THE SCIENCE OF INTERSTELLAR

SPOILER ALERT:
This e-book explains the fantastic climax and ending of *Interstellar*

KIP THORNE

FOREWORD BY CHRISTOPHER NOLAN

THE SCIENCE OF INTERSTELLAR

KIP THORNE

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FOREWORD

One of the great pleasures of working on *Interstellar* has been getting to know Kip Thorne. His infectious enthusiasm for science was obvious from our first conversation, as was his reluctance to proffer half-formed opinions. His approach to all the narrative challenges that I threw him was always calm, measured and above all, *scientific*. In trying to keep me on the path of plausibility, he never showed impatience with my unwillingness to accept things on trust (although my two-week challenge to his faster-than-light prohibition might have elicited a gentle sigh).

He saw his role not as science police, but as narrative collaborator—scouring scientific journals and academic papers for solutions to corners I'd written myself into. Kip has taught me the defining characteristic of science—its humility in the face of nature's surprises. This attitude allowed him to enjoy the possibilities that speculative fiction presented for attacking paradox and unknowability from a different angle—storytelling. This book is ample demonstration of Kip's lively imagination and his relentless drive to make science accessible to those of us not possessed of his massive intellect or his immense body of knowledge. He wants people to understand and get excited about the crazy truths of our universe. This book is structured to let the reader dip in to a topic as deeply as their affinity for science prompts them—no one is left behind, and everyone gets to experience some of the fun I had trying to keep up with Kip's agile mind.

Christopher Nolan
Los Angeles, California
July 29, 2014

PREFACE

I've had a half-century-long career as a scientist. It's been joyously fun (most of the time), and has given me a powerful perspective on our world and the universe.

As a child and later as a teenager, I was motivated to become a scientist by reading science fiction by Isaac Asimov, Robert Heinlein, and others, and popular science books by Asimov and the physicist George Gamow. To them I owe so much. I've long wanted to repay that debt by passing their message on to the next generation; by enticing youths and adults alike into the world of science, real science; by explaining to nonscientists how science works, and what great power it brings to us as individuals, to our civilization, and to the human race.

Christopher Nolan's film *Interstellar* is an ideal messenger for that. I had the great luck (and it *was* luck) to be involved with *Interstellar* from its inception. I helped Nolan and others weave real science into the film's fabric.

Much of *Interstellar*'s science is at or just beyond today's frontiers of human understanding. This adds to the film's mystique, and it gives me an opportunity to explain the differences between firm science, educated guesses, and speculation. It lets me describe how scientists take ideas that begin as speculation, and prove them wrong or transform them into educated guesses or firm science.

I do this in two ways: First, I *explain* what is known today about phenomena seen in the movie (black holes, wormholes, singularities, the fifth dimension, and the like), and I explain how we learned what we know, and how we hope to master the unknown. Second, I *interpret*, from a scientist's viewpoint, what we see in *Interstellar*, much as an art critic or ordinary viewer interprets a Picasso painting.

My interpretation is often a description of what I imagine might be going on behind the scenes:

the physics of the black hole Gargantua, its singularities, horizon, and visual appearance; how Gargantua's tidal gravity could generate 4000-foot water waves on Miller's planet; how the tesseract, an object with four space dimensions, could transport three-dimensional Cooper through the five-dimensional bulk; . . .

Sometimes my interpretation is an *extrapolation* of *Interstellar*'s story beyond what we see in the movie; for example, how Professor Brand, long before the movie began, might have discovered the wormhole, via gravitational waves that traveled from a neutron star near Gargantua through the wormhole to Earth.

These interpretations, of course, are my own. They are not endorsed by Christopher Nolan any more than an art critic's interpretations were endorsed by Pablo Picasso. They are my vehicle for describing some wonderful science.

Some segments of this book may be rough going. That's the nature of real science. It requires thought. Sometimes deep thought. But thinking can be rewarding. You can just skip the rough parts, or you can struggle to understand. If your struggle is fruitless, then that's my fault, not yours, and I apologize.

I hope that at least once you find yourself, in the dead of night, half asleep, puzzling over something I have written, as I puzzled at night over questions that Christopher Nolan asked me when he was perfecting his screenplay. And I especially hope that, at least once in the dead of night, as you puzzle, you experience a Eureka moment, as I often did with Nolan's questions.

I'm grateful to Christopher Nolan, Jonathan Nolan, Emma Thomas, Lynda Obst, and Steven Spielberg for welcoming me into Hollywood, and giving me this wonderful opportunity to fulfill my dream, to pass on to the next generation my message of the beauty, the fascination, and the power of science.

Kip Thorne
Pasadena, California
May 15, 2014

THE SCIENCE OF
INTERSTELLAR

1

A Scientist in Hollywood:

THE GENESIS OF *INTERSTELLAR*

Lynda Obst, My Hollywood Partner

The seed for *Interstellar* was a failed romance that warped into a creative friendship and partnership.

In September 1980, my friend Carl Sagan phoned me. He knew I was a single father, raising a teenaged daughter (or trying to do so; I wasn't very good at it), and living a Southern California single's life (I was only a bit better at that), while pursuing a theoretical physics career (at *that* I was a lot better).

Carl called to propose a blind date. A date with Lynda Obst to attend the world premier of Carl's forthcoming television series, *Cosmos*.

Lynda, a brilliant and beautiful counterculture-and-science editor for the *New York Times Magazine*, was recently transplanted to Los Angeles. She had been dragged there kicking and screaming by her husband, which contributed to their separation. Making the best of a seemingly bad situation, Lynda was trying to break into the movie business by formulating the concepts for a movie called *Flashdance.*

The *Cosmos* premier was a black-tie event at the Griffith Observatory. Klutz that I was, I wore a baby-blue tuxedo. Everybody who was anybody in Los Angeles was there. I was completely out of my element, and had a glorious time.

For the next two years, Lynda and I dated on and off. But the chemistry just wasn't right. Her intensity enthralled and exhausted me. I debated whether the exhaustion was worth the highs, but the choice wasn't mine. Perhaps it was my velour shirts and double-knit pants; I don't know. Lynda soon lost romantic interest in me, but something better was growing: a lasting and creative friendship and partnership between two very different people, from very different worlds.

Fast-forward to October 2005, another of our occasional one-on-one dinners, where conversation would range from recent cosmological discoveries, to left-wing politics, to great food, to the shifting sands of moviemaking. Lynda by now was among Hollywood's most accomplished and versatile producers (*Flashdance, The Fisher King, Contact, How to Lose a Guy in Ten Days*). I had married. My wife, Carolee Winstein, had become best friends with Lynda. And I'd not done badly in the world of physics.

Over dinner, Lynda described an idea she had conceived for a science-fiction movie and asked me to help her flesh it out. This would be her second venture into science fiction: a collaboration with me, modeled on her previous collaboration with Carl Sagan on the movie *Contact*.

I never imagined myself helping create a movie. I never coveted a presence in Hollywood, beyond a vicarious one, through Lynda's adventures. But working with Lynda appealed to me, and her ideas involved wormholes, an astrophysics concept I had pioneered. So she easily lured me into brainstorming with her.

During the next four months, over a few dinners and e-mails and phone calls, we formulated a rough vision for the film. It included wormholes, black holes, and gravitational waves, a universe with five dimensions, and human encounters with higher-dimensional creatures.

But most important to me was our vision for a blockbuster movie *grounded from the outset in real science*. Science at and just beyond the frontiers of human knowledge. A film in which the director, screenwriters, and producers respect the science, take inspiration from it, and weave it into the movie's fabric, thoroughly and compellingly. A film that gives the audience a taste of the wondrous things that the laws of physics can and might create in our universe, and the great things humans can achieve by mastering the physical laws. A film that inspires many in the audience to go learn about the science, and perhaps even pursue careers in science.

Nine years later, *Interstellar* is achieving all we envisioned. But the path from there to here has been a bit like the "Perils of Pauline," with many a spot where our dream could have collapsed. We acquired and then lost the legendary director Steven Spielberg. We acquired a superb young screenwriter, Jonathan Nolan, and then lost him twice, at crucial stages, for many months each. The movie sat in limbo, directorless, for two and a half years. Then, wondrously, it was resurrected and transformed in the hands of Jonathan's brother, Christopher Nolan, the greatest director of his young generation.

Steven Spielberg, the Initial Director

In February 2006, four months after we began brainstorming, Lynda had lunch with Todd Feldman, Spielberg's agent at the Creative Artists Agency, CAA. When Feldman asked what movies she was working on, she described her collaboration with me, and our vision for a sci-fi movie with real science woven in from the outset—our dream for *Interstellar*. Feldman got excited. He thought Spielberg might be interested and urged Lynda to send him a treatment *that very day!* (A "treatment" is a description of the story and characters, usually twenty pages or longer.)

All we had in writing were a few e-mail exchanges and notes from a few dinner conversations. So we worked at whirlwind speed for a couple of days to craft an eight-paged treatment we were proud of, and sent it off. A few days later Lynda e-mailed me: "Spielberg has read it and is very interested. We may need to have a little meeting with him. Game? XX Lynda."

Of course I was game! But a week later, before any meeting could be arranged, Lynda phoned: "Spielberg is signing on to direct our *Interstellar!*" Lynda was ecstatic. I was ecstatic. "This kind of thing never happens in Hollywood," she told me. "Never." But it did.

I then confessed to Lynda that I had seen only one Spielberg movie in my life—*ET*, of course. (As an adult, I had never been all that interested in movies.) So she gave me a homework assignment: Spielberg Movies Kip Must Watch.

A month later, on March 27, 2006, we had our first meeting with Spielberg—or Steven, as I began to call him. We met in a homey conference room in the heart of his movie production company Amblin, in Burbank.

At our meeting, I suggested to Steven and Lynda two guidelines for the science of *Interstellar*:

1. Nothing in the film will violate firmly established laws of physics, or our firmly established knowledge of the universe.
2. Speculations (often wild) about ill-understood physical laws and the universe will spring from real science, from ideas that at least some "respectable" scientists regard as possible.

Steven seemed to buy in, and then accepted Lynda's proposal to convene a group of scientists to brainstorm with us, an *Interstellar* Science Workshop.

The workshop was on June 2 at the California Institute of Technology (Caltech), in a conference room down the hall from my office.

It was an eight-hour, free-wheeling, intoxicating discussion among fourteen scientists (astrobiologists, planetary scientists, theoretical physicists, cosmologists, psychologists, and a space-policy expert) plus Lynda, Steven, and Steven's father Arnold, and me. We emerged, exhausted but exhilarated with a plethora of new ideas and objections to our old ideas. Stimuli for

Lynda and me, as we revised and expanded our treatment.

It took us six months due to our other commitments, but by January 2007 our treatment had grown to thirty-seven pages, plus sixteen pages about the science of *Interstellar*.

Jonathan Nolan, the Screenwriter

In parallel, Lynda and Steven were interviewing potential screenwriters. It was a long process that ultimately converged on Jonathan Nolan, a thirty-one-year-old who had coauthored (with his brother Christopher) just two screenplays, *The Prestige* and *The Dark Knight,* both big hits.

Jonathan, or Jonah as his friends call him, had little knowledge of science, but he was brilliant and curious and eager to learn. He spent many months devouring books about all the science relevant to *Interstellar* and asking probing questions. And he brought to our film big new ideas that Steven, Lynda, and I embraced.

Jonah was wonderful to work with. He and I brainstormed together many times about the science of *Interstellar*, usually over a two- or three-hour lunch at the Caltech faculty club, the Athenaeum. Jonah would come to lunch brimming with new ideas and questions. I would react on the spot: this is scientifically possible, that isn't, . . . My reactions were sometimes wrong. Jonah would press me: Why? What about . . . ? But I'm slow. I would go home and sleep on it. In the middle of the night, with my gut reactions suppressed, I would often find some way to make what he wanted to work, work. Or find an alternative that achieved the end he sought. I got good at creative thinking when half asleep.

The next morning, I would assemble the semicoherent notes I had written during the night, decipher them, and write Jonah an e-mail. He would respond by phone or e-mail or another lunch, and we would converge. In this way we came to gravitational anomalies, for example, and the challenge of harnessing them to lift humanity off Earth. And I discovered ways, just beyond the bounds of current knowledge, to make the anomalies scientifically possible.

At crucial times we brought Lynda into the mix. She was great at critiquing our ideas and would send us spinning off in new directions. In parallel with our brainstorming, she was working her magic to keep Paramount Pictures at bay so we could maintain our creative autonomy, and planning the next phases of turning *Interstellar* into a real movie.

By November 2007, Jonah, Lynda, Steven, and I had agreed on the structure for a radically revised story based on Lynda's and my original treatment, Jonah's big ideas, and the many other ideas that arose from our discussions—and Jonah was deep into writing. Then, on November 5, 2007, the Writers Guild of America called a strike. Jonah was forbidden to continue writing, and disappeared.

I panicked. Will all our hard work, all our dreams, be for naught? I asked Lynda. She counseled patience, but was clearly very upset. She vividly tells the story of the strike in scene 6 of her book *Sleepless in Hollywood*. The scene is titled “The Catastrophe.”

The strike lasted three months. On February 12, when it ended, Jonah returned to writing and to intense discussions with Lynda and me. Over the next sixteen months, he produced a long, detailed outline for the screenplay, and then three successive drafts of the screenplay itself. When each was finished, we met with Steven to discuss it. Steven would ask probing questions for an hour or more before proffering suggestions, requests, or instructions for changes. He was not very hands-on, but he was thoughtful, incisive, creative—and sometimes firm.

In June 2009, Jonah gave Steven draft 3 of the screenplay, and disappeared from the scene. He had long ago committed to write *The Dark Knight Rises*, and had been delaying for month after month while working on *Interstellar*. He could delay no more, and we were without a screenwriter. On top of that, Jonah’s father became gravely ill. Jonah spent many months in London by his father’s side, until his father’s death in December. Through this long hiatus, I feared that Steven would lose interest.

But Steven hung in there with us, awaiting Jonah’s return. He and Lynda could have hired somebody else to complete the screenplay, but they so valued Jonah’s talents that they waited.

Finally in February 2010 Jonah was back, and on March 3, Steven, Lynda, Jonah, and I had a very productive meeting to discuss Jonah’s nine-month-old draft 3. I was feeling a bit giddy. At last we were back on track.

Fig. 1.1. Jonah Nolan, Kip, and Lynda Obst.

Then on June 9, with Jonah deep into draft 4, I got an e-mail from Lynda: “We have a Steven deal problem. I’m into it.” But it was not soluble. Spielberg and Paramount could not reach an agreement for the next phase of *Interstellar*, and Lynda couldn’t broker a solution. Suddenly we had no director.

Interstellar was going to be very expensive, Steven and Lynda had independently told me. There were very few directors with whom Paramount would entrust a movie of this magnitude. I envisioned *Interstellar* in limbo, dying a slow death. I was devastated. So was Lynda, at first. But she is a superb problem solver.

Christopher Nolan, the Director and Screenwriter

Only thirteen days after Lynda's we-have-a-Steven-deal-problem e-mail, I opened my e-mail queue to find a euphoric follow-on message: "Great talk with Emma Thomas . . ." Emma is Christopher Nolan's wife/producer and collaborator on all his movies. She and Christopher were interested. Lynda was tremulous with excitement. Jonah called and told her, "This is the best possible outcome." But the deal, for many reasons, would not be finalized for two and a half years, though we were fairly certain Christopher and Emma were committed.

So we sat. And waited. June 2010, through 2011, to September 2012. Throughout, I fretted. In front of me, Lynda projected an air of confidence. But she later confided having written these words to herself: "Tomorrow we could wake up and Chris Nolan could be gone, after two and a half years of waiting. He could come up with his own idea. Another producer could hand him a script he likes more. He could decide to take a break. Then I would have been wrong to have waited for him all this time. It happens. That is my life, the lives of creative producers. But he's the perfect director for us. So we wait."

At last negotiations began, far, far above my pay grade. Christopher Nolan would direct only if Paramount would share the movie with Warner Bros., the studio that had made his last few movies, so a deal—an extremely complex deal—had to be struck between the two studios, normally rivals.

Finally, on December 18, 2012, Lynda e-mailed: "par and warners agreed to terms. Well chop my liver! starting in spring!!!" And from then on, with *Interstellar* in Christopher Nolan's hands, so far as I could tell all was clear sailing. At last! Clear, fun, and invigorating.

Christopher knew Jonah's screenplay well. They are brothers, after all, and had talked as Jonah wrote. They have a phenomenally successful history of collaborating on screenplays: *The Prestige, The Dark Knight*, *The Dark Knight Rises*. Jonah writes the initial drafts, and then Christopher takes over and rewrites, thinking carefully about how he will film each scene as he crafts it on paper.

With *Interstellar* now fully in Christopher's own hands, he combined Jonah's script with the script from another project he'd been working on, and he injected a radically fresh perspective and a set of major new ideas—ideas that would take the movie in unexpected new directions.

In mid-January, Chris, as I soon came to call him, asked to meet me one-on-one in his office at

Syncopy, his movie production company on the Warner Bros. lot.

As we talked, it became clear that Chris knew a remarkable amount of relevant science and had deep intuition about it. His intuition was occasionally off the mark, but usually right on. And he was tremendously curious. Our conversations often diverged from *Interstellar* to some irrelevant science issue that fascinated him.

