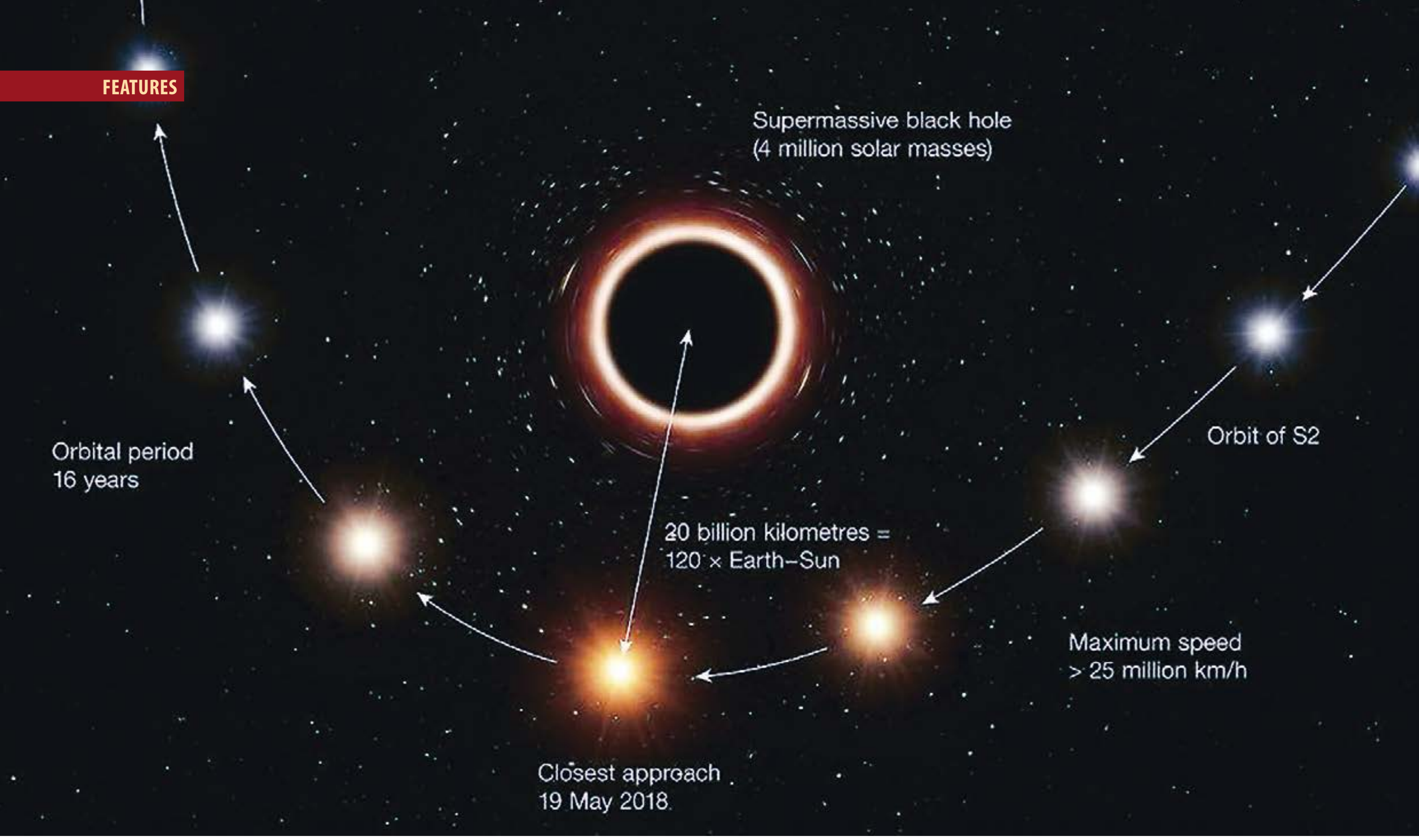

NEW HORIZONS IN BLACK HOLE ASTROPHYSICS

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Black holes, a seemingly inevitable consequence of Einstein's general theory of relativity and stellar and galactic evolution are being observed in many new ways with masses ranging from roughly three to ten billion solar masses. Their masses and spins determine how they power the most luminous objects in the universe and impact their environments.

