SUPERMASSIVE BLACK HOLES

Written by an international leader in the field, this is a coherent and accessible account of the concepts that are now vital for understanding cutting-edge work on supermassive black holes. These include accretion disc misalignment, disc breaking and tearing, chaotic accretion, the merging of binary supermassive holes, the demographics of supermassive black holes, and the defining effects of feedback on their host galaxies. The treatment is largely analytic and gives in-depth discussions of the underlying physics, including gas dynamics, ideal and non-ideal magnetohydrodynamics, force-free electrodynamics, accretion disc physics, and the properties of the Kerr metric. It stresses aspects where conventional assumptions may be inappropriate and encourages the reader to think critically about current models. This volume will be useful for graduate or master's courses in astrophysics, and as a handbook for active researchers in the field. eBook formats include colour figures while print formats are greyscale only.

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Faced with the choice between changing one's
mind and proving there is no need to do so,
almost everyone gets busy on the proof.

J. K. Galbraith

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Preface

More than a century after Einstein formulated general relativity (GR), black holes are firmly established as one of its most striking and inescapable consequences. The perceived complexity of the theory meant that this realization itself arrived only after half a century and several missed opportunities. But the mathematics leaves no room for doubt – GR describes all non-quantum properties of black holes in the form of the Kerr (1963) family of exact solutions. General relativity itself has survived unscathed a very large number of observational tests with exquisite precision, notably involving stellar-mass pulsar binary systems, the detailed orbital dynamics of stars orbiting the black hole at the Galactic Centre, and LIGO–Virgo observations of gravitational waves from black hole mergers.

A vast body of observations now shows that black holes are not simply a theoretical possibility, but have central importance in the real Universe. Gas infall – accretion – on to a black hole is the most efficient way of getting energy from ordinary matter. Only matter–antimatter annihilation is more efficient, but probably impossible to realize on scales larger than subnuclear. It follows that black hole accretion must power the most luminous astrophysical sources at every mass scale. The discovery of the huge intrinsic luminosities of quasars led Salpeter (1964) and Zeldovich (1964) to suggest independently that they contained supermassive black holes (SMBH) with masses $\gtrsim 10^8 M_\odot$, accreting at suitably high rates from some unknown source. The idea that accretion on to the hole took place through a gas disc, allowing mass and angular momentum to diffuse in opposite directions, quickly followed (Lynden-Bell, 1969), as well as the suggestion that the hole might in some way channel energy outwards in collimated jets (Rees, 1971). These ideas remain the paradigm for understanding active galactic nuclei (AGN).

Not long afterwards, astronomers realized that a scaled-down version of the same process, with black holes of stellar masses, was a likely driver of some stellar-mass X-ray binary systems. Here the source of the accreting matter was easier to understand in terms of mass transfer from a companion star, driven by stellar evolutionary expansion or systemic loss of orbital angular momentum, or capture of some of the companion's stellar wind. This picture related accretion in these systems closely to their stellar evolution, and together with their conveniently observable timescales explains why most progress in understanding accretion has until recently come largely from studying accreting stellar-mass binaries. The three editions of the book *Accretion Power in Astrophysics* (Frank, King & Raine, 1985, 1992, 2002) (denoted as APIA1, APIA2, APIA3 – collectively APIA – in this book) illustrate this clearly. The wealth of data on stellar-mass systems has driven continued theoretical progress in areas such as accretion disc stability, although the need for a directly applicable first-principles treatment of the fundamental mechanism transporting angular momentum outwards in accretion discs remains. Theory has otherwise progressed relatively steadily, with probably only one major surprise (ultraluminous X-ray sources – see Section 6.3 of this book) since APIA3 in 2002. In contrast, although the idea of SMBH accretion remains unchallenged, and indeed strengthened by recent discoveries, progress in understanding it was until recently slower, because of the far longer timescales needed for meaningful observations, and the continuing difficulty in understanding how galaxies supply large amounts of mass to the SMBH.

The major change came with the discovery of scaling relations between SMBH and their host galaxies, particularly the M–σ relation (Ferrarese & Merritt, 2000; Gebhardt et al., 2000). The idea that some of the SMBH's huge binding energy is communicated to its host galaxy through feedback from accretion implies a set of constraints as tight as those relating stellar evolution and accretion in X-ray binaries. These insights have already largely overthrown the older view that SMBH disc accretion is essentially a scaled-up version of the same process in close binaries.

We can now see that these two accretion regimes differ in very significant ways. In stellar-mass binary systems the binary orbit generally defines a stable plane for at least the outer accretion disc, mass supply to the disc is often effectively steady on timescales of interest, and the disc mass is almost always low enough that self-gravity is negligible.

It is likely that none of these restrictions hold for SMBH accretion. Mass is supplied sporadically, so the disc is effectively always globally time-dependent, probably undergoing repeated episodes of evolution from fixed initial masses rather than transmitting a constant supply of mass from outside. Each feeding event like this probably has completely random orientation compared with earlier ones, and in most cases the outer parts of the disc spread to take up the angular momentum lost by the inner parts, and so eventually reach the self-gravity radius. These features have the surprising consequence that in some ways understanding aspects of SMBH accretion physics may have more in common with following the evolution of discs around protostars than those in close stellar-mass binaries. One can add more complexities – where binary stellar evolution offers a stable framework for understanding close binaries, for SMBH we have to connect with the far more uncertain details of how galaxies form and evolve at high redshift. But despite the lack of a full understanding of angular momentum transport in accretion discs, there have been significant advances in understanding at both stellar-mass and supermassive scales.

