The Odd Couple: Quasars & Black Holes

Scott Tremaine

Abstract : Quasars emit more energy than any other object in the universe, yet are not much bigger than our solar system. Quasars are powered by giant black holes of up to ten billion (10^{10}) times the mass of the sun. Their enormous luminosities are the result of frictional forces acting upon matter as it spirals toward the black hole, heating the gas until it glows. We also believe that black holes of one million to ten billion solar masses – dead quasars – are present at the centers of most galaxies, including our own. The mass of the central black hole appears to be closely related to other properties of its host galaxy, such as the total mass in stars, but the origin of this relation and the role that black holes play in the formation of galaxies are still mysteries.

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Black holes are among the most alien predictions of Einstein's general theory of relativity : regions of space-time in which gravity is so strong that nothing – not even light – can escape. More precisely, a black hole is a singularity in space-time surrounded by an event horizon, a surface that acts as a perfect one-way membrane : matter and radiation can enter the event horizon, but, once inside, can never escape. Although black holes are an inevitable consequence of Einstein's theory, their main properties were only understood – indeed, the name was only coined – a half-century after Einstein's work.[1] Remarkably, an isolated, uncharged black hole is completely characterized by only two parameters : its mass and its spin (or angular momentum). An eloquent tribute to the austere mathematical beauty of these objects is given by the astrophysicist Subrahmanyan Chandrasekhar in the prologue to his monograph *The Mathematical Theory of Black Holes* : "The black holes of nature are the most perfect macroscopic objects there are in the universe : the only elements in their construction are our concepts of space and time. And since the general theory of relativity provides only a single unique

family of solutions for their descriptions, they are the simplest objects as well."[2] (Anyone who scans the six hundred pages that follow, however, is unlikely to agree that they are as simple as claimed.) Simple or complex, we are now almost certain, for reasons outlined in this essay, that black holes do exist and that a giant black hole of several million times the mass of the sun is present at the center of our galaxy.

Laboratory study of a black hole is impossible with current or foreseeable technology, so the only way to test these predictions of Einstein's theory is to find black holes in the heavens. Not surprisingly, isolated black holes are difficult to see. Not only are they black, they are also very small: a black hole with the mass of the sun is only a few kilometers in diameter (this statement is deliberately vague: because black holes bend space to such extremes, our notions of "distance" close to a black hole cease to be unique). However, the prospects for detecting black holes in gas-rich environments are much better. The gas close to the black hole normally takes the form of a rotating disk, called an accretion disk: rather than falling directly into the black hole, the orbiting gas gradually spirals in toward the event horizon as it loses orbital energy, most likely transferred to turbulence and magnetic fields in the disk.[3] The energy is eventually transformed into thermal energy, which heats the gas until it begins to glow, mostly at ultraviolet and X-ray wavelengths. By the time the inward-spiraling gas disappears behind the event horizon, deep within the gravitational well of the black hole, a vast amount of radiation has been emitted from every kilogram of accreted gas.

In this process, the black hole can be thought of as a furnace: when provided with fuel (the inward-spiraling gas) it produces energy (the outgoing radiation). Einstein's iconic formula $E = Mc^2$ relates mass M and the speed of light c to an energy E called the rest-mass energy. Using this relation, there is a natural measure of the efficiency of this or any other furnace: the ratio of the energy it produces to the rest-mass energy of the fuel that it consumes. For furnaces that burn fossil fuels, the efficiency is extraordinarily small (about 5×10^{-10}), and all combustion processes based on chemical reactions have similarly low efficiencies. For fission reactors using uranium fuel, the efficiency is much better, around 0.1 percent; and for the fusion reactions that power the sun and stars, the efficiency can reach 0.3 percent.

Black-hole furnaces can have far higher efficiency than any of these: between 10 and 40 percent for accretion of gas from a thin accretion disk. In the unlikely event that we could ever domesticate black holes, the entire electrical energy consumption in the United States could be provided by a black-hole furnace consuming only a few kilograms of fuel per year.