In that first meeting, I laid on Chris my proposed science guidelines: Nothing will violate firmly established laws of physics; speculations will all spring from science. He seemed positively inclined, but told me that if I didn't like what he did with the science, I didn't have to defend him in public. That shook me up a bit. But with the movie now in postproduction, I'm impressed how well he followed those guidelines, while making sure they didn't get in the way of making a great movie.

Chris worked intensely from mid-January to early May rewriting Jonah's screenplay. From time to time he or his assistant, Andy Thompson, would phone me and ask that I come to his office or his home to talk about science issues, or come to read a new draft of his screenplay and then meet to discuss it. Our discussions were long, typically ninety minutes, sometimes followed by long phone calls a day or two later. He raised issues that made me think. As when working with Jonah, my best thinking was in the dead of night. The next morning I would write up my thoughts in a several-paged memo with diagrams and pictures, and hand carry them to Chris. (Chris worried about our ideas leaking out and spoiling his fans' mounting anticipation. He's one of the most secretive filmmakers in Hollywood.)

Chris's ideas occasionally seemed to violate my guidelines but, amazingly, I almost always found a way to make them work, scientifically. Only once did I fail miserably. In response, after several discussions over a two-week period, Chris backed off and took that bit of the film in another direction.

So in the end I have no qualms about defending what Chris did with the science. On the contrary, I'm enthusiastic! He turned into reality Lynda's and my dream of a blockbuster movie with foundations of real science, and with real science woven throughout its fabric.

In the hands of Jonah and Chris, *Interstellar*'s story changed enormously. It resembles Lynda's and my treatment only in broadest brushstrokes. It is so much better! And as for the science ideas: they are not all mine by any means. Chris brought remarkable science ideas of his own to the film, ideas that my physicist colleagues will assume were mine, ideas that I said to myself, when I saw them, Why didn't I think of that? And remarkable ideas arose from my discussions with Chris, with Jonah, and with Lynda.

Fig. 1.2. Kip and Christopher Nolan talking on set in the *Endurance*'s control module.

One April evening, Carolee and I threw a big party for Stephen Hawking at our home in Pasadena, with a diverse crowd of a hundred people: scientists, artists, writers, photographers, filmmakers, historians, schoolteachers, community organizers, labor organizers, business entrepreneurs, architects, and more. Chris and Emma came, as well as Jonah Nolan and his wife Lisa Joy, and of course Lynda. In the late evening, we stood together for a long time on a balcony, under the stars, far from the party noise, talking quietly—my first opportunity to get to know Chris as a man, rather than a filmmaker. It was so enjoyable!

Chris is down to earth, fascinating to talk with, and has a great sense of wry humor. He reminds me of another friend of mine, Gordon Moore, the founder of Intel: Both, at the pinnacle of their fields, completely unpretentious. Both driving old cars, preferring them to their other, more luxurious cars. Both making me feel comfortable and, introvert that I am, that's not easy.

Paul Franklin, Oliver James, Eugénie von Tunzelmann: The Visual-Effects Team

One day in mid-May 2013 Chris phoned me. He wanted to send a guy named Paul Franklin over to my home to discuss the computer graphics for *Interstellar*. Paul came the next day, and we spent a delightful two hours brainstorming in my home office. He was modest in demeanor, by contrast with Chris's forcefulness. He was brilliant. He showed a deep knowledge of the relevant science, despite having majored in the arts in college.

As Paul was leaving, I asked him which graphics company he was thinking of using for the visual effects. "Mine," he responded, mildly. "And what company is that?" I asked, naively. "Double Negative. We have 1000 employees in London and 200 in Singapore."

After Paul departed I Googled him and discovered that not only had he cofounded Double Negative, he had also won an Academy Award for the visual effects in Chris's movie *Inception*. "It's time I get educated about this movie business," I murmured to myself.

In a video conference a few weeks later, Paul introduced me to the London-based leaders of his *Interstellar* visual-effects team. Most relevant to me were Oliver James, the chief scientist who would write computer code underlying the visual effects; and Eugénie von Tunzelmann, who led the artistic team that would take Oliver's computer code and add extensive artistic twists to produce compelling images for the movie.

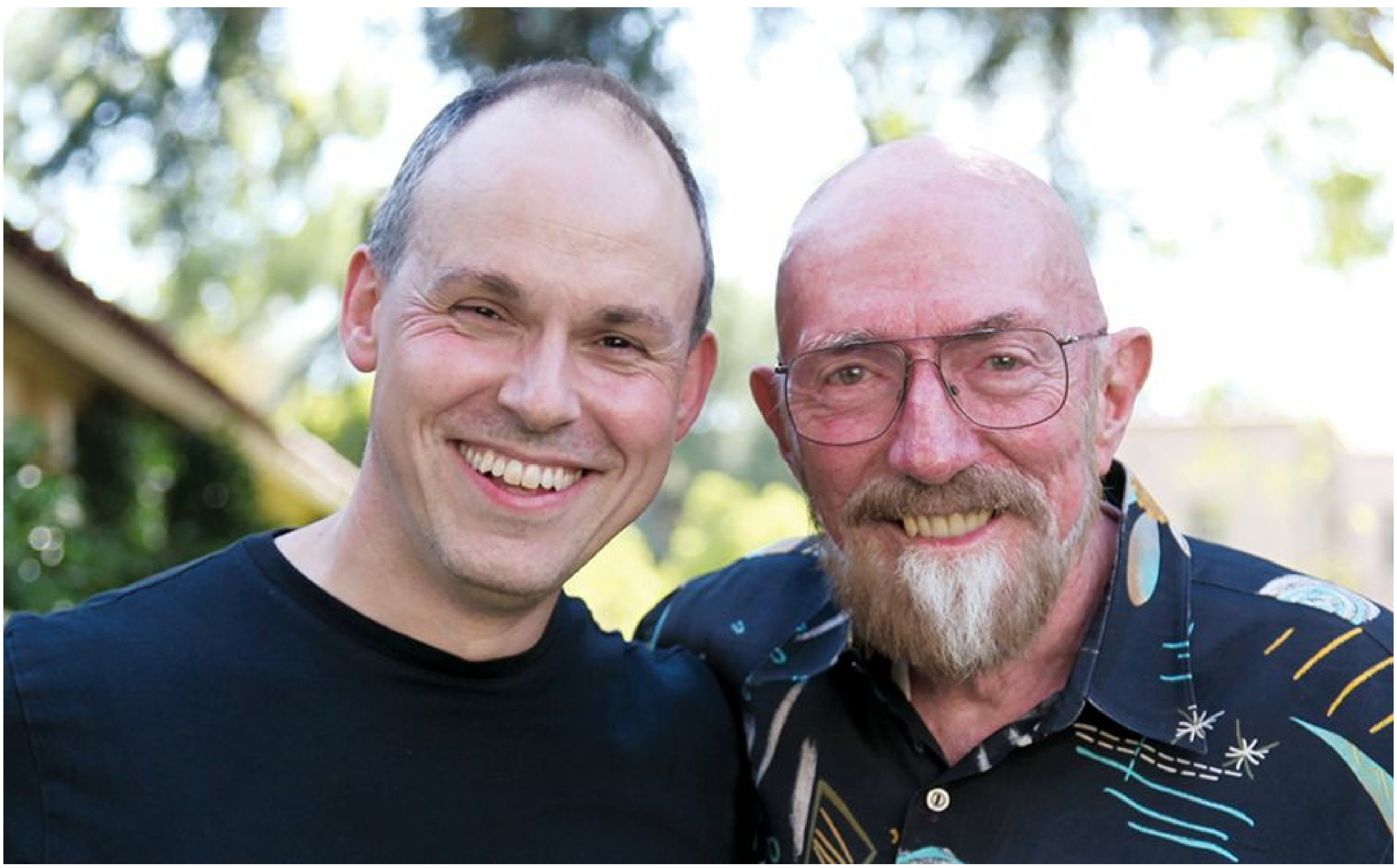

Fig. 1.3. Paul Franklin and Kip.

Oliver and Eugénie were the first people with physics training that I had met on *Interstellar*. Oliver has a degree in optics and atomic physics, and knows the technical details of Einstein's special relativity. Eugénie is an engineer, trained at Oxford, with a focus on data engineering and computer science. They speak my language.

We quickly developed a great working relationship. For several months, I struggled near full time, formulating equations for images of the universe near black holes and wormholes (Chapters 8 and 15). I tested my equations using low-resolution, user-friendly computer software called Mathematica, and then sent the equations and Mathematica code to Oliver. He devoured them, converted them into sophisticated computer code that could generate the ultra-high-quality IMAX images needed for *Interstellar*, and then passed them on to Eugénie and her team. It was a joy working with them.

Fig. 1.4. Eugénie von Tunzelmann, Kip, and Oliver James.

And the end product, the visualizations in *Interstellar*, are amazing! And scientifically accurate.

You cannot imagine how ecstatic I was when Oliver sent me his initial film clips. For the first time ever—and before any other scientist—I saw in ultrahigh definition what a fast-spinning black hole looks like. What it does, visually, to its environment.

Matthew McConaughey, Anne Hathaway, Michael Caine, Jessica Chastain

On July 18, two weeks before filming was to begin, I received an e-mail from Matthew McConaughey, who plays Cooper: "per Interstellar," he wrote, "I'd like to ask you some questions and . . . If you are around L.A. area, in person is preferable. Lemme know please, thanks, in process, mcConaughey."

We met six days later, in a suite at L'Hermitage, a boutique hotel in Beverly Hills. He was ensconced there, struggling to wrap his head around the role of Cooper and the science of *Interstellar*.

When I arrived, he opened the door dressed in shorts and a tank top, barefooted and thin from having just filmed *Dallas Buyers' Club* (for which he later won the Oscar for best actor). He asked if he could call me "Kip"; I said of course and asked what I should call him. "Anything but Matt; I hate Matt." "Matthew." "McConaughey." "Hey you." "Whatever you like." I chose "McConaughey" as it trips off the tongue so nicely, and there are too many Matthews in my life.

McConaughey had removed all the furniture from the suite's huge living/dining room, except an L-shaped couch and a coffee table. Strewn over the floor and table were 12-by-18-inch sheets of paper, each covered with notes dealing with a particular topic, written in random directions, squiwampus. We sat on the couch. He would pick up a sheet, browse it, and ask a question. The question was usually deep, and triggered a long discussion during which he would write notes on the sheet.

Often the discussion would take off in unexpected directions, with the sheet forgotten. It was one of the most interesting and enjoyable conversations I've had in a long time! We wandered from the laws of physics, especially quantum physics, to religion and mysticism, to the science of *Interstellar*, to our families and especially our children, to our philosophies of life, to how we each get inspirations, how our minds work, how we make discoveries. I left, two hours later, in a state of euphoria.

Later I told Lynda about our meeting. "Of course," she responded. She could have told me what to expect; *Interstellar* is her third film with McConaughey. I'm glad she didn't tell me. It was a joy to discover for myself.

The next e-mail, a few weeks later, was from Anne Hathaway, who plays Amelia Brand. "Hi Kip! I hope this e-mail finds you well. . . . Emma Thomas passed along your e-mail in case I had any questions. Well, the subject matter is pretty dense so I have a few! . . . would we be able to chat? Thank you very much, Annie."

We talked by phone, as our schedules couldn't be meshed for an in-person meeting. She described herself as a bit of a physics geek, and said that her character, Brand, is expected to know the physics cold—and then she launched into a series of surprisingly technical physics questions: What is the relationship of time to gravity? Why do we think there might be higher dimensions? What is the current status of research on quantum gravity? Are there any experimental tests of quantum gravity? . . . Only at the end did she let us wander off subject, to music, in fact. She played trumpet in high school; I played sax and clarinet.

During the filming of *Interstellar*, I was on set very, very little. I was not needed. But one morning Emma Thomas toured me through the *Endurance* set—a full-scale mockup of the *Endurance* spacecraft's command and navigation pod, in Stage 30 at Sony Studios.

It was tremendously impressive: 44 feet long, 26 feet wide, 16 feet high, suspended in midair; able to shift from horizontal to nearly vertical; exquisite in detail. It blew me away, and piqued my curiosity.

"Emma, why build these enormous, complex sets, when the same thing could be done with computer graphics?" "It's not clear which would be cheaper," she responded. "And computer graphics can't yet produce the compelling visual details of a real set." Wherever possible, she and Chris use real sets and real practical effects, except for things that can't actually be shot that way, like the black hole Gargantua.

On another occasion, I wrote dozens of equations and diagrams on Professor Brand's blackboards, and watched as Chris filmed in the Professor's office with Michael Caine as the Professor and Jessica Chastain as Murph.[1] I was astonished by the warm and friendly deference that Caine and Chastain showed me. Despite having no role in the filming, I was notorious as *Interstellar*'s real scientist, the guy who inspired everyone's best effort to get the science right for this blockbuster movie.

That notoriety triggered fascinating conversations with Hollywood icons: not just the Nolans, McConaughey, and Hathaway, but also Caine, Chastain, and others. A fun bonus from my creative friendship with Lynda.

Now comes the final phase of Lynda's and my *Interstellar* dream. The phase where you, the audience, have become curious about *Interstellar*'s science and seek explanations for bizarre things you saw in the movie.

The answers are here. That's why I wrote this book. Enjoy!

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1 See Chapter 25.

I

FOUNDATIONS

2

Our Universe in Brief

Our universe is vast. Achingly beautiful. Remarkably simple in some ways, intricately complex in others. From our universe's great richness, we'll need only a few basic facts that I'll now lay bare.

The Big Bang

Our universe was born in a gigantic explosion 13.7 billion years ago. The explosion was given the irreverent name "the big bang" by my friend Fred Hoyle, a cosmologist who at that time (the 1940s) thought it an outrageous, fictional idea.

Fred was proved wrong. We've since seen radiation from the explosion, even in just the last week (as I write this) tentative evidence for radiation emitted in the first trillionth of a trillionth of a trillionth of a second after the explosion began![2]

We don't know what triggered the big bang, nor what, if anything, existed before it. But somehow the universe emerged as a vast sea of ultrahot gas, expanding fast in all directions like the fireball ignited by a nuclear bomb blast or by the explosion of a gas pipeline. Except that the big bang was not destructive (so far as we know). Instead, it *created* everything in our universe, or rather the seeds for everything.

I would love to write a long chapter about the big bang, but with great force of will I restrain myself. We don't need it for the rest of this book.

Galaxies

As our universe expanded, its hot gas cooled. In some regions the gas's density was a bit higher than in others, randomly. When the gas got cold enough, gravity pulled each high-density region inward on itself, giving birth to a galaxy (a huge cluster of stars and their planets and diffuse gas between the stars); see Figure 2.1. The earliest galaxy was born when the universe was a few hundred million years old.

There are roughly a trillion galaxies in the visible universe. The largest galaxies contain a few trillion stars and are about a million light-years across;[3] the smallest, about 10 million stars and a thousand light-years across. At the center of most every large galaxy there is a huge black hole (Chapter 5), one that weighs a million times the sun's weight or more.[4]

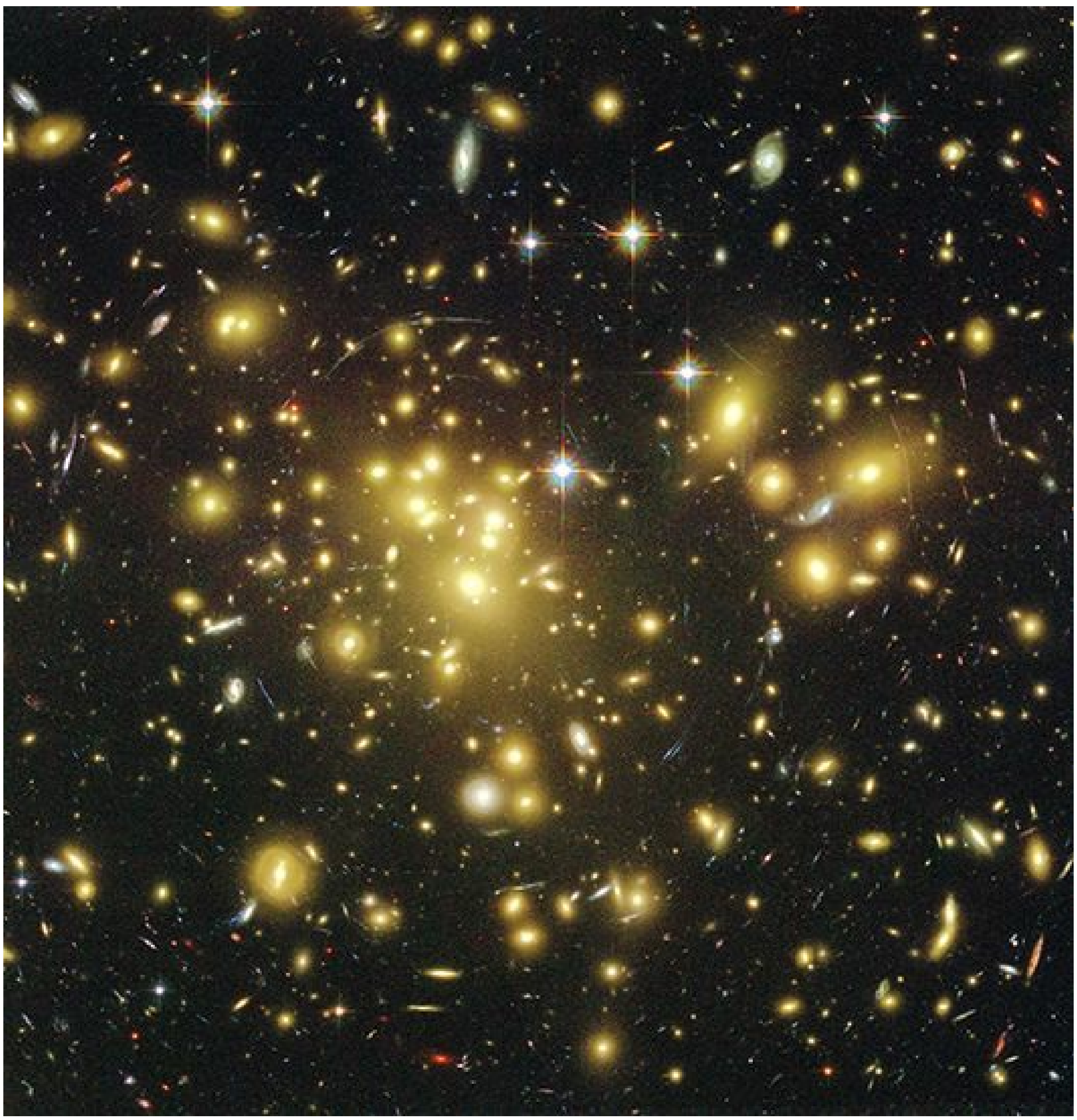

Fig. 2.1. A rich cluster of galaxies named Abell 1689 and many other more distant galaxies, as photographed by the Hubble Space Telescope.

