Chapter 2
Black Hole Observations—Towards the Event Horizon

Silke Britzen

Abstract Black Holes are probably the most elusive solutions of Einstein's theory of General Relativity. Despite numerous observations of the direct galactic environment and indirect influence of astrophysical black holes (e.g. jets, variable emission across the wavelength spectrum, feedback processes, etc.)—a direct proof of their existence is still lacking. This article highlights some aspects deduced from many observations and concentrates on the experimental results with regard to black holes with masses from millions to billions of solar masses. The focus will be on the challenges and remaining questions. The Event Horizon Telescopce (EHT) project to image the photon sphere of Sgr A* and its potential is briefly sketched. This instrumental approach shall lead to highest resolution observations of the supermassive black hole at the center of the Milky Way (Sgr A*).

2.1 Active Galactic Nuclei (AGN)

Black Holes (hereafter BH) as physical objects play an important role in many astrophysical environments and processes (e.g. [13]). Whether as the endproduct and final stages of massive stars or as the central machines at the cores of actively radiating galaxies as Active Galactic Nuclei (AGN). Many questions related to AGN are still open. Assuming that the standard big bang scenario describes correctly the early phases of the Universe (for alternative models see e.g. [57]), then the first question to ask is: How could the earliest supermassive BHs (with masses in excess of 10^9 $M_\odot$), observed as luminous AGN at redshifts $z > 6$, be already in place when the Universe was less than a billion years old (e.g. [19, 20, 43, 58, 59])? How were supermassive BHs formed in the early phases of the Universe? Some of the competing theories suggest they formed as the remnants of the first generation of Pop III stars (e.g. [30, 42]) or through the 'direct collapse' of atomic-cooling gas (e.g. [4, 11]). Did the BHs grow through mergers of their host galaxies with other galaxies (e.g. [52])? Is accretion the more important process as some investigations (e.g. [1])

S. Britzen (✉)
Max-Planck-Institut für Radioastronomie, Auf dem Huegel 69, 53121 Bonn, Germany
e-mail: sbritzen@mpifr.de

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suggest? Are collisions the major and common cause of growth and activity? Major mergers of galaxies are suspected to be associated with quasar activity (e.g. [2, 3, 38, 50]). Is activity a phase in the life of a BH and how is this activity triggered? Observations at lower redshifts ($z \leq 1.5$) show that only a small fraction of supermassive BHs are undergoing quasar (the most luminous type of AGN) episodes, which are estimated to last for 1–100 Myr (e.g. [31, 55]). This would argue against the expectation of uninterruped accretion. How many life cycles will an average AGN undergo and how can this be tested? A most influential result was the discovery of a tight correlation between BH mass and the velocity dispersion of the bulge component of the host galaxy (e.g. [21, 24]). This and similar correlations lead to the assumption of a coevolution of black holes and galactic bulges. However, recent investigations showed, that supermassive BHs correlate differently with different galaxy components (e.g. [39]) and the details remain to be studied. AGN interact with their astrophysical environment in a variety of ways and can induce feedback processes, which in turn may influence the evolution of AGN themselves or members of galaxy clusters within which they lie. Clusters of galaxies constitute an excellent laboratory for the study of the feedback between the accretion and star formation processes. It is still unclear whether the AGN activity can account for the energy budget in clusters of galaxies and the Intracluster medium.

2.2 Jets

Zooming in on the central BH: Our knowledge regarding supermassive Black Holes has to be deduced from what is observable and can be extrapolated into the unobservable regime. AGN produce up to 5 % of the energy content of the Universe. The energy output can be more easily measured and observed compared to the feeding process (e.g. [7]). It seems extremely difficult to decipher the details of the accretion process. A careful monitoring of the complex details of feedback processes on all observable scales around the central object seems to be required (in the case of Cen A: e.g. [36]; NUGA-NUclei of GAlaxies—sample: e.g. [29]). Direct imaging of the accretion disk is beyond the current observational capabilities. Though, by help of gravitational lensing, a size measurement and spectral data of an AGN accretion disk could be obtained with HST-measurements [44].

The most obvious and probably best studied observational signatures of supermassive Black Holes are their jets (e.g. [33]), which seem to be a natural consequence of accretion disks with magnetic fields under certain conditions (e.g. [41]). These plasma-streams extend from the most central region of a galxy much beyond the optically visible galaxy into intergalactic space. While the jets are observable from large scales down to micro-arcsecond scales, the jet base as well as the jet-launching mechanisms are still not amenable to observations and have to be inferred indirectly [7]. Several theoretical jet launching scenarios have been proposed. The most prominent and often discussed are the Blandford and Znajek [5] and the Blandford and Payne [6] mechanism. The former model describes jet production via electromagnetic extraction of energy from Kerr BHs. The latter model explores the possibility that angular momentum could be removed magnetically from an accretion disk by field lines that leave the disk surface, and could eventually be carried off in a jet moving perpendicular to the disk. Acceleration and collimation of jets, the jet composition, the dominant dissipation and radiation processes remain to be studied and clarified (e.g. [49]). AGN jets have been studied in great detail in many Very Long Baseline Interferometry (VLBI) radio observations for several decades. The observational work has been accompanied by theoretical modelling and simulations (e.g. [32, 51]). Jets, although observed with all available radio telescope arrays at all available frequencies in the last decades remain enigmatic (e.g. [8, 28]). Many questions are related to the jet "components" which reveal apparent superluminal motions. Are these features shocks or instabilities in the plasma flow or do both phenomena co-exist in one jet? Helicity and geometrical effects seem to play a more important role than previously thought and can be used to explain the observed patterns [10]. These findings quite naturally lead to a questioning of the standard paradigm inevitably causally connecting broad-band flaring and jet component ejection (e.g. [9]).