Despite the relatively low efficiency of fusion reactions, most of the light in the universe comes from stars. Most of the stars in the universe are organized in galaxies: assemblies of up to 10^{11} stars orbiting in a complex dance determined by their mutual gravitational attraction. Our own galaxy contains a few tens of billions of stars arranged in a disk; the nearest of these is about 1 parsec (3.26 light years) from us, and the distance to the center of our galaxy is about 8 kiloparsecs (or about 26,000 light years). The diffuse light from distant stars in the galactic disk is what we observe as the Milky Way.[4]

A small fraction of galaxies contain mysterious bright and compact sources of radiation at or near their centers, called active galactic nuclei.[5] The brightest of these are the quasars; remarkably, they can emit up to 10^{13} times more light than stars like the sun, thereby outshining the entire gal-

axy that hosts them. Even though quasars are much rarer than galaxies, they are so bright that they contribute almost 10 percent of the light emitted in the universe.

Ironically, the extraordinary luminosity of quasars is what made them hard to discover. Except in a few cases, they are so bright that the host galaxy cannot be seen in the glare from the quasar, and so small that they look like stars, even at the resolution of the Hubble Telescope (in fact, "quasar" is a contraction of "quasi-stellar object"). Thus, even the brightest quasars are usually indistinguishable from millions of stars of similar brightness. Fortunately, some quasars are also strong sources of radio emission, and in 1963 this clue enabled astronomer Maarten Schmidt at Caltech to identify a radio source called 3C 273 with a faint optical source that otherwise looked like an undistinguished star.[6] With this identification in hand, Schmidt was able to show that 3C 273's spectral lines were redshifted – Doppler shifted by the cosmological expansion of the universe – to wavelengths 16 percent longer than laboratory spectra, and thus that 3C 273 was at a distance of eight hundred megaparsecs, ten million times farther away than it would have been if it were a normal star.

Now almost one hundred thousand quasars have been identified. The most distant of them is almost one hundred times farther away from Earth than 3C 273, and its light was emitted when the universe was only 6 percent of its present age. However, the formation of quasars that early in the history of the universe was a very rare event. Most were formed when the universe was 20–30 percent of its current age, and quasars today are a threatened species: the population has declined from its peak by almost two orders of magnitude, presumably because the fuel supply for quasars dried up as the universe expanded at an accelerating rate.

How can quasars emit so much energy? The suggestion that they are black-hole furnaces was made independently by Edwin Salpeter in the United States and Yakov Zel'dovich in the Soviet Union, soon after quasars were first discovered. But in the 1960s the black hole was a novel and exotic concept, and staggeringly massive black holes (roughly one hundred million solar masses) were required in order to explain quasar properties. Thus, most astronomers quite properly focused on more conservative models for quasars, such as supermassive stars, dense clusters of ordinary stars or neutron stars, and collapsing gas clouds. Over the next two decades, however, all of these models were subjected to intense scrutiny that increasingly suggested that they were inadequate to explain the growing body of observations of quasars. Furthermore, other studies showed that the alternative models generically evolve into a black hole containing most of the mass of the original system, thereby suggesting that the formation of massive black holes is natural and perhaps even inevitable.

A number of indirect but compelling arguments also support the black-hole furnace hypothesis. The first of these relates to efficiency. The luminous output of a bright quasar over its lifetime corresponds to a rest-mass energy of about one hundred million times the mass of the sun. If this were produced by the fusion reactions that power stars with the efficiency of 0.3 percent given earlier, the mass of fuel required would be almost the total of all the stars in our galaxy. There is no plausible way to funnel this much mass into the tiny central region that the quasar occupies, nor is there evidence that so much mass resides there. On the other hand, for a black-hole furnace the efficiency is 10 percent or more, so the required mass is less than 10^9 solar masses, and this much gas is not hard to

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find close to the center of many galaxies. Thus, the black-hole furnace is the only model that does not bankrupt the host galaxy's fuel budget.