The Earth resides in a galaxy called the Milky Way. Most of the Milky Way's stars are in the bright band of light that stretches across Earth's sky on a clear, dark night. And almost all the pinpricks of light that we see in the sky at night, not just those in the bright band, also lie in the Milky Way.

The nearest large galaxy to our own is called Andromeda (Figure 2.2). It is 2.5 million light-years from Earth. It contains about a trillion stars and is about 100,000 light-years across. The Milky Way is a sort of twin to Andromeda, about the same in size, shape, and number of stars. If Figure 2.2 were the Milky Way, then the Earth would be where I placed the yellow diamond.

Andromeda contains a gigantic black hole, 100 million times heavier than the Sun and as big across as the Earth's orbit (the same weight and size as *Interstellar*'s Gargantua; Chapter 6). It resides in the middle of the central bright sphere in Figure 2.2.

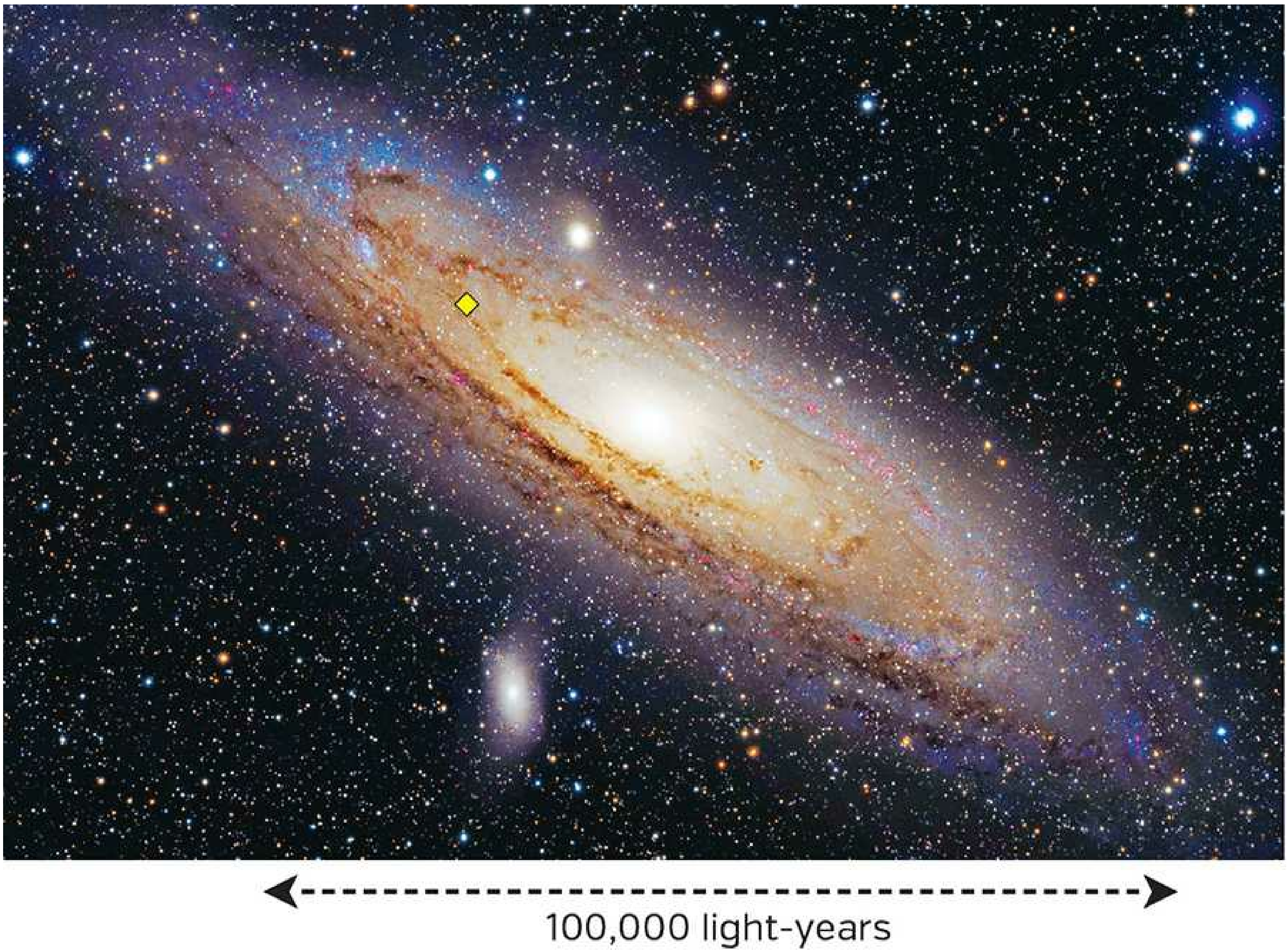

Fig. 2.2. The Andromeda galaxy.

Solar System

Stars are large, hot balls of gas, usually kept hot by burning nuclear fuel in their cores. The Sun is a fairly typical star. It is 1.4 million kilometers across, about a hundred times larger than the Earth. Its surface has flares and hot spots and cooler spots, and is fascinating to explore through a telescope (Figure 2.3).

Eight planets, including the Earth, travel around the Sun in elliptical orbits, along with many dwarf planets (of which Pluto is the most famous) and many comets, and smaller, rocky bodies called asteroids and meteoroids (Figure 2.4). Earth is the third planet from the Sun. Saturn, with its gorgeous rings, is the sixth planet out and plays a role in *Interstellar* (Chapter 15).

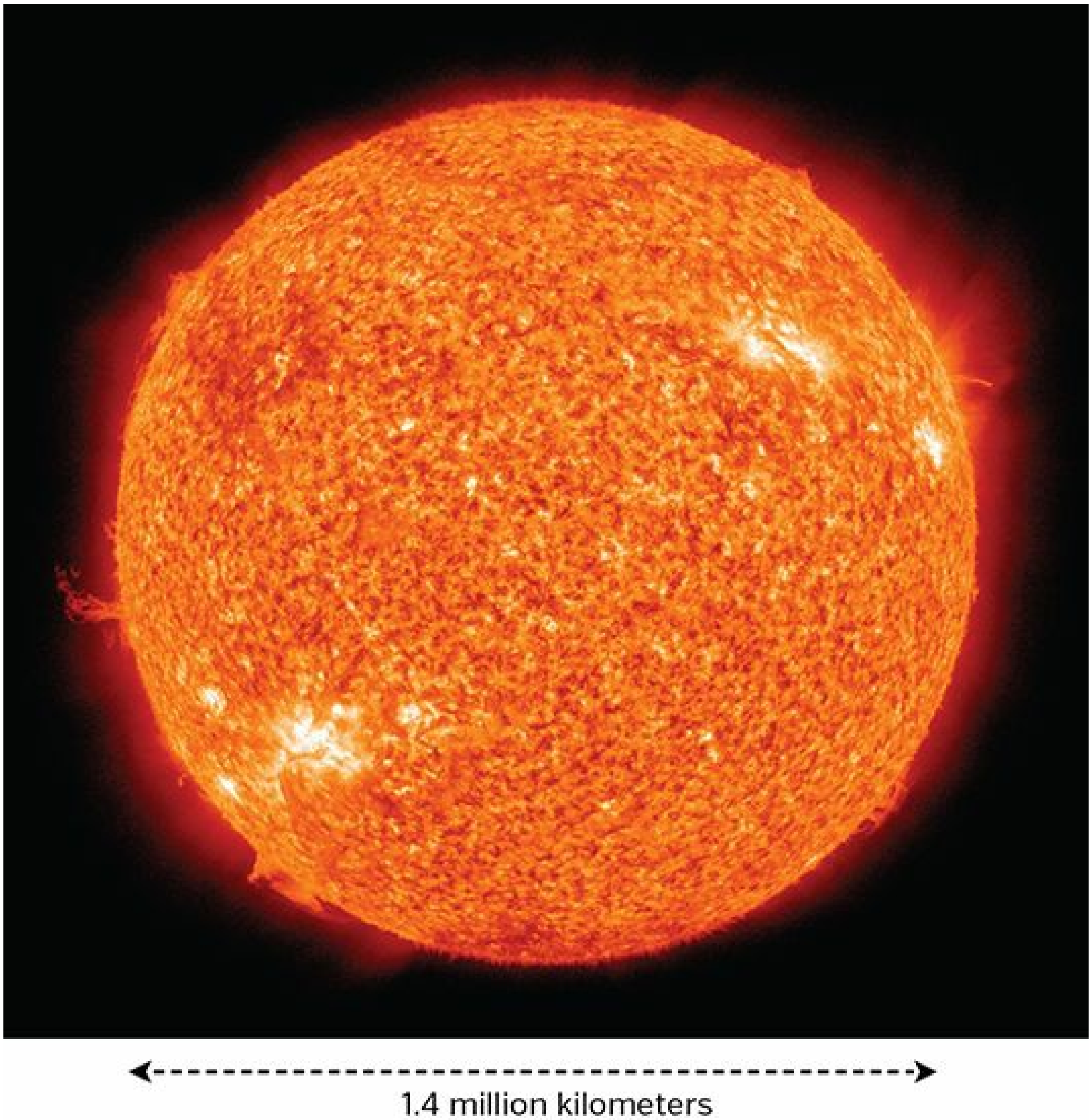

Fig 2.3. The Sun as photographed by NASA's Solar Dynamics Observatory.

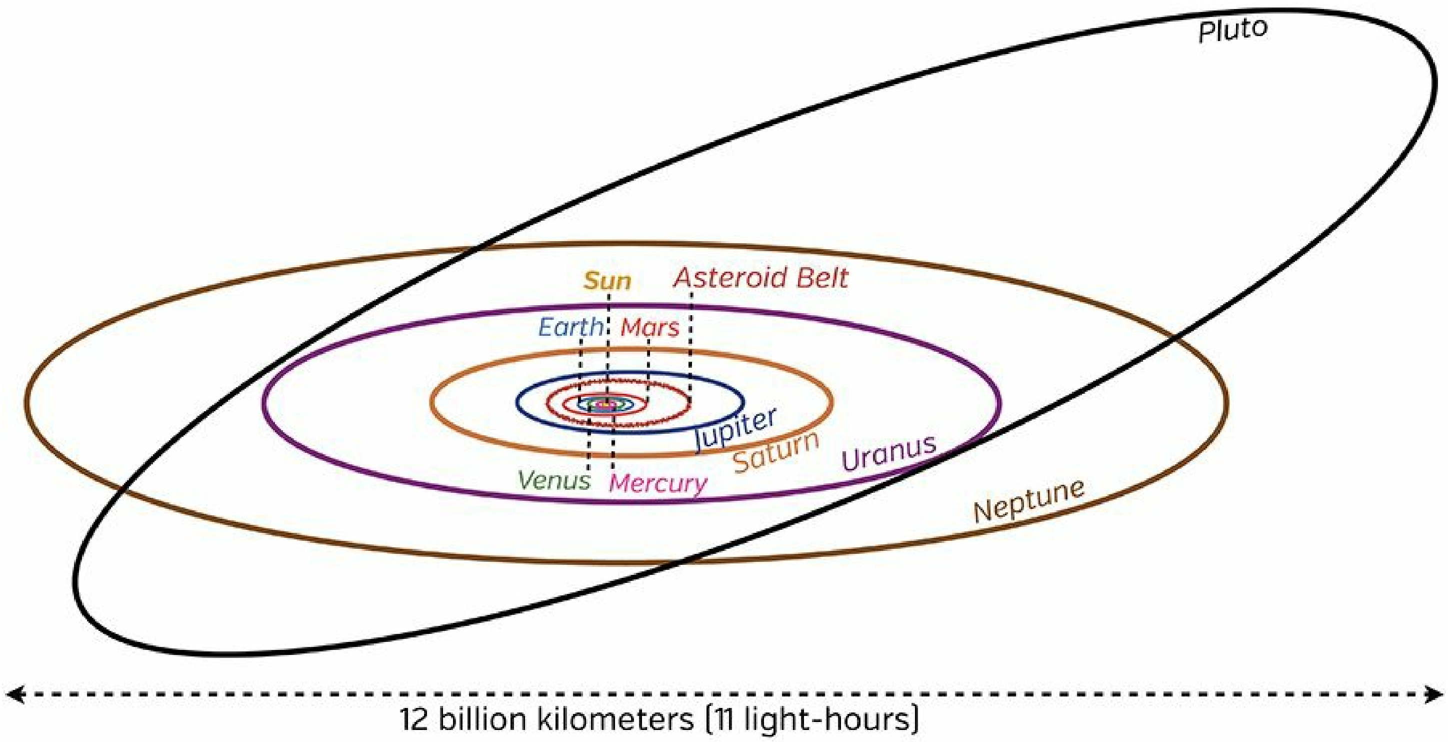

Fig. 2.4. The orbits of the Sun's planets and Pluto, and a region containing many asteroids.

The solar system is a thousand times bigger than the Sun itself; light needs eleven hours to travel across it.

The distance to the nearest star other than the Sun, Proxima Centauri, is 4.24 light-years, 2500 times farther than the distance across the solar system! In Chapter 13, I discuss the awful implications for interstellar travel.

Stellar Death: White Dwarfs, Neutron Stars, and Black Holes

The Sun and Earth are about 4.5 billion years old, about a third the age of the universe. After another 6.5 billion years or so, the Sun will exhaust the nuclear fuel in its core, the fuel that keeps it hot. The Sun then will shift to burning fuel in a shell around its core, and its surface will expand to engulf and fry the Earth. With the shell's fuel spent and the Earth fried, the Sun will shrink to become a white dwarf star, about the size of the Earth but with density a million times higher. The white dwarf will gradually cool, over tens of billions of years, to become a dense, dark cinder.

Stars much heavier than the Sun burn their fuel much more quickly, and then collapse to form a neutron star or a black hole.

Neutron stars have masses about one to three times that of the Sun, circumferences of 75 to 100 kilometers (about the size of Chicago), and densities the same as the nucleus of an atom: a hundred trillion times more dense than rock and the Earth. Indeed, neutron stars are made of almost pure nuclear matter: atomic nuclei packed side by side.

Black holes (Chapter 5), by contrast, are made fully and solely from warped space and warped time (I'll explain this weird claim in Chapter 4). They contain no matter whatsoever, but they have surfaces, called “event horizons,” or just “horizons,” through which nothing can escape, not even light. That’s why they are black. A black hole’s circumference is proportional to its mass: the heavier it is, the bigger it is.

A black hole with about the same mass as a typical neutron star or white dwarf (say 1.2 times as heavy as the Sun) has a circumference of about 22 kilometers: a fourth that of the neutron star and a thousandth that of the white dwarf. See Figure 2.5.

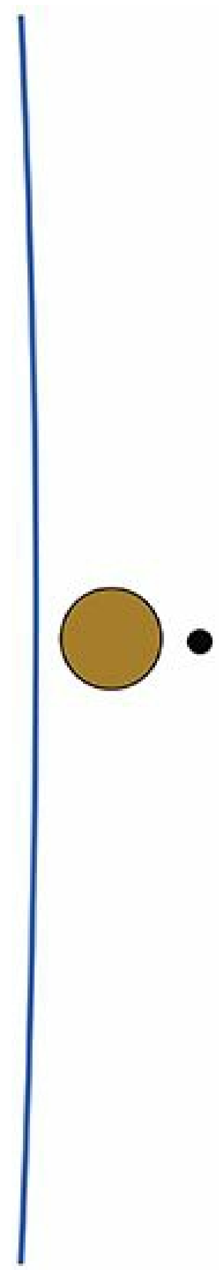

Fig. 2.5. A white dwarf (*left*), neutron star (*middle*), and black hole (*right*) that all weigh as much as 1.2 Suns. For the white dwarf I show only a tiny segment of its surface.

