Preface

Since the 1960s, when the connection between quasar energetics and supermassive black holes was first established, galactic nuclei have remained objects of intense interest to astrophysicists. Nowadays, the community of scientists with an interest in galactic nuclei is enormous: not just the astronomers who study so-called active galaxies, but also the relativists who hope to detect gravitational waves, cosmologists concerned with the role of feedback in structure formation, and particle physicists searching for radiation produced by the annihilation of dark matter particles clustered around supermassive black holes. This book is intended as a basic resource for all of these researchers, and for graduate students who are planning to work in a field that is related, directly or indirectly, to galactic nuclei.

Supermassive black holes are sometimes accompanied by gas, but as near as we can tell, they are always associated with stars: the stars of the galactic nuclei in which they sit. Furthermore, this association appears to be more than a casual one since there are strong correlations between black-hole mass and the large-scale properties—mass, velocity dispersion, central concentration—of the host stellar systems. Correlations on smaller scales exist as well; for instance, with the so-called "mass deficits" observed at the centers of bright galaxies. While the origin of these correlations is still debated, they suggest a deep connection between supermassive black holes and the stellar components of galaxies.

Partly for this reason, the emphasis in this book is on dynamical interactions involving stars: either interactions of (single or binary) stars with (single or binary) supermassive black holes, or interactions of stars with each other in the vicinity of supermassive black holes. Gas dynamics is covered in a much less comprehensive way, and only in contexts where its role appears essential: in the late evolution of binary supermassive black holes (chapter 8), or in theories that attempt to explain the tight empirical correlations by invoking radiative feedback (chapter 2). The reader who needs to know more about nuclear gas dynamics, or emission mechanisms related to black holes, is directed toward the "Suggestions for Further Reading" at the end of this book.

On the other hand, the treatment here of stellar dynamics is as complete and as self-contained as I could make it in a book of prescribed length. Chapter 3, on collisionless models of nuclei, may be slightly more terse than the other chapters, but this is due to the availability of *Galactic Dynamics*, the comprehensive (if largely black-hole-free) text by J. Binney and S. Tremaine. Likewise, some parts of chapters 5 and 7 overlap with L. Spitzer's superbly succinct, and sadly out-of-print, *Dynamical Evolution of Globular Clusters*. But chapters 6 (Loss-cone dynamics), 7 (Collisional evolution of nuclei), and 8 (Binary and multiple supermassive black

holes) deal with topics that appear not to have been treated in any detail in textbooks before now.

From a dynamical point of view, galactic nuclei occupy an interesting middle ground. They are denser than the other parts of the galaxies in which they sit; but not so dense that they are likely to be "collisionally relaxed," in the way that most globular clusters appear to be. That is, gravitational encounters between the stars in most galactic nuclei do not appear to be frequent enough to have established a statistically "most likely" distribution around the supermassive black hole—even in nuclei as dense as that of the Milky Way. One consequence is that we probably cannot trust intuition derived from the relaxed models to predict the distribution of stars on subparsec scales around supermassive black holes. This is a relatively new insight, and one that is still resisted in some circles, perhaps because it complicates the calculation of event rates. On the other hand, the much larger variety of steady states associated with "collisionless" nuclei implies more freedom for the theorist to construct models—a positive development, at least in the author's eyes. The collisionless nature of galactic nuclei is a recurring theme in this book. If I sometimes seem to press the point a little too strongly, it is with the good intention of motivating others to think carefully about this important question.

It would be natural in a book like this to devote a separate chapter to the Galactic center—the nucleus of our own galaxy, the Milky Way. Instead, the decision was made to spread the discussion of the Galactic center among several chapters, using the data and theoretical models to illustrate concepts as they arise. So, for instance, the use of stellar kinematics to infer gravitational potentials is illustrated in chapter 3 via proper motion studies of stars in the inner parsec of the Milky Way; the "clockwise disk" at the Galactic center is introduced in chapter 5 in the context of spin-orbit torques; the interaction of binary stars with supermassive black holes is presented in chapter 6 together with a discussion of the Milky Way data that seem to verify such interactions. The reader who is interested in specific topics related to the Galactic center is directed to the index.

The author has always felt that there are two, equally important sorts of textbook: those that are intended as reference works, to be dipped into as needed, and those that are meant to be read from cover to cover. This book belongs to the second category. What it lacks in comprehensiveness, it hopefully makes up for in quality of exposition. There are no appendices, or problems for the reader to work out; all the material that is deemed important is included in the main body of the text, and derivations are presented from first principles whenever feasible. Readers who wish to get a quick feeling for the topics covered are invited to begin by reading chapters 1 and 2 and the introductory sections of chapters 3–8.

Finally, the acknowledgments. Much of what I know about galactic nuclei and black holes is owed to conversations over the years with colleagues in Rochester who are knowledgable about such things: D. Axon, S. Baum, J. Faber, D. Figer, P. Kharb, R. Mittal, B. Mundim, H. Nakano, C. O'Dea, and A. Robinson. My understanding of post-Newtonian dynamics has benefited enormously from my collaborations with C. Will. Some sections of this book are based in part on review articles that I wrote with various collaborators: chapter 1 is a revised and extended version of an article on supermassive black holes written with L. Ferrarese and

published in *Physics World* (vol. 15N6, pp. 41–46, June 2002); section 3.1.1 is based on a review of torus construction written with M. Valluri (*Astronomical Society of the Pacific Conference Series*, vol. 182, pp. 178–190); section 8.4.5, on interactions of binary black holes with gas, is adapted from material in a review article with M. Milosavljevic in *Living Reviews in Relativity* (vol. 8, no. 8, 2005). M. Milosavljevic, E. Vasiliev, and C. Will kindly gave their permissions to reproduce unpublished calculations in sections 6.1.2, 4.4.2.2, and 4.6, respectively. T. Alexander, H. Cohn, M. Colpi, A. Graham, M. Kesden, A. King, A. Marconi, H. Perets, and E. Vasiliev were kind enough to read substantial parts of the manuscript and to make detailed suggestions for improvements. A draft version of the manuscript was used as the basis for a course on galactic nuclei taught at the Rochester Institute of Technology in the winter of 2011–2012. I thank the students in that course, M. Freeman, D. Lena, P. Peiris, I. Ruchlin, C. Trombley, and S. Vaddi, for checking many of the derivations and identifying typos. I thank S. Vaddi also for her assistance in making many of the figures. Parts of this book were written during a sabbatical semester that was taken at various places, including Leiden University, and the Weizmann Institute; I thank, respectively, Simon Portegies Zwart and Tal Alexander for hosting me during these visits. Last but far from least, I thank my wife for putting up with me during the hectic year in which this book was written.

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