A second argument is based on the small size of quasars. We have known since their discovery that quasars appear as unresolved point sources of light even in the best optical telescopes; this observation alone implies that they must be less than about a kiloparsec across, and long-baseline radio interferometry shows that quasars must be far smaller, less than one parsec across. Even stronger limits on the size come from indirect measurements. Quasars vary irregularly in brightness on a wide range of timescales, from weeks to decades and probably even longer. It proves quite difficult to construct any plausible model of a luminous astrophysical object that varies strongly on a timescale smaller than the time it takes light to travel across the object: the separate parts of the object are not causally connected on this timescale, so they vary independently and their contributions tend to average out. This argument suggests that the size of the most rapidly varying quasars must be less than the distance light travels in a few weeks (which is around a few hundredths of a parsec or a few thousand times the Earth-sun distance). This upper limit is consistent with size estimates from a number of other methods, such as reverberation mapping, photoionization models, and gravitational lensing.[7]

A few hundredths of a parsec is large by our standards but extremely small on galactic scales: a millionth of the size of the galaxy as a whole. A black hole of one hundred million solar masses and its surrounding accretion disk would fit comfortably inside this volume – its relativistic event horizon has a radius of about the Earth-sun distance – but almost all of the alternative models that might explain quasars fail to do so.

In a few cases space-based observatories can measure X-ray spectral lines emitted by quasars. These are not the narrow lines seen in spectra of the sun, stars, or interstellar gas; instead they are grossly misshapen, with broad tails extending to much longer wavelengths than such lines would have in weak gravitational fields. The only plausible explanation for these distortions is that they arise from gravitational redshift – the loss of energy as the X-rays climb out of a deep gravitational well on their way to us – and/or from extreme Doppler shifts caused by relativistic motions, most probably in a rotating accretion disk. Either explanation requires that the X-rays were emitted from a region only a few times larger than the event horizon of a black hole, as no other known astrophysical system has such high velocities and deep potential wells.[8]

Some quasars emit powerful jets of plasma that extend for up to a megaparsec (see Figure 1),[9] probably collimated and accelerated by magnetic fields near the black hole that are twisted up by the rotation of the surrounding accretion disk. The production of these jets is not so remarkable: for example, various kinds of star also produce jets, though on a much smaller scale. What is more striking is that quasar jets typically travel at close to the speed of light. Once again, there is no plausible way to produce such high velocities except close to the event horizon of a black hole. Moreover, in most cases the jets are accurately straight, even though the innermost plasma in the jet was emitted a million years after the material at the far end. Thus, whatever mechanism collimated the jet must maintain its alignment over several million years; this is easy to do if the jets are squirted out along the polar axis of a spinning black hole, but difficult or impossible in other quasar models.

Finally, there is strong evidence that a handful of systems that emit strong X-ray

Figure 1
An Image at Radio Wavelengths of Jets from the Quasar Cygnus A
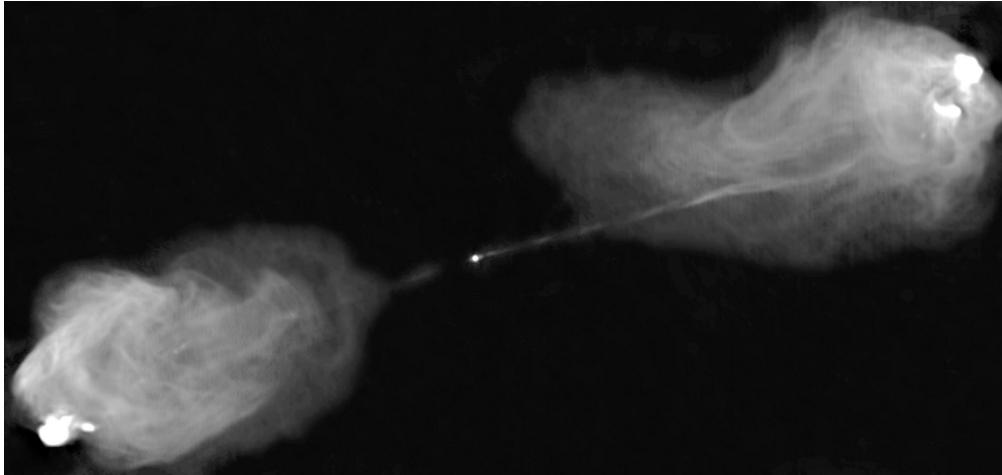
The bright spot at the center of the image is the quasar, which is located in a galaxy 240 megaparsecs away. The long, thin jets emanating from the quasar terminate in bright "hotspots" when they impact the intergalactic gas that surrounds the galaxy. The hotspots are roughly 70 kiloparsecs (or 228,000 light years) from the quasar. The brighter of the two jets is traveling toward us; its brightness has been boosted by relativistic effects. Source: National Radio Astronomy Observatory/Associated Universities Inc.; reproduced by permission of the American Astronomical Society. From R. A. Perley et al., "The Jet and Filaments in Cygnus A," *The Astrophysical Journal* 285 (1984): L35 – L38.

