GRAVITATIONAL LENSING

Gravitational lensing is a consequence of general relativity, where the gravitational force due to a massive object bends the paths of light originating from distant objects lying behind it. Using very little general relativity and no higher level mathematics, this text presents the basics of gravitational lensing, focusing on the equations needed to understand the phenomenon. It then applies them to a diverse set of topics, including multiply imaged objects, time delays, extrasolar planets, microlensing, cluster masses, galaxy shape measurements, cosmic shear, and lensing of the cosmic microwave background. This approach allows undergraduate students and others to get quickly up to speed on the basics and the important issues. The text will be especially relevant as large surveys such as LSST and Euclid begin to dominate the astronomical landscape. Designed for a one-semester course, it is accessible to anyone with two years of undergraduate physics background.

SCOTT DODELSON is a Distinguished Scientist at Fermilab and Professor in the Department of Astrophysics and Astronomy at the University of Chicago. He has written more than 180 research papers on the connections between physics and astronomy. He is the author of *Modern Cosmology,* a standard graduate textbook, and he has recently taken leadership roles in surveys that employ gravitational lensing as a tool to get at basic physics. Through these roles and by teaching courses devoted to lensing, he realized that learning enough about lensing to begin research is both simple and rewarding. This volume was written to help potential researchers at all levels learn this fascinating, rapidly emerging field.

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This book is dedicated to the memory of Danielle Bessler,
who saw life through her own lens, thereby bringing joy to
her family and friends

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Preface

There are three reasons why I wanted to write this book. First, gravitational lensing is emerging as a powerful tool in many areas of astronomy, from exoplanets to cosmology. This breadth of applications emerging from a single phenomenon – the bending of light by curved space-time – is the second reason, for it is yet another example of why physics is so interesting: we can explain many things with a few simple laws.

The final reason for this book is that, while important for many different applications, lensing is not that hard. There have been elegant, beautiful papers and books exploring the foundations of lensing and many of its formal aspects. But most of the applications simply do not require all that much formalism. General relativity makes several appearances here, but even if you skip those few sections, you will still learn essentially everything that's here: multiple images, magnification, micro-lensing, shear, etc. And armed with that information, I hope you will be able to begin research on real problems that are opening up in so many areas of astronomy and be prepared to analyze the ever-improving datasets that are coming our way.

The goal then is that this book can serve as the text for an undergraduate or graduate course on gravitational lensing or be used for independent study by someone interested in jumping into research.

Thanks are due to colleagues who generously gave of their time to answer questions: Gary Bernstein, Daniel Fabrycky, Bhuvnesh Jain, Rachel Mandelbaum, and Ben Wandelt. I am very grateful to the students who took this course, especially in 2015, as they helped immensely by providing feedback on an early draft of this book. So thank you to these rising stars: Adam Anderson, Gourav Khullar, Meng-Xiang Lin, Monica Mocanu, Pavel Motloch, Andrew Neil, Zhaodi Pan, Jason Poh, Amy Tang, Rito Thakur, and Alexander Tolish.

I am extraordinarily grateful to the people who fund my research, especially Fermilab, the Office of High Energy Physics at the Department of Energy and, by extension, the citizens of the United States. I am so fortunate to live in a society that values basic research. Some of this work was carried out at the Aspen Center for Physics, which is supported by National Science Foundation grant PHY-1066293.