History

In 1916, just a few weeks after Albert Einstein published his general theory of relativity, Karl Schwarzschild, found a spherically symmetric solution to the field equations. Although this was not widely understood until the 1960s, this solution describes a non-spinning *black hole*, uniquely described by its mass [1]. It exhibits an event horizon, which can be thought of as a limiting, spherical surface in space from behind which light and material particles do not escape and, instead, as shown by Nobel Laureate Roger Penrose, proceeds towards a *singularity* where classical space and time come to an end [2]. The radius of the event horizon, measured by its circumference, is only 3 km for each solar mass in its total mass.

In parallel, astronomers realised that evolved, high mass stars were unlikely to escape ending their lives as black holes. They also discovered that the nuclei of galaxies could outshine the tens of billions of surrounding stars. One of the early interpretations of these sources, called quasars, was that they were due to gas accreting onto massive (millions to billions of solar masses) black holes and releasing gravitational energy as heat and radiation. This turned out to be correct.

Around this time, Roy Kerr generalised Schwarzschild's solution introducing a second parameter, the spin, and this suffices to describe essentially all astrophysical black holes. In addition, Penrose demonstrated that rotational energy could be extracted from a Kerr black hole to provide a competitive power source to accretion.

Stellar Mass Black Holes

The first explicit demonstration that black holes really do exist, outside the febrile imaginings of theorists, came from observing X-ray sources in orbit around regular stars [3]. The sources have masses which were measured, using Kepler's laws, to exceed the maximum possible mass of a neutron star or a white dwarf and so, they had to be black holes. Gas is transferred from the regular star onto the black hole with sufficient angular momentum to form an *accretion disk*, within which magnetic "friction" allows gas to spiral inward, releasing energy and emitting X-rays. The luminosity is determined by the rate at which gas is supplied.

These disks can be very efficient radiators, in the sense that the energy that is radiated before gas plunges across the event horizon can be a much larger fraction of its rest mass, typically ten percent, than is released by the nuclear reactions inside stars (typically half a per cent). Accretion disks are complicated, subject to instability on a variety of timescales and capable of driving powerful, *magnetised outflows*. When the mass supply is low, the gas is either expelled or ingested, before it can radiate, and so these disks are not so efficient. The manner in which disks radiate away the internal frictional heating and reflect incident radiation is also quite subtle but can be highly diagnostic of these complex flows and the black hole spin.

Massive Black Holes

Most normal galaxies have a massive black hole in their nucleus [3]. This is true of our galaxy which hosts a four million solar mass black hole (Fig. 1). However, it is almost dormant, emitting very weakly at radio through X-ray wavelengths because it is ill-fed. (We should not be upset. We would not want to live next to a quasar!) Our black hole is orbited by many stars, just like our sun is orbited by planets. These orbits have been followed using extremely careful infrared observations by teams led by Nobel Laureates Reinhard Genzel and Andrea Ghez and provide a compelling manifestation of the black hole [2].

Another important example is provided by the very massive (six billion solar masses) black hole in the nearby galaxy, M87 (Fig. 2). The moderate gas supply does not match the black hole's appetite and what it must have been in the past when M87 would have been one of the brightest "stars" on the sky. Recently, the Event Horizon Telescope collaboration has imaged gas orbiting close to the black hole, affirming its size as well as predictions from general relativity [4].

When a massive black hole is well-fed, the galaxy nucleus becomes "active". This happened much more when the universe was younger. The accompanying accretion disks radiate in the ultraviolet, not X-ray bands and excite emission lines from nearby gas.