radiation consist of a normal star and a black hole. The black holes are much less massive than those in quasars, only a few times the mass of the sun.[10] The black hole and the normal star orbit one another at a small enough distance – a few stellar radii – that material lost from the normal star fuels a miniature black-hole furnace. These systems reinforce our confidence in the existence of black holes, and allow us to refine our understanding of the complex physics of a black-hole furnace.

Based on these and other arguments, there is near-complete agreement among astrophysicists that the power source for quasars is the accretion of gas onto black holes of one hundred million solar masses or more. Accepting this position leads to a simple syllogism that has driven much of the research on this subject for the past sev-

eral decades: if quasars are found in galaxies, and the number of quasars shining now is far smaller than when the universe was young, and quasars are black-hole furnaces, then many "normal" galaxies should still contain the massive black holes that used to power quasars at their centers, but are now dark. Can we therefore find "dead quasars" in nearby galaxies?

There are two important guideposts in the search for dead quasars. The first comes from a simple argument by the Polish astronomer Andrzej Sołtan.[11] We know that the universe is homogeneous on large scales, and therefore on average the energy density in quasar light must be the same everywhere in the universe (here *average* means averaged over scales greater than about ten to twenty megaparsecs, which is still small compared to the overall "size" of the universe, at a few thousand mega-

parsecs). We can measure this energy density by adding up the contributions from all the quasars found in surveys (after straightforward corrections for incompleteness). If this energy were produced by black-hole furnaces with an efficiency of 10 percent, for example, then a mass M of material accreted by black holes would produce $0.1Mc^2$ in quasar light. Similarly, if the average mass density of dead quasars is ρ, then the energy density of quasar light must be $0.1\rho c^2$.

Since we know the latter figure, we can invert the calculation to determine the mass density of dead quasars. The power of this argument is that it requires no assumptions about the masses or numbers of black holes; no knowledge of when, where, or how quasars formed; and no understanding of the physics of the quasar furnace except its efficiency. Sołtan's argument tells us that the density of dead quasars should be a few hundred thousand solar masses per cubic megaparsec, compared to a density of large galaxies of about one per hundred cubic megaparsecs. What it does not tell us is how common dead quasars are: on average there could be, for example, one dead quasar of ten million solar masses in every galaxy, or one of one billion solar masses in 1 percent of galaxies.

The second guidepost is that the centers of galaxies are the best places to prospect for dead quasars. There are several reasons for this. First, live quasars seem to be found near the centers of their host galaxies (although this is difficult to tell with precision because the glare from the quasar obscures the structure of the host). Second, the fuel supply for a black hole sitting at rest in the center of the galaxy is likely to be much larger than the fuel supply for one orbiting in the outskirts of the galaxy. Third, massive black holes orbiting in a galaxy tend to lose orbital energy through gravitational interactions with passing stars, so they spiral into the center of the galaxy.[12] And

finally, like the drunkard looking for his keys under the lamppost, we look for dead quasars at the centers of galaxies because that is where it is easiest to find them: the search area is small and the density of stars that are affected by the black hole's gravitational field is high.