Since stars are generally no heavier than about 100 Suns, the black holes to which they give birth are also no heavier than 100 Suns. The giant black holes in the cores of galaxies, a million to 20 billion times heavier than the Sun, therefore, cannot have been born in the death of a star. They must have formed in some other way, perhaps by the agglomeration of many smaller black holes;

perhaps by the collapse of massive clouds of gas.

Magnetic, Electric, and Gravitational Fields

Because magnetic force lines play a big role in our universe and are important for *Interstellar*, let's discuss them, too, before diving into *Interstellar*'s science.

As a student in science class, you may have met magnetic force lines in a beautiful little experiment. Do you remember taking a sheet of paper, placing a bar magnet under it, and sprinkling iron filings (elongated flakes of iron) on top of the paper? The iron filings make the pattern shown in Figure 2.6. They orient themselves along magnetic force lines that otherwise are invisible. The force lines depart from one of the magnet's poles, swing around the magnet, and descend into the other pole. The magnetic *field* is the collection of all the magnetic force lines.

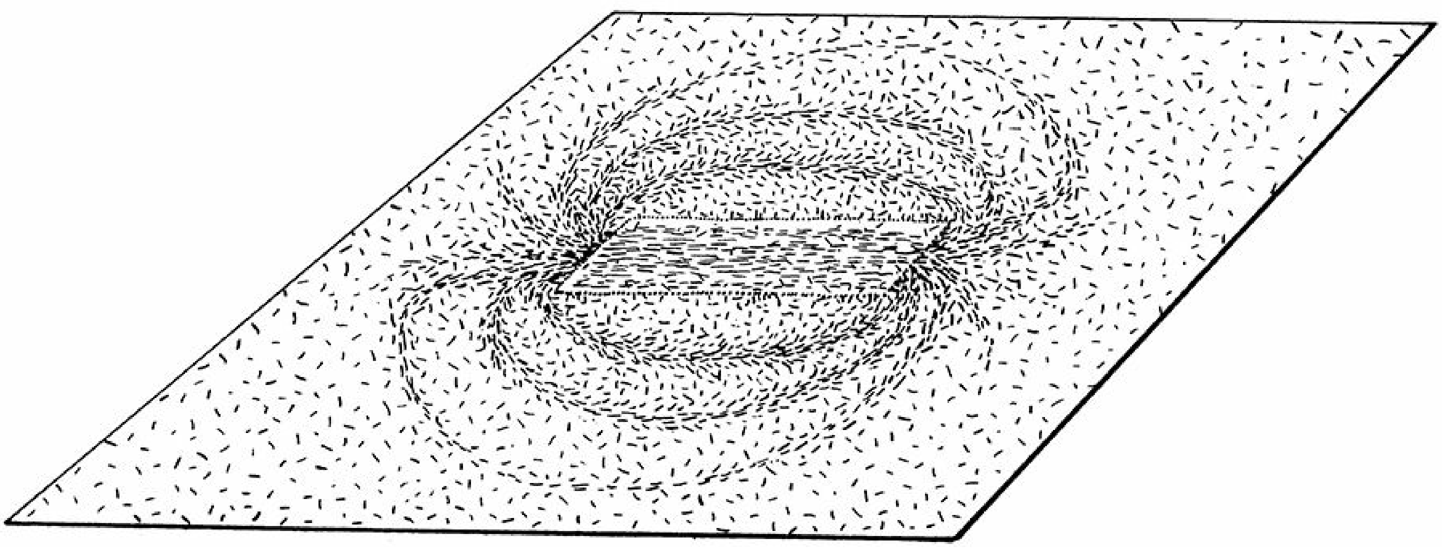

Fig. 2.6. Magnetic force lines from a bar magnet, made visible by iron filings sprinkled on a sheet of paper. *[Drawing by Matt Zimet based on a sketch by me; from my book* Black Holes & Time Warps: Einstein's Outrageous Legacy.*]*

When you try to push two magnets together with their north poles facing each other, their force lines repel each other. You see nothing between the magnets, but you feel the magnetic field's repulsive force. This can be used for magnetic levitation, suspending a magnetized object—even a railroad train (Figure 2.7)—in midair.

The Earth also has two magnetic poles, north and south. Magnetic force lines depart from the south magnetic pole, swing around the Earth, and descend into the north magnetic pole (Figure 2.8). These force lines grab a compass needle, just as they grab iron filings, and drive the needle to point as nearly along the force lines as possible. That's how a compass works.

Fig. 2.7. The world's first commerical magnetically levitated train, in Shanghai, China.

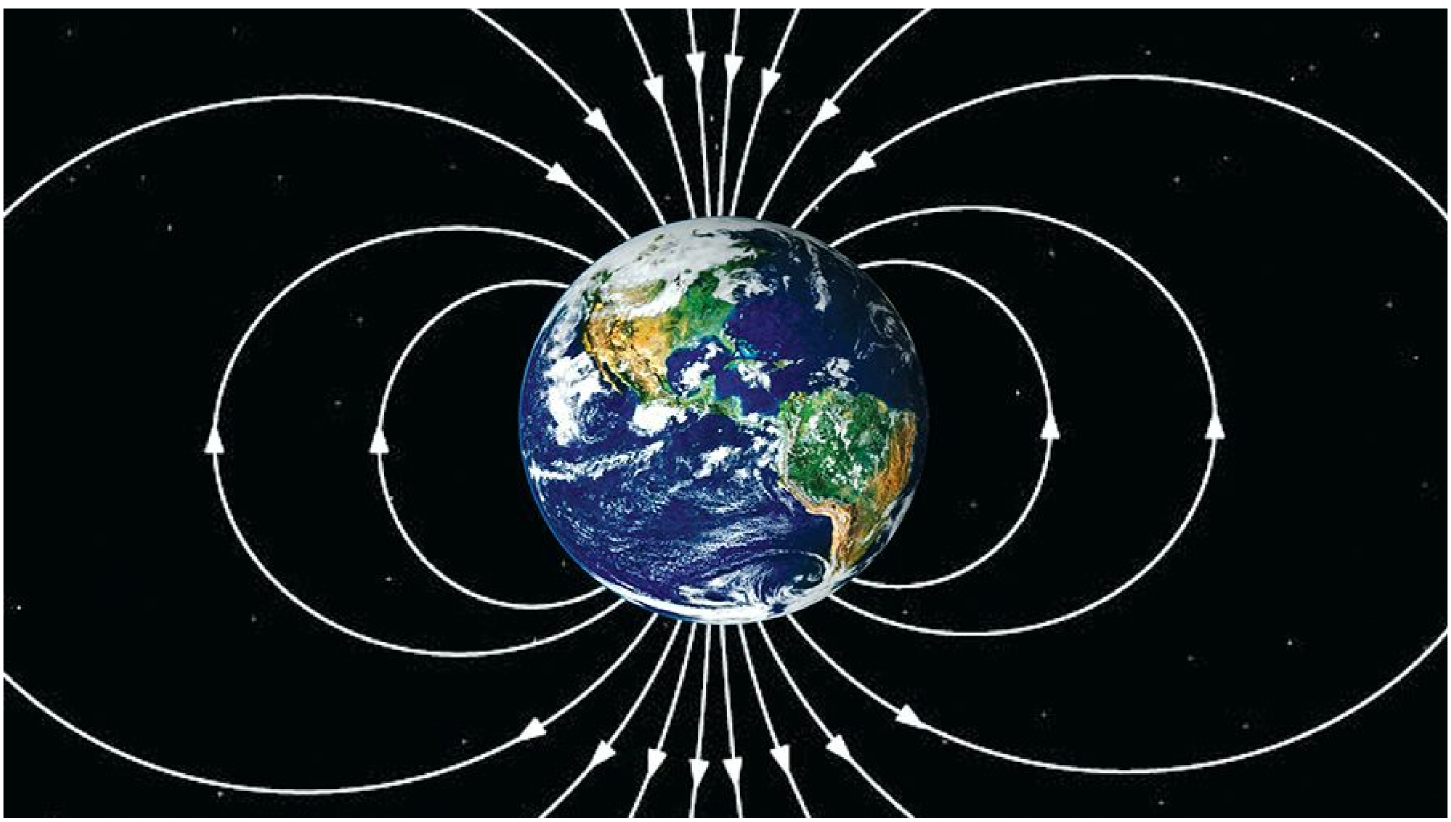

Fig. 2.8. The Earth's magnetic force lines.

The Earth's magnetic force lines are made visible by the Aurora Borealis (the Northern Lights; Figure 2.9). Protons flying outward from the Sun are caught by the force lines and travel along them into the Earth's atmosphere. There the protons collide with oxygen and nitrogen molecules, making the oxygen and nitrogen fluoresce. That fluorescent light is the Aurora.

Fig. 2.9. The Aurora Borealis in the sky over Hammerfest, Norway.

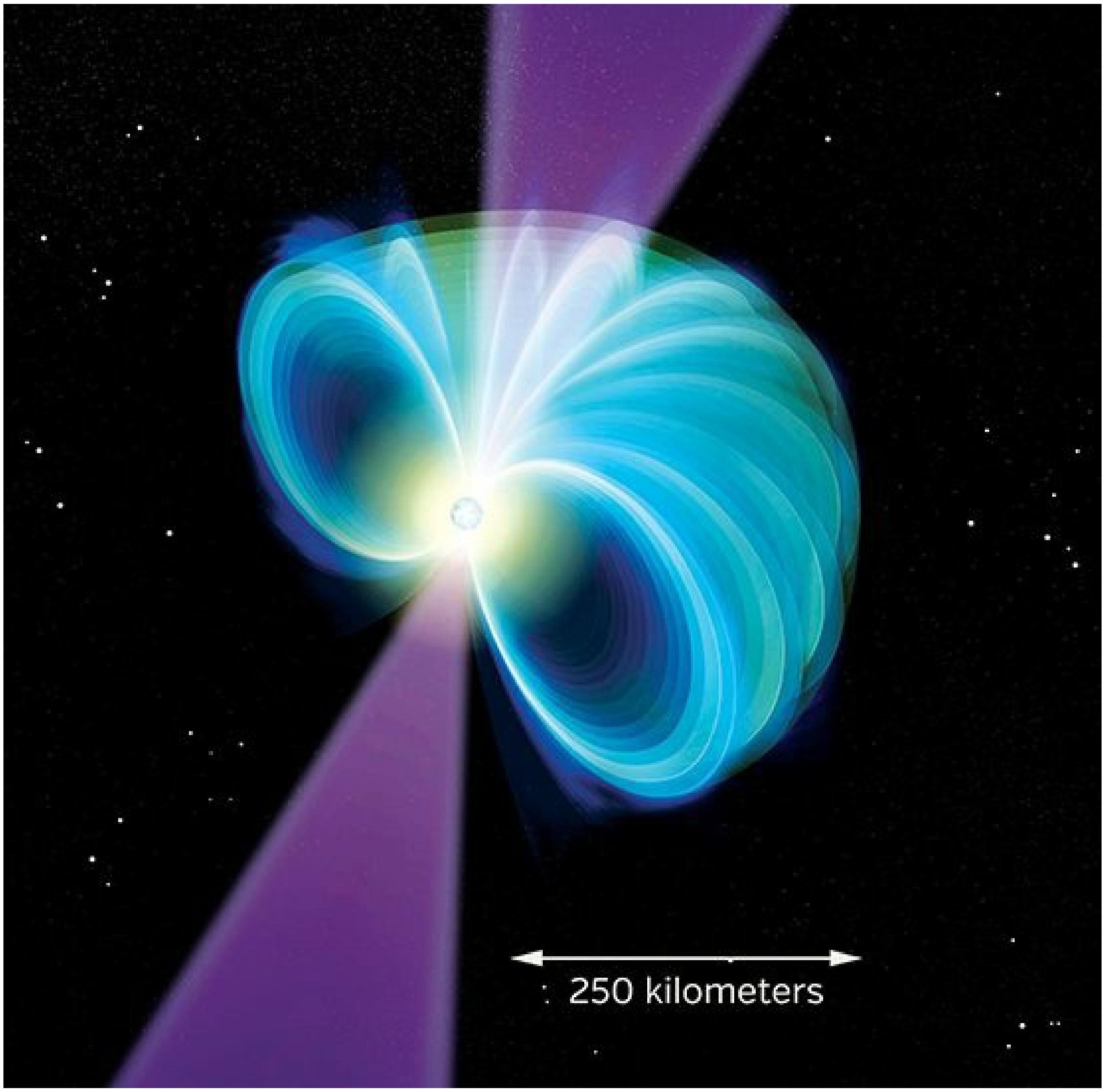

Fig. 2.10. Artist's conception of a neutron star with its donut-shaped magnetic field and its jets.

Neutron stars have very strong magnetic fields, whose force lines are donut-shaped, like the Earth's. Fast-moving particles trapped in a neutron star's magnetic field light up the force lines, producing the blue rings in Figure 2.10. Some of the particles are liberated and stream out the field's poles, producing the two violet jets in the figure. These jets consist of all types of radiation: gamma rays, X-rays; ultraviolet, visual, infrared, and radio waves. As the star spins, its luminous jets sweep around the sky above the neutron star, like a searchlight. Every time a jet sweeps over the Earth, astronomers see a pulse of radiation, so astronomers have named these objects "pulsars."

The universe contains other kinds of fields (collections of force lines) in addition to magnetic fields. One example is electric fields (collections of electric force lines that, for example, drive electric current to flow through wires). Another example is gravitational fields (collections of gravitational force lines that, for example, pull us to the Earth's surface).

The Earth's gravitational force lines point radially into the Earth and they pull objects toward the Earth along themselves. The strength of the gravitational pull is proportional to the density of the force lines (the number of lines passing through a fixed area). As they reach inward, the force lines pass through spheres of ever-decreasing area (dotted red spheres in Figure 2.11), so the lines' density must go up inversely with the sphere's area, which means the Earth's gravity grows as you travel toward it, as 1/(the red spheres' area). Since each sphere's area is proportional to the square of its distance r from the Earth's center, the strength of the Earth's gravitational pull grows as $1/r^2$. This is Newton's inverse square law for gravity—an example of the fundamental laws of physics that are Professor Brand's passion in *Interstellar* and our next foundation for *Interstellar*'s science.

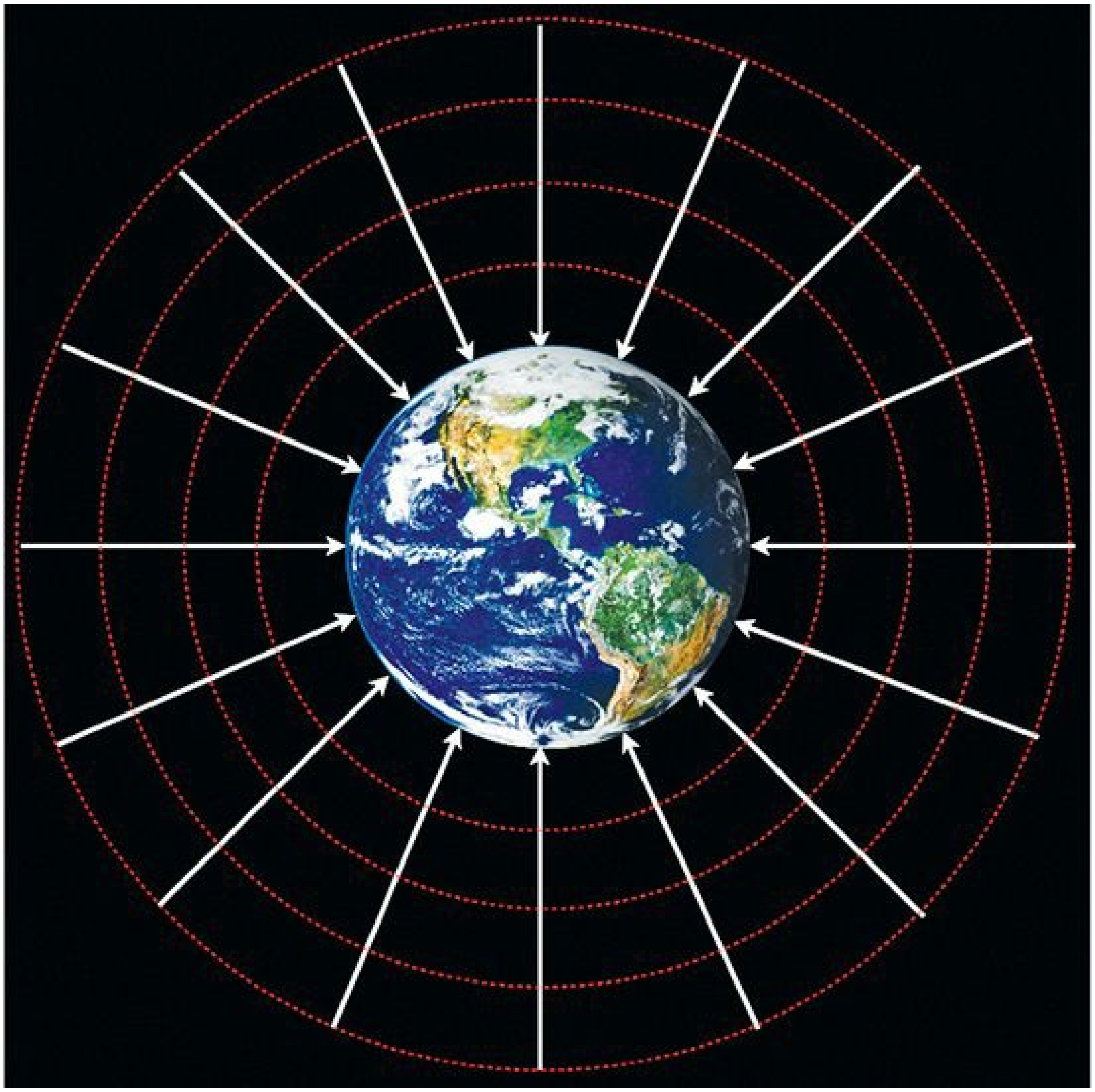

Fig. 2.11. The Earth's gravitational force lines.