2.2.1 Supermassive Binary Black Holes

The collision of galaxies and subsequent merging of the black holes at the centres of these galaxies is most likely one of the two relevant processes in the growth of the supermassive black hole mass and in the evolution of its spin. Theoretical and computational studies of the evolution of merging binaries taking into account conservative dynamics (post-Newtonian relativistic and finite size couplings, like spinorbit, spinspin, mass quadrupole mass monopole) or dissipative elements (gravitational radiation, dynamical friction and interaction with accretion disks) are of importance (e.g. [12]). Of equal importance is the observational evidence for supermassiv binary BHs through high-resolution radio imaging and optical spectroscopy as well as modelling of periodicities observed in total flux density and structural variations (e.g. [40, 48]).

2.2.2 Broadband—Flaring

AGN reveal variability over the entire electromagnetic spectrum on different timescales. Assuming that variable emission carries information about the structure and energy changes which occur at the centre of the AGN, non-imaging techniques (such as time series analysis) can be helpful in studying variable emission. Blazars—those AGN that are most likely viewed under a small viewing angle, pointing their jet directly at the observer—are known for significant and rapid variability at all wavelengths observed. Luminosities can appear to be (quasi)-periodic and might reveal important insight into the physics of the BH-system. As an example, [56] reconfirm based on a detailed analysis of the periodicities in 1156+295 that global p-mode oscillations of the accretion disc are coupled to the jet. They suspect that the osciallation of the disc is driven by Kelvin-Helmholtz instabilites in the inner edge of the accretion disc. High energy emission can probe the inner region around the BH. In particular, the Fermi Gamma-ray space telescope currently detects and observes many AGN producing so far unprecedented lightcurves in these wavelength regimes (e.g. [47]). However, it remains unclear where the ultra-relativistic particles are produced either close to the core or far outside (e.g. [14, 37]).

2.3 The Galactic Center Black Hole Sgr A*

The closest supermassive BH is the source Sgr A* at the centre of the Milky Way with a mass of about 4 million solar masses inferred from stellar orbits (e.g. [17, 25]). Whether this close-by supermassive BH can serve as prototype for the more active but also more distant AGN is so far unclear. Ideally, Sgr A* could be studied as a less active and lightweight version of the typical BH in AGN. Sgr A* is the most promising candidate and best case for a direct "image-proof" of the photon sphere around the dark object, which may be detectable by mm- and/or submm-VLBI. Imaging of the shadow of the BH might probe directly the existence of BHs (e.g. [15, 18]). It is a technically challenging project and still requires more time and improvement in resolution (e.g. [15]). 1-mm observations suggest that there might be structure on sizes below the size of the event horizon [22]. It is not yet clear, whether this indicates the need for an event horizon dependent on BH rotation (BH spin), hot spots orbiting in the accretion disk, or relativistic distortions of the inner accretion disk near the last stable orbit. Future (sub-) mm interferometric observations with about 10 micro-arcseconds angular resolution corresponding to a spatial scale of about the size of the BH in the Galactic Centre (1 Schwarzschild radius) are required to solve this question. The comparison of the shape and spectrum of the emission around the BH with BH-simulations will provide information on the observable GR effects and MHD physics in the accretion disk. Sgr A* displays extremely rapidly variable outbursts a few times a day in the Near-infrared and X-rays (e.g. [35, 53, 60]). These flares probe regions in the accretion flow as compact as or even smaller than the Schwarzschild radius. The interpretation of this flaring and the question whether this is periodic or not bears potential for a better understanding of the accretion process. Ever larger numbers of young, massive stars are being found throughout the Nuclear star cluster around Sgr A (e.g. [25]). Another challenge is to understand how star formation in this region works and whether the existing evidence for an initial stellar mass function different from the rest of the Galaxy will be confirmed. Further questions related to Sgr A* deal with the amount of the current gas inflow rate into the central parsec around the BH and whether or not a detectable collimated outflow from Sgr A* exists. Several scientific teams aim at proving the strength of gravity closer and closer to the assumed event horizon. Up-coming large observation facilities—

interferometric beam combiners at the VLTI (GRAVITY, e.g. [27]), instrumentation for the E-ELT (METIS), and mm/submm-VLBI (Event Horizon Telescope, e.g. [15]) will play an important role in probing the inner regions or providing the first direct evidence of a BH.

2.3.1 Event Horizon or Apparent Horizon

The observational evidence in favor of an event horizon of Sgr A* seems compelling [45]. However, recent publications (e.g. [54]) discuss the point that event horizons are (generically) not physically observable. In contrast, apparent horizons (and the closely related trapping horizons) seem to be generically physically observable—in the sense that they can be detected by observers working in finite-size regions of spacetime. Event horizons thus seem inappropriate tools for defining astrophysical black holes, or indeed for defining any notion of evolving black hole, (evolving either due to accretion or Hawking radiation). According to [54] the only situation in which an event horizon becomes physically observable is for the very highly idealized stationary or static black holes. This topic was recently discussed by [34] by claiming that a gravitational collapse produces apparent horizons but no event horizons behind which information is lost. Most important will be to test theoretical predictions with regard to the physics of BH versus the observationl results. In particular it will be as important as challengig to search for possible quantum effects of the BH (e.g. [16, 26]).

Despite the relevance of BHs in the astrophysical context, the most important questions related to their pure existence or proof of existence and their physics are still open. With technological progress, several scientific teams aim at proving the strength of gravity closer and closer to the assumed event horizon. Many questions with regard to BHs are still open. Yet they all touch important scientific questions.

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