Stars that come under the influence of the black hole's gravitational field – typically those within a distance of a few tenths of a parsec to a few tens of parsecs, depending on the black hole's mass – are accelerated to higher velocities; although individual stars cannot be detected in galaxies other than our own, this acceleration leads to increased Doppler shifts, which broaden the spectral lines from the collective stellar population. This broadening can be detected by spectroscopic observations with sufficiently high spatial resolution and signal-to-noise ratios. The search for this effect in the centers of nearby galaxies began around 1980 and yielded evidence for black holes in a handful of cases. Strictly, the evidence was for massive dark objects with masses of millions to billions of solar masses, since the angular resolution (the smallest size of distinct object that the telescope can clearly image) of these observations was still far larger than the size of the event horizon of the putative black hole. These results were tantalizing, but incomplete: the problem was that the angular resolution of ground-based telescopes is limited by blurring caused by the atmosphere, so the effects of a black hole could be detected only in the closest galaxies, and then only over a limited range of distances from the center. Precisely this problem was one of the motivations for constructing the Hubble Space Telescope, which at the time of its launch in 1990 had roughly ten times the angular resolution of the best ground-based telescopes. Since then the Hubble Telescope has devoted many hundreds of hours to the hunt for black holes at the centers of galaxies, and by now Hubble has

confirmed and strengthened the ground-based detections in nearby galaxies and produced firm evidence for black holes in over two dozen more distant ones.[13] Even in the best cases, this method can only probe to a few tenths of a parsec from the galaxy center, but we are persuaded that the massive dark objects observed by Hubble must be black holes because the alternatives (for example, a cluster of low-luminosity stars) are far less plausible. By now the Hubble Telescope has turned to other tasks, but the search for dead quasars has been resumed by ground-based telescopes, now using adaptive optics systems that can correct for atmospheric blurring in real time. Adaptive optics is beginning to provide angular resolutions that equal or exceed Hubble's: these new observations also have far higher signal-to-noise ratios, since the collecting area of the biggest ground telescopes is ten times that of Hubble.

The painstaking measurement of stellar motions near the centers of galaxies has been supplemented by an unexpected gift from the heavens: the otherwise unremarkable galaxy NGC 4258 contains at its center a thin, nearly flat, rotating disk of gas, about a tenth of a parsec in radius. The gas includes water vapor, and the temperature and density in the disk are right for the production of maser (microwave laser) emission in the water, stimulated by a weak active galactic nucleus at the center of the disk. The maser emission consists of tiny, intensely bright sources of radiation concentrated in wavelength at the spectral line of water, and by measuring the Doppler shift of these sources and their motion across the sky using an intercontinental array of radio telescopes, we can map out the rotation of the disk with exquisite precision. The disk is found to rotate around the active nucleus; from the disk kinematics, we can deduce that the nucleus is much smaller than the inner radius

of the disk, and that its mass is 37.8 million solar masses with a measurement uncertainty of only 0.3 percent (possible systematic errors due to the choice of model are larger, with about a 1 percent margin of error). This is by far the best case we have for a massive dark object at the center of any distant galaxy.[14]

Finally, our own galaxy offers unique evidence for a black hole.[15] Very close to the geometric center of the distribution of stars in the Milky Way is a compact source of strong radio emission known as Sagittarius A*. This region is difficult to study because small solid particles in interstellar space (commonly called "dust" but really more like haze or smoke) obscure visible light coming from stars near the center. The smoke can be penetrated by infrared radiation, and high-resolution observations at these wavelengths reveal a handful of bright stars within a few hundredths of a parsec from Sagittarius A*. The positions and velocities of these stars have been tracked, some for as long as two decades; in particular, the star S2 has an orbital period of only 15.8 years and now has been tracked through more than one complete orbit. Some four centuries ago, Johannes Kepler showed that the orbits of the planets around the sun were ellipses; here the orbit of S2 is also an ellipse (Figure 2). Using first-year mechanics, we can deduce from this orbit that the star is orbiting a body that is located at the radio source Sagittarius A*, that this body has a mass of 4.3 million solar masses, with an uncertainty of less than 10 percent, and that the size of this body is less than only one hundred times the Earth-sun distance, or a few thousand times the radius of the event horizon for a black hole of this mass. This extreme concentration of mass is incompatible with any known long-lived astrophysical system other than a black hole. The center of our galaxy thus offers the single best case for the existence of black