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2 Google "gravitational waves from the big bang" or "CMB polarization" to learn about this amazing March 2014 discovery. I give some details at the end of Chapter 16.

3 A light-year is the distance light travels in one year: about a hundred trillion kilometers.

4 In more technical language, its mass is a million times that of the Sun's or more, which means its gravitational pull, when you are at some fixed distance away from it, is the same as a million Suns'. In this book I use "mass" and "weight" to mean the same thing.

3

The Laws That Control the Universe

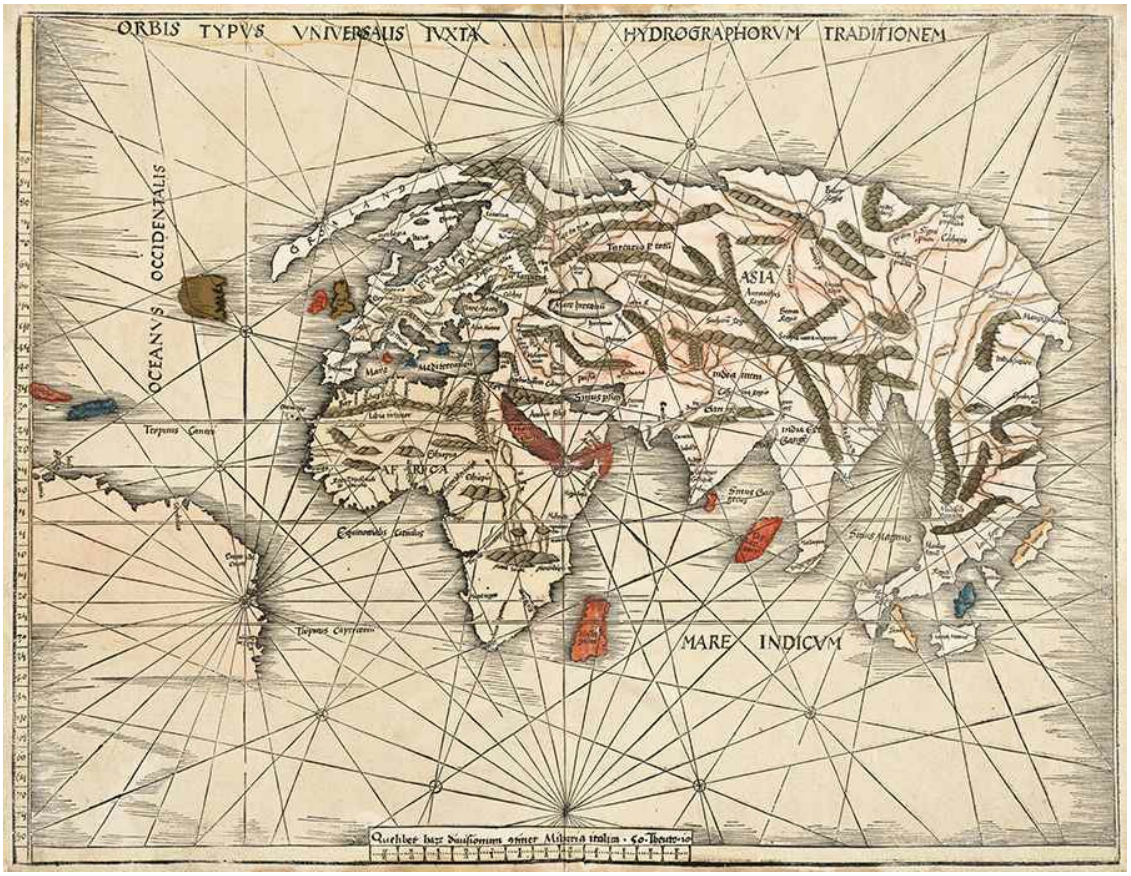
Mapping the World and Deciphering the Laws of Physics

Physicists have struggled from the seventeenth century onward to discover the physical laws that shape and control our universe. This has been like European explorers struggling to discover the Earth's geography (Figure 3.1).

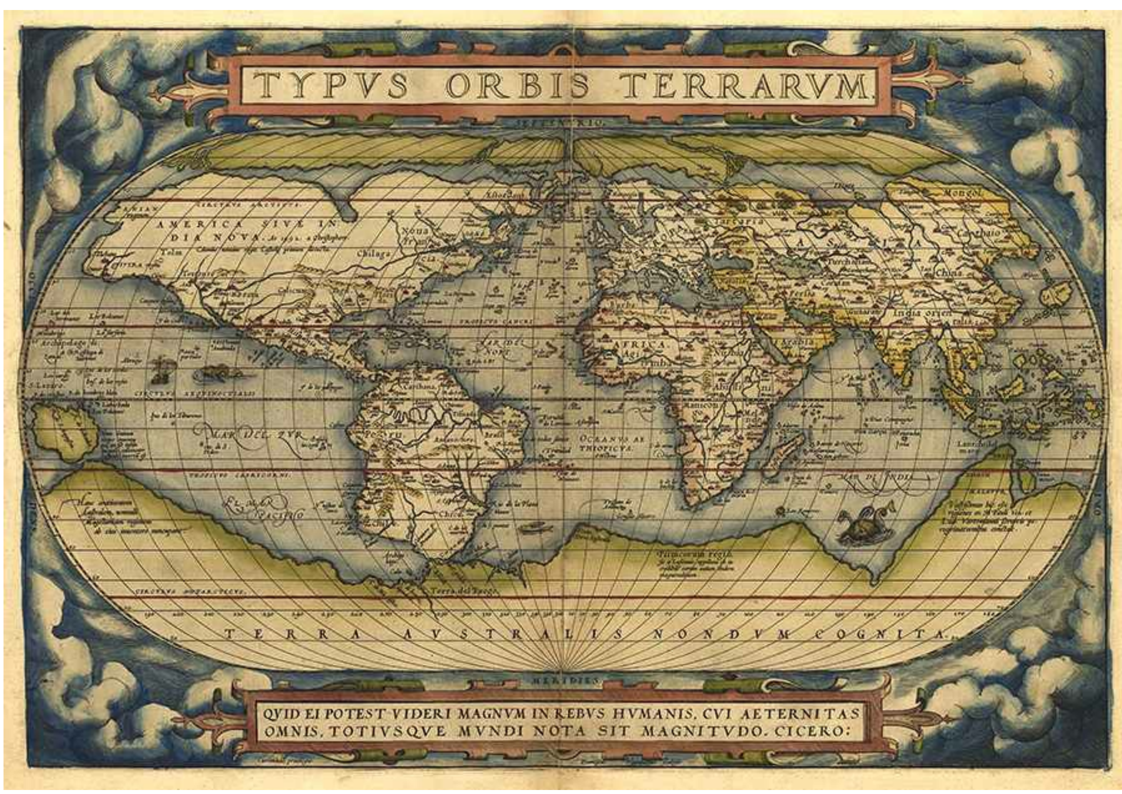
By 1506 Eurasia was coming into focus and there were glimmers of South America. By 1570 the Americas were coming into focus, but there was no sign of Australia. By 1744 Australia was coming into focus, but Antarctica was terra incognita.

Similarly (Figure 3.2), by 1690 the *Newtonian laws of physics* had come into focus. With concepts such as force, mass, and acceleration and equations that link them, such as $F = ma$, the Newtonian laws accurately describe the motion of the Moon around the Earth and the Earth around the Sun, the flight of an airplane, the construction of a bridge, and collisions of a child's marbles. In Chapter 2 we briefly met an example of a Newtonian law, the inverse square law for gravity.

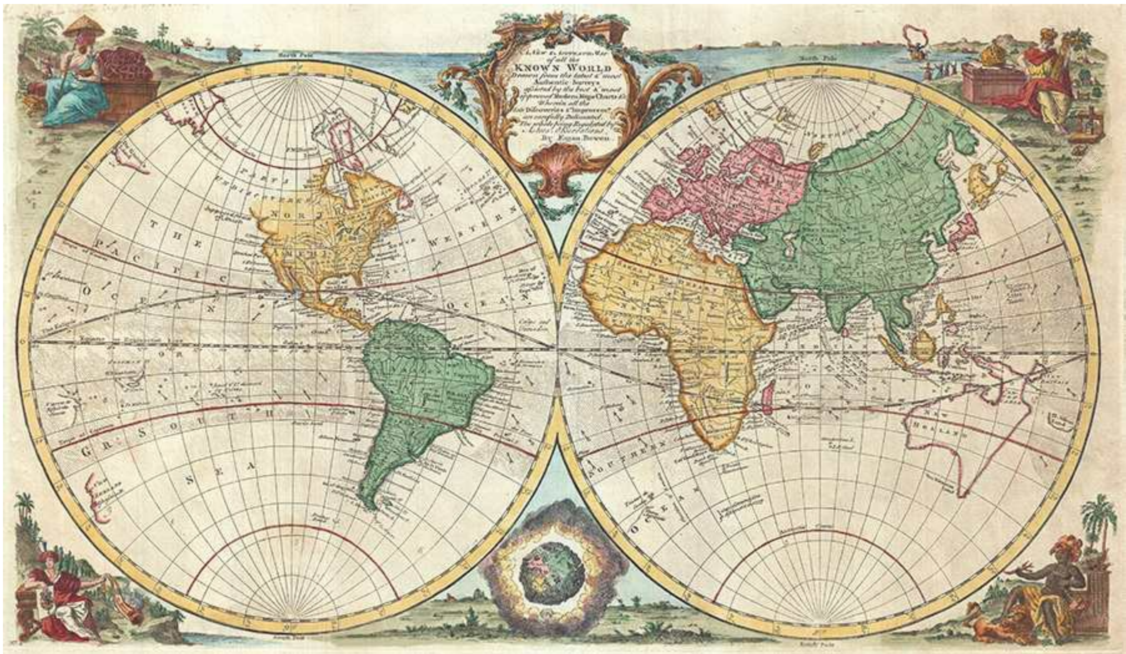
By 1915 Einstein and others had found strong evidence that the Newtonian laws fail in the realm of the very fast (objects that move at nearly the speed of light), the realm of the very large (our universe as a whole), and the realm of intense gravity (for example, black holes). To remedy these failures Einstein gave us his revolutionary *relativistic laws of physics* (Figure 3.2). Using the concepts of warped time and warped space (which I describe in the next chapter), the relativistic laws predicted and explained the expansion of the universe, black holes, neutron stars, and wormholes.



1506—Martin Waldseemuller



1570—Abraham Ortelius



1744—Emanuel Bowen

Fig. 3.1. World maps from 1506 to 1744.

By 1924 it was crystal clear that the Newtonian laws also fail in the realm of the very small (molecules, atoms, and fundamental particles). To deal with this Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and others gave us the *quantum laws of physics* (Figure 3.2). Using the concepts that everything fluctuates randomly at least a little bit (which I describe in Chapter 26), and that these fluctuations can produce new particles and radiation where before there were none, the quantum laws have brought us lasers, nuclear energy, light-emitting diodes, and a deep understanding of chemistry.

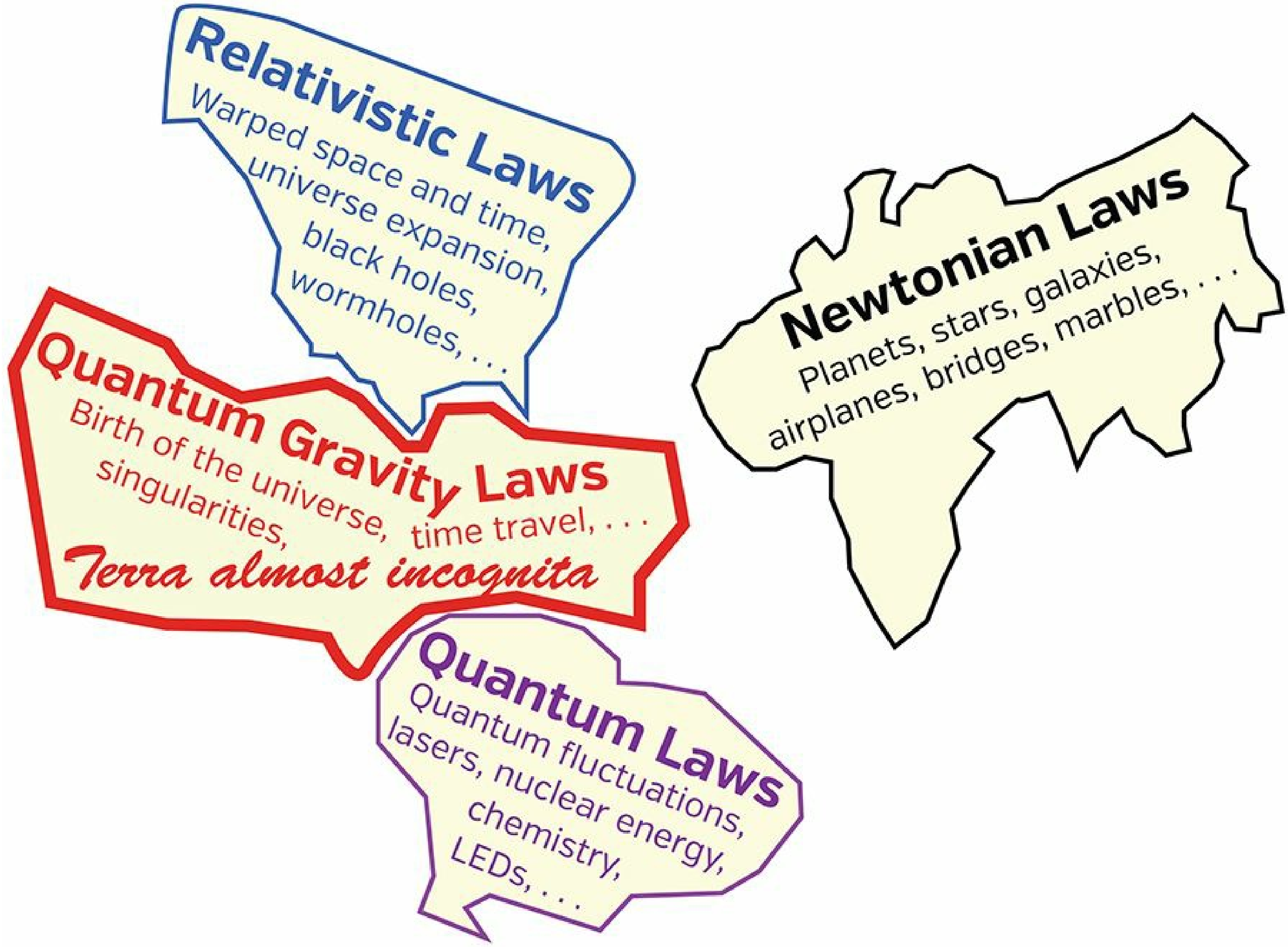


Fig. 3.2. The physical laws that govern the universe.

By 1957 it became evident that the relativistic laws and the quantum laws are fundamentally incompatible. They predict different things, incompatible things, in realms where gravity is intense *and* quantum fluctuations are strong.[5] These realms include the big bang birth of our universe (Chapter 2), the cores of black holes like Gargantua (Chapters 26 and 28), and backward time travel (Chapter 30). In these realms a "fiery marriage"[6] of the incompatible relativistic and quantum laws gives rise to new *laws of quantum gravity* (Figure 3.2).

We do not yet know the laws of quantum gravity, but we have some compelling insights, including superstring theory (Chapter 21), thanks to enormous effort by the world's greatest twenty-first-century physicists. Despite those insights, quantum gravity remains terra almost incognita (an almost unknown land). This leaves much elbow room for exciting science fiction, elbow room that Christopher Nolan exploits with great finesse in *Interstellar*; see Chapters 28–31.

Truth, Educated Guesses, and Speculations

The science of *Interstellar* lies in all four domains: Newtonian, relativistic, quantum, and quantum gravity. Correspondingly, some of the science is known to be true, some is an educated guess, and some is speculation.

To be *true*, the science must be based on well-established physical laws (Newtonian, relativistic, or quantum), and it must have enough basis in observation that we are confident of how to apply the well-established laws.

