical galaxy M87, is about $3 \times 10^9\ M_{Sun}$. Moreover, x-ray observations of some active galactic nuclei reveal emission from a hot disk of gas, apparently very close to the black hole because extreme relativistic effects are detected (10). It now seems that a supermassive black hole is found in nearly every large galaxy amenable to such searches.

Thus, in the last decade of the 20th century, black holes have moved firmly from the arena of science fiction to that of science fact. Their existence in some binary star systems, and at the centers of massive galaxies, is nearly irrefutable. They provide marvelous laboratories in which the strong-field predictions of Einstein's general theory of relativity can be tested.

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