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Figure 2

Orbits of Stars Near the Center of Our Galaxy
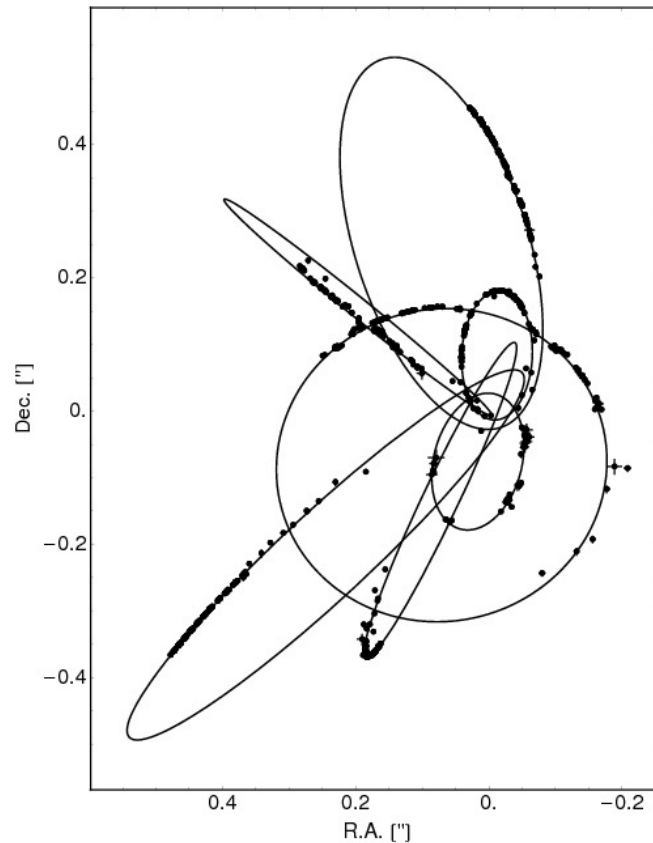
The radio source Sagittarius A*, believed to coincide with the black hole at the galaxy center, is at the zero point of the coordinates. The width of the frame is 0.03 parsecs or 6,700 times the Earth-sun distance. Each orbit is well-fit by an ellipse with one focus at Sagittarius A* (the focus is not on the symmetry axis of the orbit because the normal to the orbit is inclined to the line of sight). The smallest orbit, called S2, has a period of 15.8 years, and its point of closest approach to Sagittarius A* is 120 times the Earth-sun distance. These parameters imply that Sagittarius A* is associated with a mass of 4.3 million solar masses contained within about 100 times the Earth-sun distance. Source: Reinhard Genzel, Frank Eisenhauer, and Stefan Gillessen, "The Galactic Center Massive Black Hole and Nuclear Star Cluster," *Reviews of Modern Physics* 82 (4) (2010): 3121–3195.

holes and strongly suggests that the massive dark objects found in the centers of other galaxies are also black holes.

What else have we learned from these discoveries? First, black holes seem to be present in most galaxies, except perhaps for a class known as late-type galaxies. Second, the mass of the black hole is strongly correlated with the mass or luminosity of the galaxy; roughly, the black-hole mass is about 0.2 percent of the mass of the stars in the galaxy. But are the black holes we are finding in nearby galaxies really dead quasars? From galaxy surveys we can determine the average mass density in stars in the local universe, and since black-hole masses are typically 0.2 percent of the stellar mass in a galaxy, we can estimate the mass density of black holes in the local universe. Sołtan's argument, described earlier,

gives the mass density of dead quasars in the local universe from completely different data (surveys of distant quasars as opposed to surveys of nearby galaxies). The two estimates agree to within a factor of about two – well within the uncertainties – so there is little doubt that the black holes we have found are indeed the ash from quasars or other active galactic nuclei.

This essay has described briefly what we have learned about the intimate relation between quasars, one of the most remarkable components of the extragalactic universe, and black holes, one of the most exotic predictions of twentieth-century theoretical physics. Many aspects of this relation remain poorly understood; to close, I will mention two of the most profound unanswered questions.