In precisely this sense, neutron stars and their magnetic fields, as described in Chapter 2, are true. Why? First, neutron stars are firmly predicted to exist by the quantum and relativistic laws. Second, astronomers have studied in enormous detail the pulsar radiation from neutron stars (pulses of light, X-rays, and radio waves described in Chapter 2). These pulsar observations are beautifully and accurately explained by the quantum and relativistic laws, if the pulsar is a spinning neutron star; and no other explanation has ever been found. Third, neutron stars are firmly predicted to form in astronomical explosions called supernovae, and pulsars are seen at the centers of big, expanding gas clouds, the remnants of old supernovae. Thus, we astrophysicists have no doubt; neutron stars really do exist and they really do produce the observed pulsar radiation.

Another example of a truth is the black hole Gargantua and the bending of light rays by which it distorts images of stars (Figure 3.3). Physicists call this distortion “gravitational lensing” because it is similar to the distortion of a picture by a curved lens or mirror, as in an amusement park’s fun house, for example.

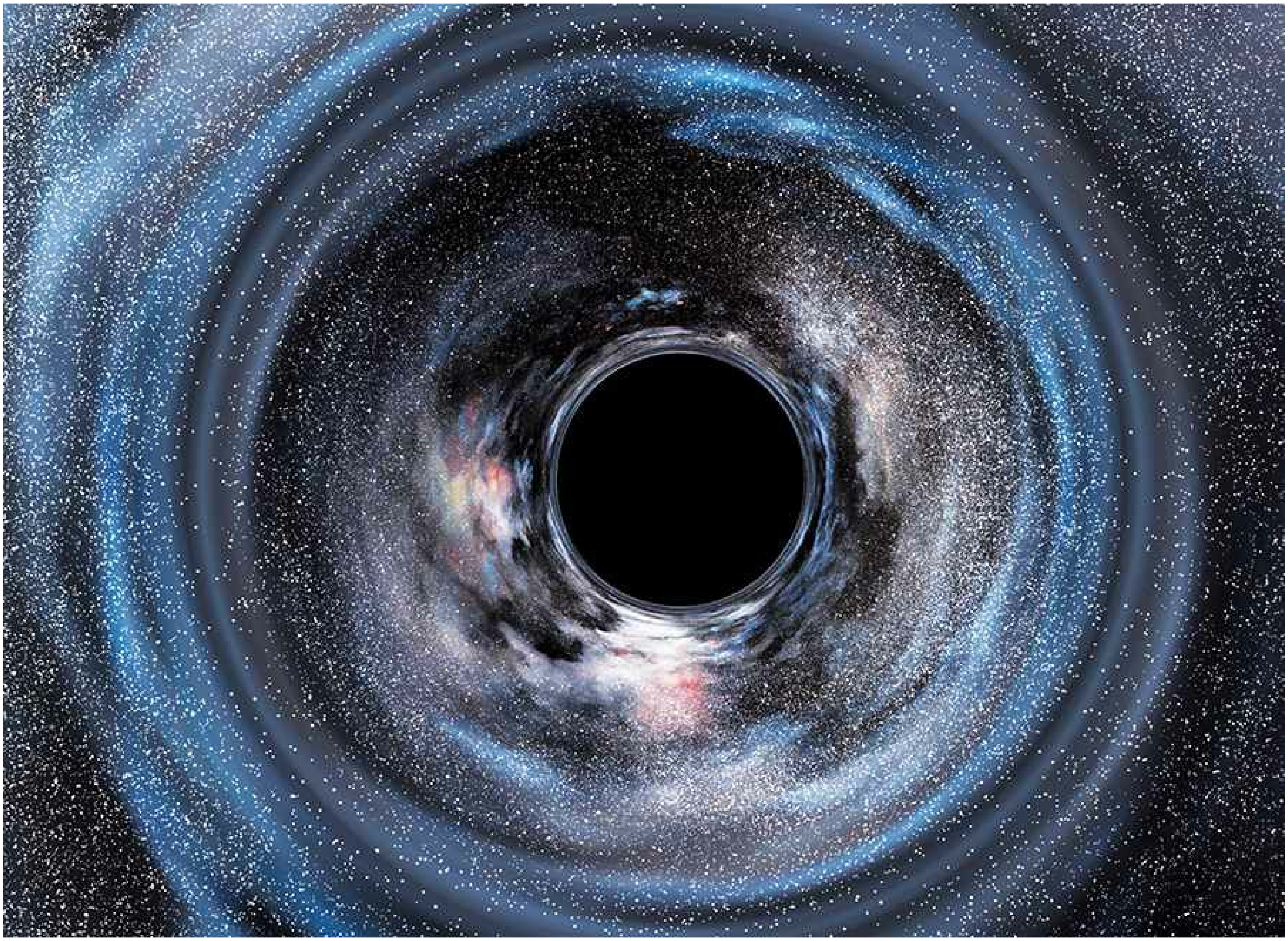


Fig. 3.3. The stars in Gargantua's galaxy, as seen around Gargantua's shadow. Gargantua bends the light rays coming from each star, thereby distorting enormously the appearance of its galaxy: "gravitationally lensing" the galaxy. *[From a simulation for this book by the Double Negative visual-effects team.]*

Einstein's relativistic laws predict, unequivocally, all the properties of black holes from their surfaces outward, including their gravitational lensing.[7] Astronomers have firm observational evidence that black holes exist in our universe, including gigantic black holes like Gargantua. Astronomers have seen gravitational lensing by other objects (for example, Figure 24.3), though not yet by black holes, and the observed lensing is in precise accord with the predictions of Einstein's relativistic laws. This is enough for me. Gargantua's gravitational lensing, as simulated by Paul Franklin's Double Negative team using relativity equations I gave to them, is true. This is what it really would look like.

By contrast, the blight that endangers human life on Earth in *Interstellar* (Figure 3.4 and Chapter 11) is an educated guess in one sense, and a speculation in another. Let me explain.

Throughout recorded history, the crops that humans grow have been plagued by occasional blights (rapidly spreading diseases caused by microbes). The biology that underlies these blights is based on chemistry, which in turn is based on the quantum laws. Scientists do not yet know how to deduce, from the quantum laws, *all* of the relevant chemistry (but they can deduce *much* of it); and they do not yet know how to deduce from chemistry all of the relevant biology. Nevertheless, from observations and experiments, biologists have learned much about blights. The blights encountered by humans thus far have not jumped from infecting one type of plant to another with such speed as to endanger human life. But nothing we know guarantees this can't happen. That such a blight is possible is an *educated guess*. That it might someday occur is a *speculation* that most biologists regard as very unlikely.

Fig. 3.4. Burning blighted corn. *[From* Interstellar*, used courtesy of Warner Bros. Entertainment Inc.]*

The gravitational anomalies that occur in *Interstellar* (Chapters 24 and 25), for example, the coin Cooper tosses that suddenly plunges to the floor, are *speculations*. So is harnessing the anomalies to lift colonies off Earth (Chapter 31).

Although experimental physicists when measuring gravity have searched hard for anomalies—behaviors that cannot be explained by the Newtonian or relativistic laws—no convincing gravitational anomalies have ever been seen on Earth.

However, it seems likely from the quest to understand quantum gravity that our universe is a membrane (physicists call it a "brane") residing in a higher-dimensional "hyperspace" to which physicists give the name "bulk"; see Figure 3.5 and Chapters 4 and 21. When physicists carry Einstein's relativistic laws into this bulk, as Professor Brand does on the blackboard in his office

(Figure 3.6), they discover the possibility of gravitational anomalies—anomalies triggered by physical fields that reside in the bulk.

We are far from sure that the bulk really exists. And it is only an educated guess that, if the bulk does exist, Einstein's laws reign there. And we have no idea whether the bulk, if it exists, contains fields that can generate gravitational anomalies, and if so, whether those anomalies can be harnessed. The anomalies and their harnessing are a rather extreme speculation. But they are a speculation based on science that I and some of my physicist friends are happy to entertain—at least late at night over beer. So they fall within the guidelines I advocated for *Interstellar:* "Speculations . . . will spring from real science, from ideas that at least some 'respectable' scientists regard as possible" (Chapter 1).

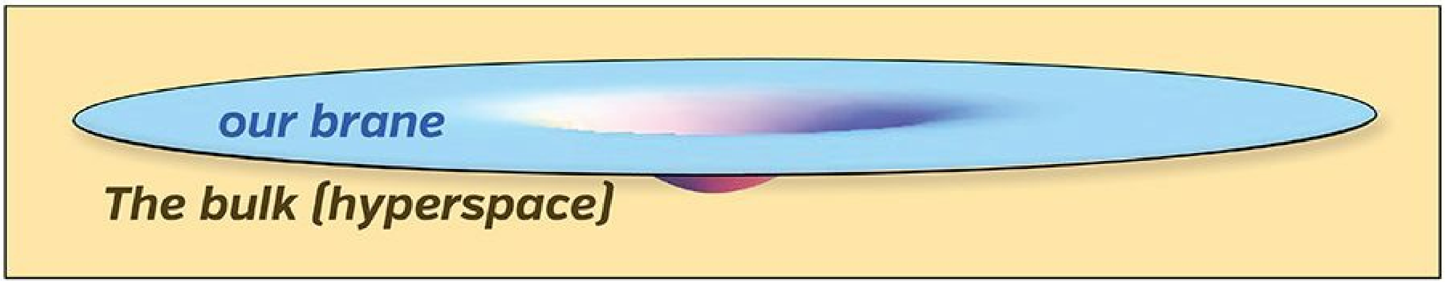


Fig. 3.5. Our universe, in the vicinity of the Sun, depicted as a two-dimensional surface or brane, residing in a three-dimensional bulk. In reality, our brane has three space dimensions and the bulk has four. This figure is explained further in Chapter 4; see especially Figure 4.4.

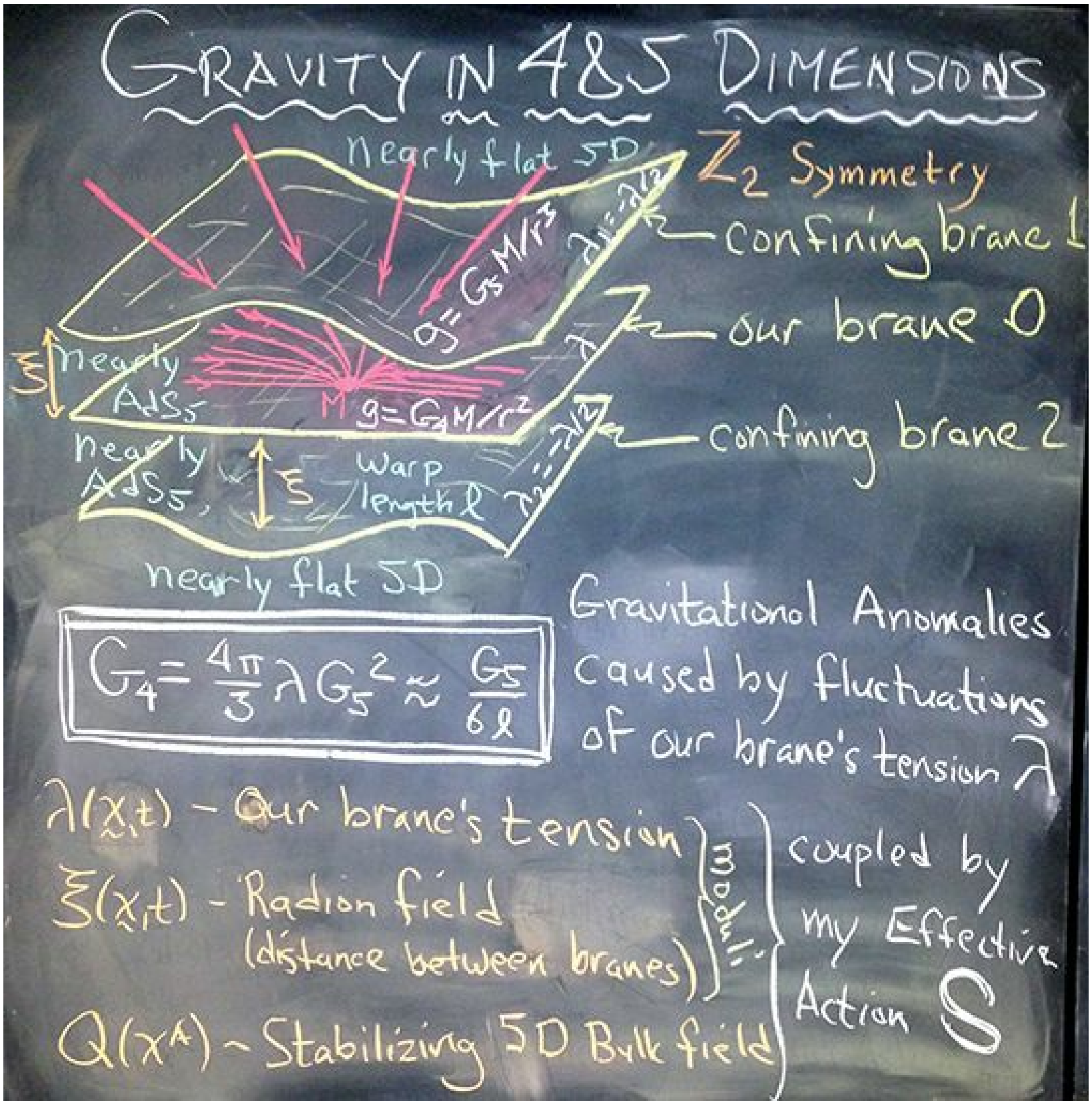


Fig. 3.6. Relativity equations on Professor Brand's blackboard, describing possible foundations for gravitational anomalies. For details see Chapter 25.

Throughout this book, when discussing the science of *Interstellar*, I explain the status of that science—truth, educated guess, or speculation—and I label it so at the beginning of a chapter or section with a symbol:

- (T) for truth
- (EG) for educated guess
- (S) for speculation

Of course, the status of an idea—truth, educated guess, or speculation—can change; and you'll meet such changes occasionally in the movie and in this book. For Cooper, the bulk is an educated guess that becomes a truth when he goes there in the tesseract (Chapter 29); and the laws of quantum gravity are a speculation until TARS extracts them from inside a black hole so for Cooper and Murph they become truth (Chapters 28 and 30).

For nineteenth-century physicists, Newton's inverse square law for gravity was an absolute truth. But around 1890 it was revolutionarily upended by a tiny observed anomaly in the orbit of Mercury around the Sun (Chapter 24). Newton's law is very nearly correct in our solar system, but not quite. This anomaly helped pave the way for Einstein's twentieth-century relativistic laws, which—in the realm of strong gravity—began as speculation, became an educated guess when observational data started rolling in, and by 1980, with ever-improving observations, evolved into truth (Chapter 4).

Revolutions that upend established scientific truth are exceedingly rare. But when they happen, they can have profound effects on science and technology.

Can you identify in your own life speculations that became educated guesses and then truth? Have you ever seen your established truths upended, with a resulting revolution in your life?

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5 In these realms, for example, the energy of light has huge quantum fluctuations. They are so huge that they warp space and time enormously and randomly. The fluctuating warpage is beyond the scope of Einstein's relativistic laws, and the warpage's influence on the light is beyond the scope of the light's quantum laws.

6 The phrase "fiery marriage" was coined by my mentor John Wheeler, who was superb at naming things. John also coined the words "black hole" and "wormhole" and the phrase "a black hole has no hair"; Chapters 14 and 5. He once described to me lying in a warm bath for hours on end, letting his mind soar in a search for just the right word or phrase.

7 Chapters 5, 6, and 8.

4

Warped Time and Space, and Tidal Gravity

Ⓣ

Einstein's Law of Time Warps

Einstein struggled to understand gravity on and off from 1907 onward. Finally in 1912 he had a brilliant inspiration. Time, he realized, must be warped by the masses of heavy bodies such as the Earth or a black hole, and that warping is responsible for gravity. He embodied this insight in what I like to call "Einstein's law of time warps," a precise mathematical formula[8] that I describe qualitatively this way: *Everything likes to live where it will age the most slowly, and gravity pulls it there*.

The greater the slowing of time, the stronger gravity's pull. On Earth, where time is slowed by only a few microseconds per day, gravity's pull is modest. On the surface of a neutron star, where time is slowed by a few hours per day, gravity's pull is enormous. At the surface of a black hole, time is slowed to a halt, whence gravity's pull is so humungous that nothing can escape, not even light.

This slowing of time near a black hole plays a major role in *Interstellar*. Cooper despairs of ever seeing his daughter Murph again, when his travel near Gargantua causes him to age only a few hours while Murph, on Earth, is aging eight decades.

Human technology was too puny to test Einstein's law until nearly half a century after he formulated it. The first good test came in 1959 when Bob Pound and Glen Rebca used a new technique called the Mössbauer effect to compare the rate of flow of time in the basement of a 73-foot tower at Harvard University with time in the tower's penthouse. Their experiment was exquisitely accurate: good enough to detect differences of 0.0000000000016 seconds (1.6 trillionths of a second) in one day. Remarkably, they found a difference 130 times larger than this accuracy and in excellent agreement with Einstein's law: Time flows more slowly in the basement than in the penthouse by 210-trillionths of a second each day.