Relativistic Jets

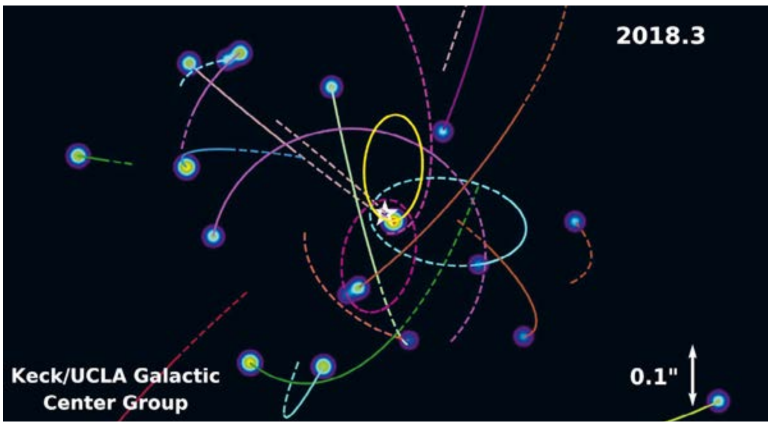
Active galactic nuclei can also produce *jets* [5]. These are pairs of linear outflows launched perpendicular to the accretion disk along opposite directions. The outflow speeds are generally near to that of light and, as a consequence of special relativistic kinematics, they can exhibit "superluminal" expansion. In addition, the small minority of jets that are directed towards us will appear to be unusually luminous and dominate samples of such sources observed by astronomers. They comprise the majority of the powerful gamma-ray sources seen on the sky.

The power for these jets appears to derive from the spin of the black hole, extracted electromagnetically. The horizon of the black hole behaves like a rotating electrical conductor, similar to a Faraday wheel. In the most powerful cases, an EMF ~ 10^{20} V is generated driving a current ~ 10^{18} A, producing a power ~ 10^{38} W again exceeding the total luminosity of a galaxy. If this is correct, then a magnetised, spinning massive black hole can plausibly accelerate an atomic nucleus to an energy more than 10^{20} eV and thereby account for the very highest energy cosmic rays that are observed hitting the earth's atmosphere.

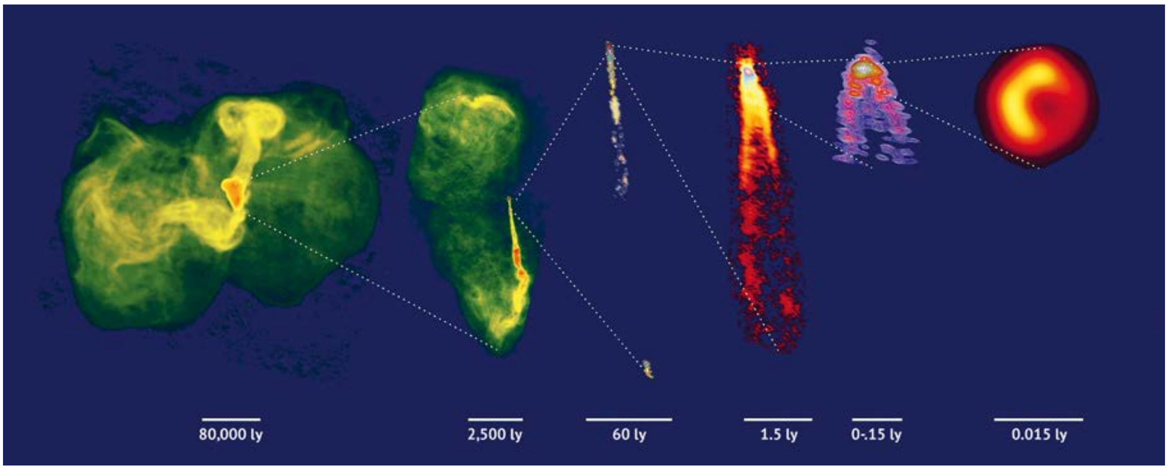
Jet collimation is attributable to magnetised outflow from the accretion disk, an interaction which renders them visible. Despite this, jets can travel for millions of light years through the intergalactic medium. It is remarkable that a nuclear source, no larger than our solar system, can have a major, environmental impact on the gas far beyond the host galaxy.