The first of these is the relation between black holes and galaxy formation. Although black holes make up only a fraction of a percent of the mass of the stars in galaxies, the energy released in forming them is hundreds of times larger than the energy released in forming the rest of the galaxy. If even a small fraction of the energy emitted by the black-hole furnace is fed back to the surrounding gas and stars, it would

have a dramatic influence on the galaxy *Scott* formation process. In an extreme case, the *Tremaine* quasar feedback could blow the gas out of the galaxy and thereby quench the formation of new stars. Are black holes and quasars an interesting by-product of galaxy formation that has no influence on the formation process, or do they play a central role in regulating it? More succinctly, do galaxies determine the properties of quasars or vice versa?

The second profound question is one of physics rather than astronomy. All of the tests of Einstein's theory so far – which it has passed with flying colors – have been conducted in weak gravitational fields, such as those on Earth or in the solar system. In contrast, we have no direct evidence that the theory works in strong gravitational fields. Many naturally occurring processes near black holes in galaxy centers – tidal disruption of stars, swallowing of stars, accretion disks, and even black-hole mergers – may potentially be measured with the next generation of astronomical observatories. Can we understand these processes well enough to test the unique predictions of general relativity for physics in strong gravitational fields, and will Einstein turn out to be right?

ENDNOTES

[1] Textbooks on general relativity include Bernard Schutz, *A First Course in General Relativity*, 2nd ed. (Cambridge: Cambridge University Press, 2009); James B. Hartle, *Gravity: An Introduction to Einstein's General Relativity* (San Francisco: Addison-Wesley, 2003); Sean Carroll, *Spacetime and Geometry* (San Francisco: Addison-Wesley, 2004); and Robert M. Wald, *General Relativity* (Chicago: University of Chicago Press, 1984). Monographs on black holes include Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes* (Oxford: Clarendon Press, 1992); and Valeri P. Frolov and Andrei Zelnikov, *Introduction to Black Hole Physics* (Oxford: Clarendon Press, 2011). A popular account closely related to the subject of this essay is Mitchell Begelman and Martin J. Rees, *Gravity's Fatal Attraction*, 2nd ed. (Cambridge: Cambridge University Press, 2009).

[2] Subrahmanyan Chandrasekhar, *The Mathematical Theory of Black Holes* (Oxford: Clarendon Press, 1992), prologue.

[3] The physics of accretion disks is described in Marek A. Abramowicz and P. Chris Fragile, "Foundations of Black Hole Accretion Disk Theory," *Living Reviews in Relativity* 16 (2013): 1, arXiv:1104.5499; H. C. Spruit, "Accretion Disks" (May 2010), arXiv:1005.5279 (the essay is an expanded and revised version of "Accretion Theory," a lecture Spruit delivered at the XXI

Canary Islands Winter School of Astrophysics, Puerto de la Cruz, Tenerife, Spain, November 2 – 13, 2009); and Juhan Frank, Andrew King, and Derek Raine, *Accretion Power in Astrophysics*, 3rd ed. (Cambridge: Cambridge University Press, 2002). For a review of magnetohydrodynamic turbulence, energy dissipation, and angular momentum transport in accretion disks, see Steven A. Balbus and John F. Hawley, "Instability, Turbulence, and Enhanced Transport in Accretion Disks," *Reviews of Modern Physics* 70 (1998): 1 – 53.

4 Introductory texts on galaxies include L. S. Sparke and J. S. Gallagher III, *Galaxies in the Universe: An Introduction*, 2nd ed. (Cambridge: Cambridge University Press, 2007); and Peter Schneider, *Extragalactic Astronomy and Cosmology* (Berlin: Springer, 2006). At a more advanced level there is James Binney and Michael Merrifield, *Galactic Astronomy* (Princeton, N.J.: Princeton University Press, 1998); James Binney and Scott Tremaine, *Galactic Dynamics*, 2nd ed. (Princeton, N.J.: Princeton University Press, 2008); and Houjun Mo, Frank van den Bosch, and Simon White, *Galaxy Formation and Evolution* (Cambridge: Cambridge University Press, 2010).

5 Julian H. Krolik, *Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment* (Princeton, N.J.: Princeton University Press, 1999).