The accuracy improved in 1976, when Robert Vessot of Harvard flew an atomic clock on a NASA rocket to a 10,000-kilometer height, and used radio signals to compare its ticking rate with clocks on the ground (Figure 4.1). Vessot found that time on the ground flows more slowly than at a height of 10,000 kilometers by about 30 microseconds (0.00003 seconds) in one day, and his measurement agreed with Einstein's law of time warps to within his experimental accuracy. That accuracy (the uncertainty in Vessot's measurement) was seven parts in a hundred thousand: 0.00007 of 30 microseconds in a day.

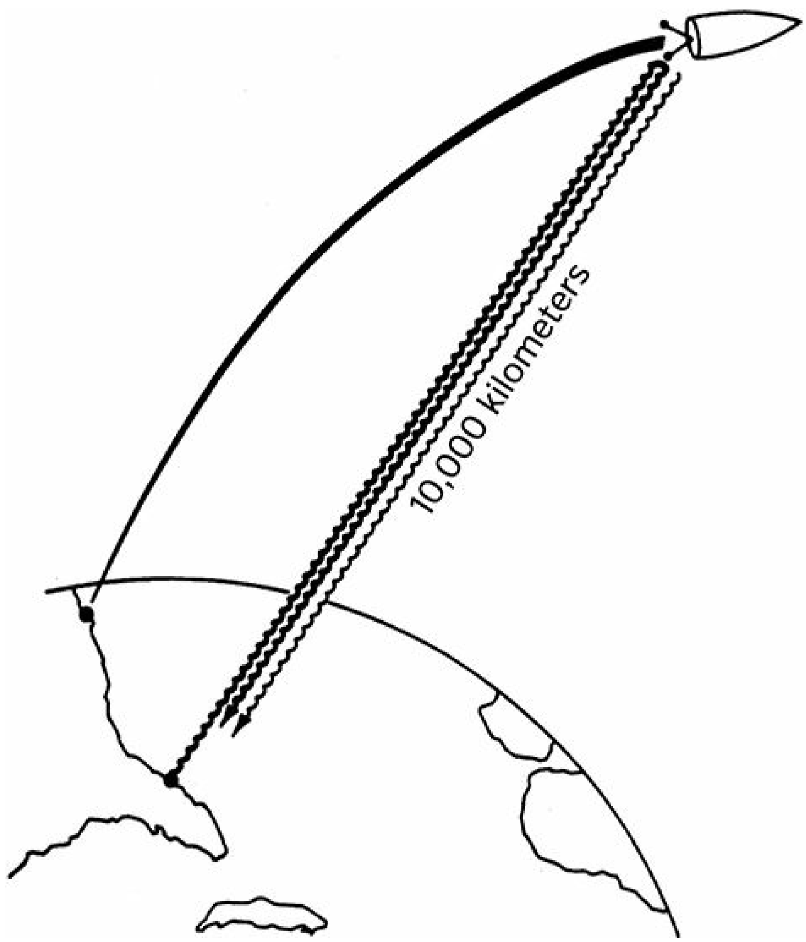

Fig. 4.1. Atomic clocks measure slowing of time on Earth.
[Reproduced from Was Einstein Right? Putting General Relativity to the Test*, by Clifford M. Will (Basic Books, 1993).]*

The global positioning system (GPS), by which our smart phones can tell us where we are to 10 meters' accuracy, relies on radio signals from a set of 27 satellites at a height of 20,000 kilometers (Figure 4.2). Typically only four to twelve satellites can be seen at once from any location on Earth. Each radio signal from a viewable satellite tells the smart phone where the satellite is located and the time the signal was transmitted. The smart phone measures the signal's arrival time and compares it with its transmission time to learn how far the signal traveled—the distance between satellite and phone. Knowing the locations and distances to several satellites, the smart phone can triangulate to learn its own location.

This scheme would fail if the signal transmission times were the true times measured on the satellite. Time at a 20,000-kilometer height flows more rapidly than on Earth by forty microseconds each day, and the satellites must correct for this. They measure time with their own clocks, then slow that time down to the rate of time flow on Earth before transmitting it to our phones.

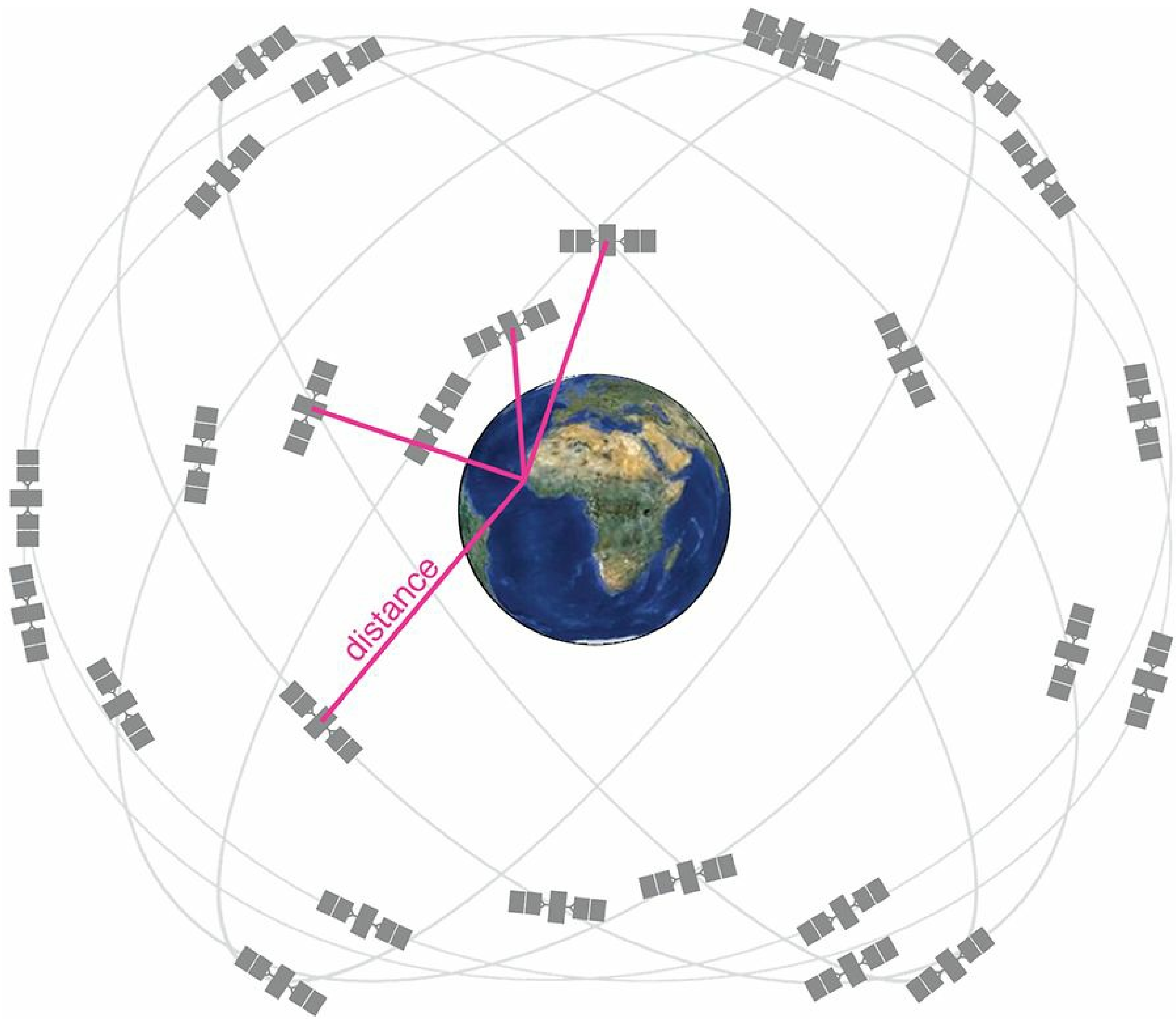

Fig. 4.2. The global positioning system.

Einstein was a genius. Perhaps the greatest scientist ever. This is one of many examples where his insights about the laws of physics could not be tested in his own day. It required a half century for technology to improve enough for a test with high precision, and another half century until the phenomena he described became part of everyday life. Among other examples are the laser, nuclear energy, and quantum cryptography.

The Warping of Space: The Bulk and Our Brane

In 1912 Einstein realized that if time can be warped by massive bodies, then space must also be warped. But despite the most intense mental struggle of his life, the full details of space warps long eluded him. From 1912 to late 1915 he struggled. Finally in November 1915, in a great Eureka moment, he formulated his "field equation of general relativity," which encapsulated all his relativistic laws including space warps.

Again, human technology was too puny for high-precision tests.[9] This time the needed improvements took sixty years, culminating in several key experiments. The one I liked best was led by Robert Reasenberg and Irwin Shapiro of Harvard. In 1976–77 they transmitted radio signals to two spacecraft in orbit around Mars. The spacecraft, called *Viking 1* and *Viking 2*, amplified the signals and sent them back to Earth, where their round-trip travel time was measured. As the Earth and Mars moved around the Sun in their orbits, the radio signals traversed paths that were changing. At first, the paths were far from the Sun, then they passed near the Sun, and then far again, as shown in the bottom half of Figure 4.3.

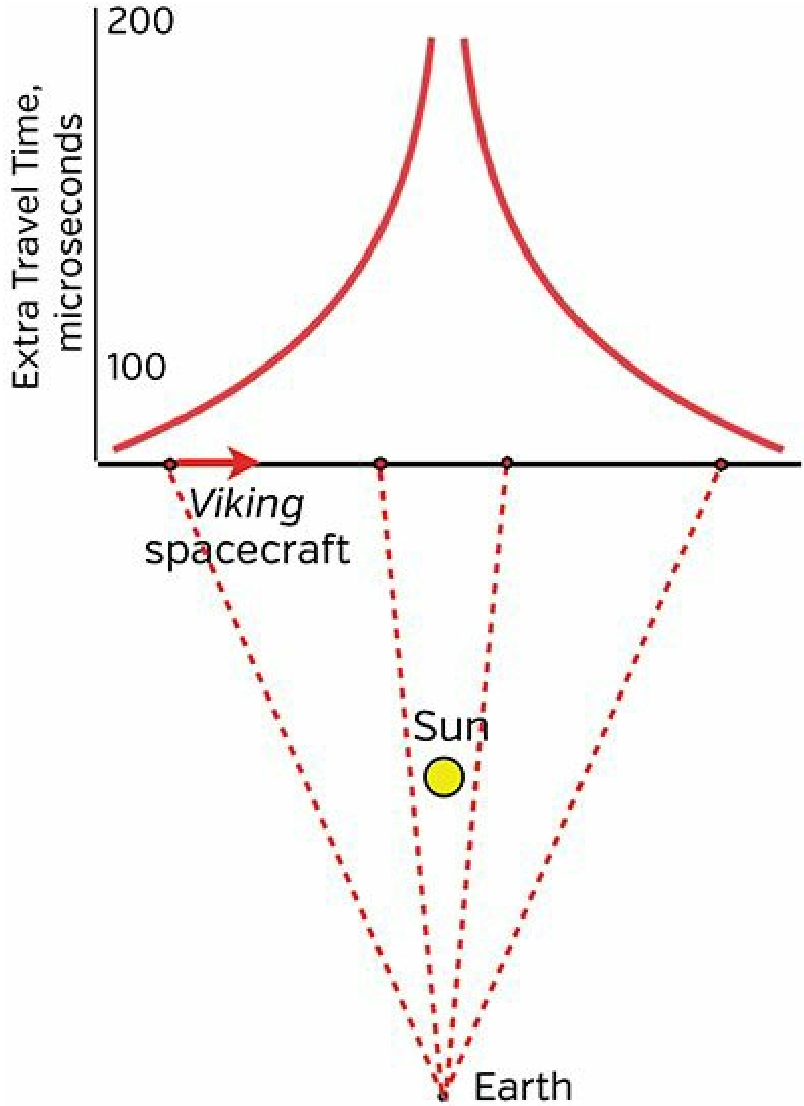

Fig. 4.3. Travel time for radio signals from Earth to *Viking* to Earth.

If space were flat, the round-trip travel time would have changed gradually and steadily. It did not. When the radio waves passed near the Sun, their travel time was longer than expected, longer by hundreds of microseconds. The extra travel time is shown, as a function of the spacecraft's location at the top of Figure 4.3; it went up and then back down. Now, one of Einstein's relativistic laws says that radio waves and light travel at an absolutely constant, unchanging speed.[10] Therefore, the distance from Earth to the spacecraft had to be longer than expected when passing near the Sun, longer by hundreds of microseconds times the speed of light: about 50 kilometers.

This greater length would be impossible if space were flat, like a sheet of paper. It is produced by the Sun's space warp. From the extra time delay and how it changed as the spacecraft moved relative to Earth, Reasenberg and Shapiro inferred the shape of the space warp. More precisely, they inferred the shape of the two-dimensional surface formed by the paths of the *Viking* radio signals. That surface was very nearly the Sun's equatorial plane, so I describe it that way here.

The shape that the team measured, for the Sun's equatorial plane, is shown in Figure 4.4 with the magnitude of the warping exaggerated. The measured shape was precisely what Einstein's relativistic laws predict—precise to within the experimental error, which was 0.001 of the actual warping, that is, a part in a thousand. Around a neutron star, the space warp is far greater. Around a black hole, it is enormously greater.

Now, the Sun's equatorial plane divides space into two identical halves, that above the plane and that below. Nonetheless, Figure 4.4 shows the equatorial plane as warped like the surface of a bowl. It bends downward inside and near the Sun, so that diameters of circles around the Sun, when multiplied by π (3.14159 . . .), are larger than circumferences—larger, in the case of the Sun, by roughly 100 kilometers. That's not much, but it was easily measured by the spacecraft, with a precision of a part in a thousand.

How can space "bend down"? Inside *what* does it bend? It bends inside a higher-dimensional hyperspace, called "the bulk," that is not part of our universe!

Let's make that more precise. In Figure 4.4 the Sun's equatorial plane is a two-dimensional surface that bends downward in a three-dimensional bulk. This motivates the way we physicists think about our full universe. Our universe has three space dimensions (east-west, north-south, up-down), and we think of it as a three-dimensional membrane or *brane* for short that is warped in a higher-dimensional *bulk*. How many dimensions does the bulk have? I discuss this carefully in Chapter 21, but for the purposes of *Interstellar*, the bulk has just one extra space dimension: four space dimensions in all.

Now, it's very hard for humans to visualize our three-dimensional universe, our full brane, living and bending in a four-dimensional bulk. So throughout this book I draw pictures of our brane and bulk with one dimension removed, as I did in Figure 4.4.

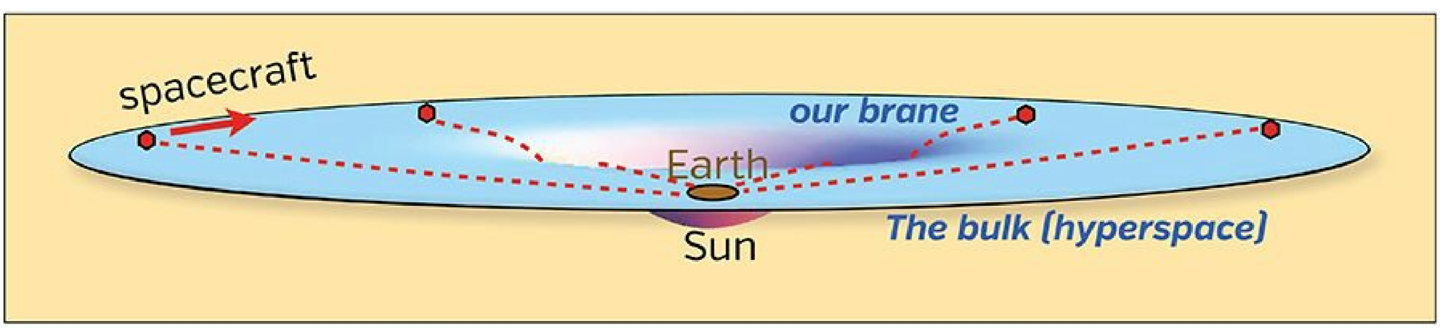

Fig. 4.4. Paths of *Viking* radio signals through the Sun's warped equatorial plane.

In *Interstellar*, the characters often refer to *five* dimensions. Three are the space dimensions of our own universe or brane (east-west, north-south, up-down). The fourth is time, and the fifth is the bulk's extra space dimension.

Does the bulk really exist? Is there truly a fifth dimension, and maybe even more, that humans have never experienced? Very likely yes. We'll explore this in Chapter 21.

The warping of space (warping of our brane) plays a huge role in *Interstellar*. For example, it is crucial to the very existence of the wormhole connecting our solar system to the far reaches of the universe, where Gargantua lives. And it distorts the sky around the wormhole and around the black hole Gargantua; this is the gravitational lensing we met in Figure 3.3.

Figure 4.5 is an extreme example of space warps. It is a fanciful drawing by my artist friend Lia Halloran, depicting a hypothetical region of our universe that contains large numbers of wormholes (Chapter 14) and black holes (Chapter 5) extending outward from our brane into and through the bulk. The black holes terminate in sharp points called "singularities." The wormholes connect one region of our brane to another. As usual, I suppress one of our brane's three dimensions, so the brane looks like a two-dimensional surface.