The scaling relations show that supermassive black hole growth is organically connected with galaxy evolution, and so ultimately with how the contents of the Universe as a whole came to be as we observe them. The aim of this book is to introduce the main ideas at play in current SMBH research. Some of these, such as the basics of disc accretion, are already widely known from the close binary context (e.g. in APIA), and I have tried to highlight how things differ in the SMBH context.

The plan of the book is straightforward. After a general introduction (Chapter 1), I detail some of the basic physics needed, starting with the description of black holes in GR (Chapter 2), and astrophysical gas dynamics, magnetohydrodynamics (MHD), and force-free electrodynamics (FFE) (Chapter 3). The next two chapters discuss accretion on to SMBH, gradually moving outwards from disc accretion (Chapter 4), followed by Chapter 5 on what we know of how the SMBH environment feeds gas into these discs. Chapters 6 and 7 discuss how SMBH have definitive effects on their host galaxies, and Chapter 8 outlines some ideas of how the demographics of SMBH in the Universe may have come about.

The treatments of GR and MHD/FFE are perhaps more detailed than usual in books of this kind, but for good reasons. The classical (non-quantum) aspects of black hole physics were all largely established in a golden decade, roughly from the mid-1960s to the mid-1970s. Since then, frontier GR research has largely moved on to less directly applicable areas, and in parallel, university courses on advanced classical GR at a level suitable for astrophysical applications have become rarer in many institutions. Some important insights from GR are now not always fully appreciated, for example that coordinates in general have no physical meaning, so that approximations and expansions are of doubtful value unless proved otherwise; that properties such as the existence of event horizons are global, and do not require extreme local physics; and that numerical treatments can have the unwanted side effect of subverting light-travel arguments even when applied to properly GR-invariant equations. Because almost all the GR literature uses geometrized units, it is often not appreciated just how weak gravity is in comparison to all other forces, particularly electromagnetism. This means, for example, that black holes can in principle (like stars) have electric charge that is completely negligible in terms of the spacetime metric, but nevertheless has significant effects on the motions of charged particles near them.

Magnetohydrodynamic treatments are now strongly prevalent in theoretical SMBH research. Although MHD is a largely classical theory, the peculiarly powerful – and therefore restrictive – nature of the ideal MHD approximation is often underestimated. In particular, by assuming complete charge neutrality everywhere, it effectively removes currents and charges from the physics, relegating them to the status of balancing items in equations. As a result, thinking about currents is often positively counterproductive in ideal MHD. Further, numerical treatments inevitably introduce spurious non-ideal MHD terms. This has long been recognized as a significant barrier to theoretical progress in the solar physics and MHD literature. But because astrophysics rarely has practical consequences, errors and misconceptions in theoretical treatments can survive for a long time.

Astrophysics is a dynamical and developing field, and observations of astrophysical phenomena often initially appear to defy current theoretical understanding. Many results like this have been important in deepening understanding of fundamental parts of the subject, but there are others whose significance is unclear. In the SMBH context a good example is the mass of results on the optical and UV emission line properties of AGN. For stellar-mass binaries a similar status applies to the large body of observations showing that their orbital periods can change over time far more rapidly (and often in the opposite direction!) compared with expectations from stellar evolutionary processes. In both cases it is not obvious that understanding the problem would really constrain the fundamental picture of the system. Although AGN emission lines are important in allowing estimates of SMBH masses and lengthscales, particularly through reverberation mapping, these lines do not carry a large fraction of the total luminosity of accreting SMBH, and their interpretation as a physical diagnostic is complex and indirect. Similarly, observed orbital period changes in stellar-mass binaries are often dominated by short-term effects that drown out the far slower systematic trends resulting from binary evolution.

The attitude I take in this book is to discuss in depth only phenomena where there is a promising route for physical understanding, or better still, a real observational challenge in detail to what might otherwise seem a temptingly reasonable theoretical picture.[1] I have not tried to aim at completeness, but rather to stimulate readers to think about the subject. As well as APIA, I refer to the book *Astrophysical Flows* (Pringle & King, 2007) (denoted as AF) for some fluid-dynamical results.

Most astrophysical publications use the cgs (centimetre, gram, second) system of units, and I have followed this practice. For electromagnetic quantities the equations differ in form between the cgs and SI (mks, i.e. metre, kilogram, second) systems. I have followed the convention of APIA that equations are given in the

[1] I recall once at a meeting remarking rather unnecessarily that science progresses by trial and error, and getting the tart response that I must have been making a lot of progress recently.

cgs system, but with multiplicative factors in square brackets giving the conversion to SI units (so a cgs reader should mentally set these square-bracket quantities to unity). These factors always involve the quantities ϵ_0, μ_0, or c, and there should be no confusion with other uses of square brackets in algebraic formulae.

I have added some problems at the end of the book. Some of these refer to published papers, and many of them are aimed at encouraging the reader to see for themselves what is involved in various topics, sometimes asking them to derive results given without proof in the relevant chapter. I have made no attempt to devise problem sets of equal difficulty.

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Some of the material of this book formed the basis of a master's-level lecture course I taught at the University of Leicester for several years. I thank the students of that course for their patience, and for their many questions. These materially helped in removing obscurities in the presentation. I apologize in advance for those that remain.

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