6 For the history of this discovery, see K. I. Kellermann, "The Discovery of Quasars," *Bulletin of the Astronomical Society of India* 41 (2013): 1 – 17. An interview with Maarten Schmidt is available at http://oralhistories.library.caltech.edu/118/. A snapshot of the intense early debates about the nature of quasars can be found in George B. Field, Halton Arp, and John N. Bahcall, *The Redshift Controversy* (Reading, Mass.: W. A. Benjamin, 1973).

7 Most measurements constrain the size of the so-called broad-line region, in which the broad optical emission lines of the quasar are produced. In black-hole models of quasars the broad-line region is much larger than the event horizon or accretion disk. Reverberation mapping is based on the average time delay between variations in the continuum luminosity, believed to arise from the accretion disk, and variations in the broad lines, which measure the light-travel time to the broad-line region. Photoionization models are based on an empirical correlation $R \propto L^{0.5}$ between the size of the broad-line region R revealed by reverberation mapping and the continuum luminosity L; this correlation is natural if the broad lines are in ionization equilibrium and brighter active galactic nuclei are simply scaled-up versions of fainter ones. For a review and references, see Yue Shen, "The Mass of Quasars," *Bulletin of the Astronomical Society of India* 41 (2013): 61 – 115. An alternative is to study quasars that are gravitationally lensed by an intervening galaxy; lensing by individual stars in the lens galaxy then leads to fluctuations in the brightness of the quasar image that depend on the ratio of the size of the broad-line region to the Einstein radius of the star. See E. Guerras et al., "Microlensing of Quasar Broad Emission Lines: Constraints on Broad Line Region Size," *The Astrophysical Journal* 764 (2013): 160.

8 J. C. Miller, "Relativistic X-Ray Lines from the Inner Accretion Disks Around Black Holes," *Annual Review of Astronomy and Astrophysics* 45 (2007): 441 – 479.

9 M. Boettcher, D. E. Harris, and H. Krawczynski, eds., *Relativistic Jets from Active Galactic Nuclei* (Weinheim, Germany: Wiley-VCH, 2012).

10 Ronald A. Remillard and Jeffrey E. McClintock, "X-Ray Properties of Black-Hole Binaries," *Annual Review of Astronomy and Astrophysics* 44 (2006): 49 – 92.

11 Andrzej Sołtan, "Masses of Quasars," *Monthly Notices of the Royal Astronomical Society* 200 (1982): 115 – 122.

12 This process, known as dynamical friction, is a manifestation of energy equipartition familiar from statistical mechanics. See James Binney and Scott Tremaine, *Galactic Dynamics* (Princeton, N.J.: Princeton University Press, 2008).

13 John Kormendy and Luis C. Ho, "Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies," *Annual Review of Astronomy and Astrophysics* 51 (2013): 511 – 653; Kayhan Gültekin et al., "The $M – \sigma$ and $M – L$ Relations in Galactic Bulges, and Determinations of Their Intrinsic Scatter," *The Astrophysical Journal* 698 (2008): 198 – 221; and Nicholas J. McConnell and

Chung-Pei Ma, "Revisiting the Scaling Relations of Black Hole Masses and Host Galaxy Properties," *The Astrophysical Journal* 764 (2013): 184. *Scott Tremaine*

[14] J. M. Moran, "The Black-Hole Accretion Disk in NGC 4258: One of Nature's Most Beautiful Dynamical Systems," in *Frontiers of Astrophysics: A Celebration of NRAO's 50th Anniversary*, ed. A. H. Bridle, J. J. Condon, and G. C. Hunt (San Francisco: Astronomical Society of the Pacific Conference Series, 2008): 395, 87; R. Herrnstein et al., "The Geometry of and Mass Accretion Rate Through the Maser Accretion Disk in NGC 4258," *The Astrophysical Journal* 629 (2005): 719–738; and Jenny E. Greene et al., "Precise Black Hole Masses from Megamaser Disks: Black Hole-Bulge Relations at Low Mass," *The Astrophysical Journal* 721 (2010): 26–45.

[15] For a comprehensive review of the central parsec of our galaxy, see Reinhard Genzel, Frank Eisenhauer, and Stefan Gillessen, "The Galactic Center Massive Black Hole and Nuclear Star Cluster," *Reviews of Modern Physics* 82 (4) (2010): 3121–3195.