Formation of Black Holes

Stellar mass black holes form when the core of a sufficiently massive star runs out of nuclear fuel and is unable to withstand the weight of the surrounding gas, even at nuclear density [3]. The ensuing gravitational collapse is accompanied by a supernova, which can outshine the host galaxy for a few months. Many of these collapses appear to produce powerful, relativistic jets, analogous to those found in active galactic nuclei. The jets are so strong that, remarkably, they are able to punch two channels through the infalling stellar gas and expand into the interstellar medium with ultrarelativistic speed. These jets are associated with the



▼ **FIG. 1:** Observed stellar orbits around the four million solar mass black hole in the nucleus of our galaxy.



▸ FIG. 2: Observations of the jets associated with the nearby galaxy M87 on scales ranging from three hundred million light years to a three hundred times the radius of the Earth's orbit around the sun [2]. The leftmost image shows the bubbles being blown into the gas around the galaxy; the rightmost image shows synchrotron radio emission from electrons in orbit around the six millon solar mass black hole.

most common type of *Gamma Ray Bursts* which are now seen at a rate of roughly one per day and typically last a few seconds. They were first discovered in the 1960s by satellites monitoring nuclear weapons.

A second type of Gamma Ray Burst has a shorter duration and is associated with the merger of two orbiting neutron stars to form a spinning black hole of roughly three solar masses. These mergers are due to the emission of gravitational radiation, that has been measured directly by the LIGO and Virgo *gravitational wave observatories*. These mergers also seem able to produce collimated relativistic jets as well. So, it appears that Gamma Ray Bursts are the "birth cries" of stellar mass black holes.

Most observed, gravitational wave signals, to date, are associated with the merger of black holes with masses in the ten to hundred solar mass range. The computation of the associated gravitational wave signals is a *tour de force* of numerical relativity and so far everything is compatible with the field equations, an impressive affirmation of general relativity in the strong gravity regime.

Similar collapses and mergers must occur with massive black holes. It is probably the case that the initial collapses make relatively low mass black holes. These then grow, up to masses that can exceed ten billion solar masses, radiating relatively efficiently, so as to account for the bright quasars. There ought to be occasional mergers of massive black holes following the mergers of the host galaxies.

New Horizons

The classical, general relativity theory of single and merging black holes is essentially complete and well-verified [6]. It provides a stage on which magnificent, high energy dramas can be watched by observational astronomers and simulated by astrophysicists.

However, the invisible kinematics of the collapse within the horizon and the extremely restrictive conditions, under which a wormhole might form, or a "naked" singularity may be viewed, still attract attention. Even more interest attends the interface with quantum mechanics - Hawking radiation, firewalls and string theory. However, none of this has been observed as yet.

Future observations hold great promise. The Event Horizon Telescope will study more sources with finer resolution informing more sophisticated simulations and may one day be deployed in space. LIGO-Virgo will continue to elaborate and inform the principles of advanced stellar evolution, including the provenance of the black hole binaries sources, and further test general relativity. The search for gravitational waves from massive black hole binaries, using accurate timing of radio pulsars, is on the threshold of discovering a background or establishing important upper limits. James Webb Space Telescope should flesh out the narrative history of galaxies and their active nuclei. However, most of all, this is a young and growing research field and one where great discoveries can still happen. ■

About the author

A native of England, **Roger Blandford** is a professor in the Physics Dept. at Stanford University and at the SLAC National Accelerator Laboratory. He has a long interest in the mechanisms through which black holes power some of the most luminous sources in the cosmos. He has also worked on neutron stars, cosmic ray physics, cosmology and gravitational lenses. Recently, he co-authored the graduate physics textbook "Modern Classical Physics" with Kip Thorne.

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