Fig. 4.5. Black holes and wormholes extending out of our brane into and through the bulk. One space dimension is removed from both our brane and the bulk. *[Drawing by the artist Lia Halloran.]*

Tidal Gravity

Einstein's relativistic laws dictate that planets, stars, and unpowered spacecraft near a black hole move along the straightest paths permitted by the hole's warped space and time. Figure 4.6 shows examples of four such paths. The two purple paths headed into the black hole begin parallel to each other. As each path tries to remain straight, the two paths get driven toward each other. The warping of space and time drives them together. The green paths, traveling circumferentially around the hole, also begin parallel. But in this case, the warping drives them apart.

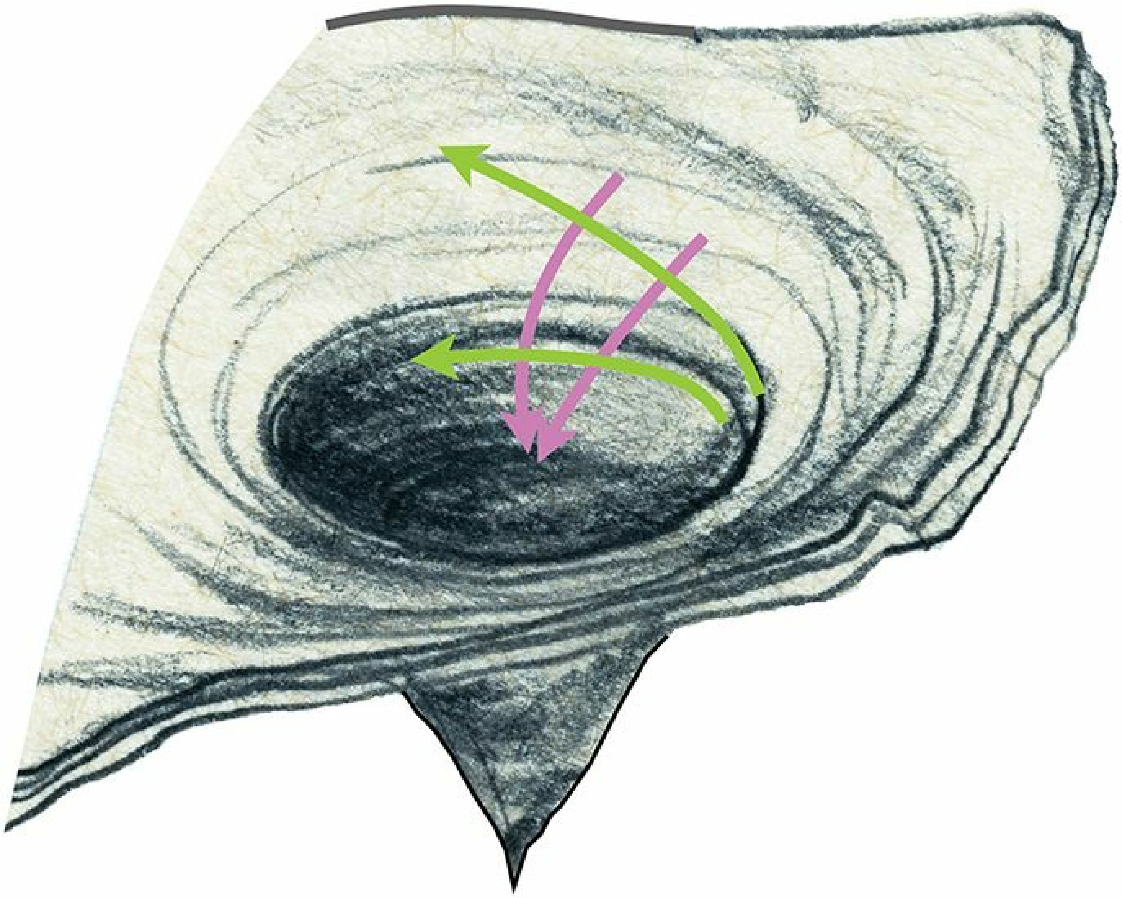

Fig. 4.6. Four paths for planetary motion in the vicinity of a black hole. The picture of the hole is extracted from Lia Halloran's drawing, Figure 4.5.

Several years ago, my students and I discovered a new point of view about these planetary paths. In Einstein's relativity theory there is a mathematical quantity called the Riemann tensor. It describes the details of the warping of space and time. We found, hidden in the mathematics of this Riemann tensor, lines of force that squeeze some planetary paths together and stretch others apart. "Tendex lines," my student David Nichols dubbed them, from the Latin word *tendere* meaning "to stretch."

Figure 4.7 shows several of these tendex lines around the black hole of Figure 4.6. The green paths begin, on their right ends, parallel to each other, and then the red tendex lines stretch them apart. I draw a woman lying on a red tendex line. It stretches her, too; she feels a stretching force between her head and her feet, exerted by the red tendex line.

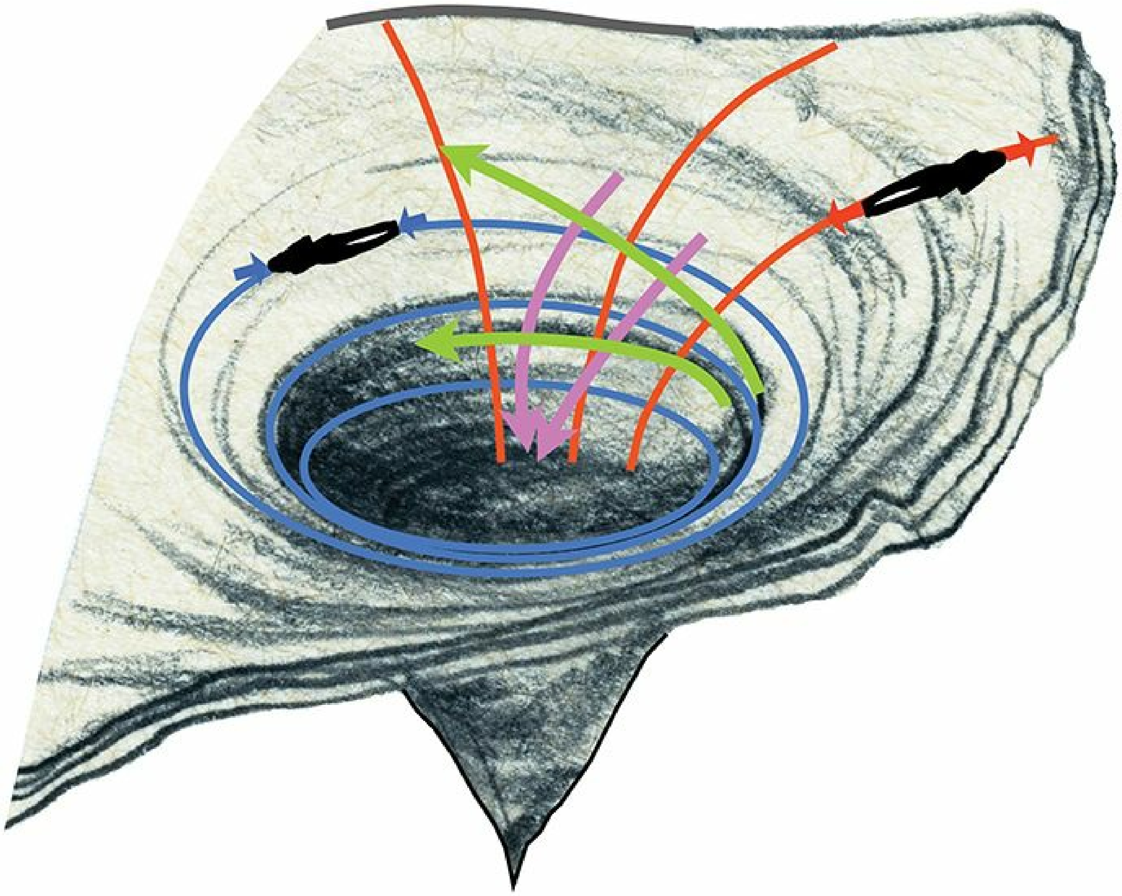

Fig. 4.7. Tendex lines around a black hole. The picture of the hole is extracted from Lia Halloran's drawing, Figure 4.5.

The purple paths begin, at their top ends, running parallel to each other. They are then squeezed together by the blue tendex lines, and the woman whose body lies along a blue tendex line is also squeezed.

This stretching and squeezing is just a different way of thinking about the influence of the warping of space and time. From one viewpoint, the paths are stretched apart or squeezed together due to the planetary paths moving along the straightest routes possible in the warped space and time. From another viewpoint it is the tendex lines that do the stretching and squeezing. Therefore, the tendex lines must, in some very deep way, represent the warping of space and time. And indeed they do, as the mathematics of the Riemann tensor taught us.

Black holes are not the only objects that produce stretching and squeezing forces. Stars and planets and moons also produce them. In 1687 Isaac Newton discovered them in his own theory of gravity and used them to explain ocean tides.

The Moon's gravity pulls more strongly on the near face of the Earth than on the far face, Newton reasoned. And the direction of pull on the Earth's sides is slightly inward, because it is toward the Moon's center, a slightly different direction on the Earth's two sides. This is the usual viewpoint about the Moon's gravity depicted in Figure 4.8.

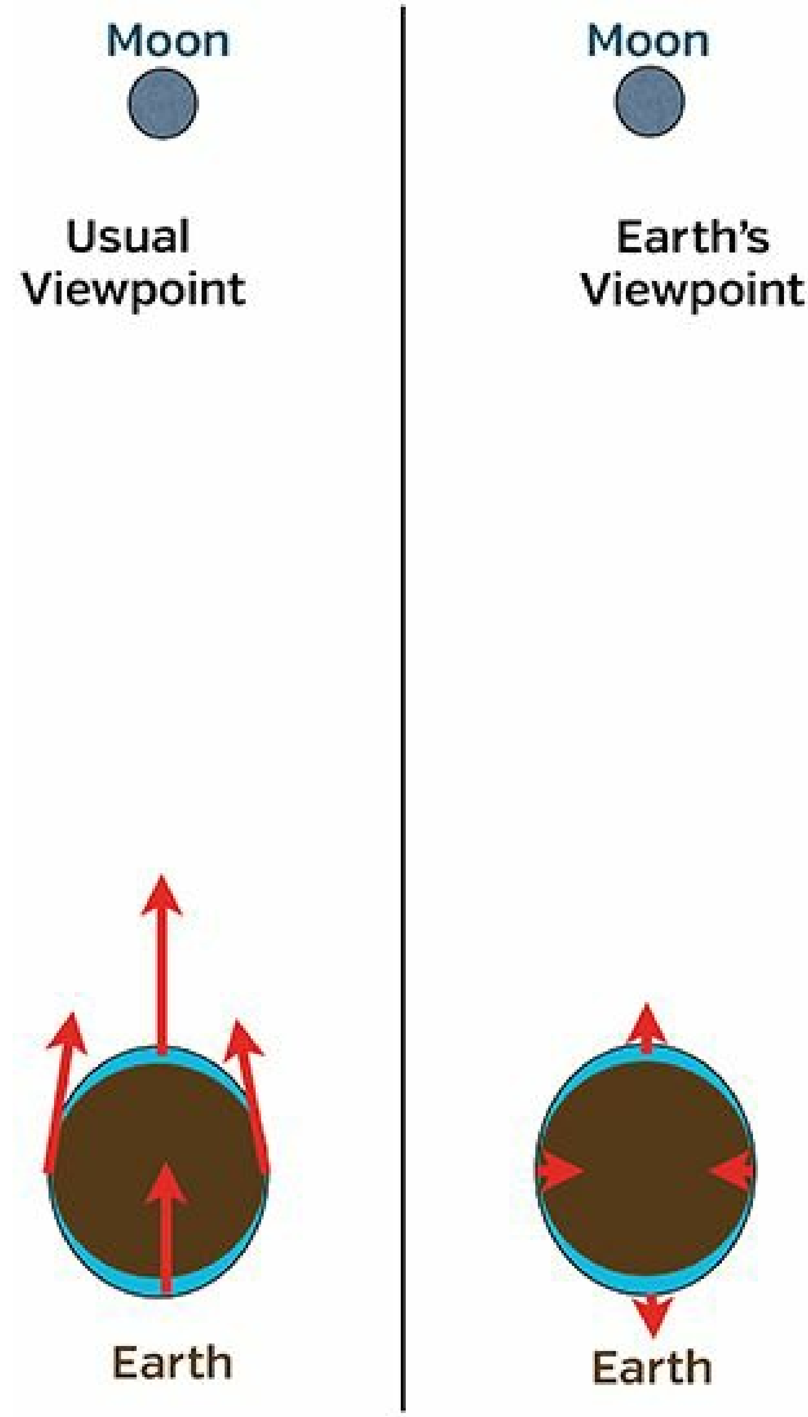

Fig. 4.8. Newton's explanation for the tides on the Earth's oceans.

Now, the Earth does *not feel the average* of these gravitational pulls, because it is falling freely along its orbit.[11] (This is like the *Endurance*'s crew not feeling Gargantua's gravitational pull when they are in the *Endurance*, in its parking orbit above the black hole. They only feel centrifugal forces due to the *Endurance*'s rotation.) What the Earth *does* feel is the red-arrowed lunar pulls in the left half of Figure 4.8, with their average subtracted away; that is, it feels a stretch toward and away from the Moon, and a squeeze on its lateral sides (right half of Figure 4.8). This is qualitatively the same as around a black hole (Figure 4.7).

These felt forces stretch the ocean away from the Earth's surface on the faces toward and away from the Moon, producing high tides there. And the felt forces squeeze the oceans toward the Earth's surface on the Earth's lateral sides, producing low tides there. As the Earth turns on its axis, one full turn each twenty-four hours, we see two high tides and two low tides. This was Newton's explanation of ocean tides, aside from a slight complication: The Sun's tidal gravity also contributes to the tides. Its stretch and squeeze get added to the Moon's stretch and squeeze.

Because of their role in ocean tides, these gravitational squeezing and stretching forces—the forces the Earth *feels*—are called tidal forces. To extremely high accuracy, these tidal forces, computed using Newton's laws of gravity, are the same as we compute using Einstein's relativistic laws. They must be the same, since the relativistic laws and the Newtonian laws always make the same predictions when gravity is weak and objects move at speeds much slower than light.

In the relativistic description of the Moon's tides (Figure 4.9), the tidal forces are produced by blue tendex lines that squeeze the Earth's lateral sides and red tendex lines that stretch toward and away from the Moon. This is just like a black hole's tendex lines (Figure 4.7). The Moon's tendex lines are visual embodiments of the Moon's warping of space and time. It is remarkable that a warping so tiny can produce forces big enough to cause the ocean tides!

Fig. 4.9. Relativistic viewpoint on tides: they are produced by the Moon's tendex lines.

On Miller's planet (Chapter 17) the tidal forces are enormously larger and are key to the huge waves that Cooper and his crew encounter.

We now have three points of view on tidal forces:

- *Newton's viewpoint* (Figure 4.8): The Earth does not feel the Moon's full gravitational pull, but rather the full pull (which varies over the Earth) minus the average pull.
- *The tendex viewpoint* (Figure 4.9): The Moon's tendex lines stretch and squeeze the Earth's oceans; also (Figure 4.7) a black hole's tendex lines stretch and squeeze the paths of planets and stars around the black hole.
- *The straightest-route viewpoint* (Figure 4.6): The paths of stars and planets around a black hole are the straightest routes possible in the hole's warped space and time.

Having three different viewpoints on the same phenomenon can be extremely valuable. Scientists and engineers spend most of their lives trying to solve puzzles. The puzzle may be how to design a spacecraft. Or it may be figuring out how black holes behave. Whatever the puzzle may be, if one viewpoint doesn't yield progress, another viewpoint may. Peering at the puzzle first from one viewpoint and then from another can often trigger new ideas. This is what Professor Brand does, in *Interstellar*, when trying to understand and harness gravitational anomalies (Chapters 24 and 25). This is what I've spent most of my adult life doing.

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8 See *Some Technical Notes* at the end of this book.

9 But see the first section of Chapter 24.

10 Unchanging after well-understood corrections for a bit of slowdown due to interaction with electrons in interplanetary space—so-called "plasma corrections."

11 In 1907, Einstein realized that if he were to fall, off the roof of his house for example, then as he fell he would feel no gravity. He called this the "happiest thought of my life," because it got him started on his quest to understand gravity, the quest that led to his concepts of warped time and space and the laws that govern the warping.

5

Black Holes

The black hole Gargantua plays a major role in *Interstellar*. Let's look at the basic facts about black holes in this chapter and then focus on Gargantua in the next.

First, a weird claim: *Black holes* are made from warped space and warped time. Nothing else—no matter whatsoever.

Now some explanation.

Ant on a Trampoline: A Black Hole's Warped Space

Imagine you're an ant and you live on a child's trampoline—a sheet of rubber stretched between tall poles. A heavy rock bends the rubber downward, as shown in Figure 5.1. You're a blind ant, so you can't see the poles or the rock or the bent rubber sheet. But you're a smart ant. The rubber sheet is your entire universe, and you suspect it's warped. To determine its shape, you walk around a circle in the upper region measuring its circumference, and then walk through the center from one side of the circle to the other, measuring its diameter. If your universe were flat, then the circumference would be π = 3.14159... times the diameter. But the circumference, you discover, is far smaller than the diameter. Your universe, you conclude, is highly warped!

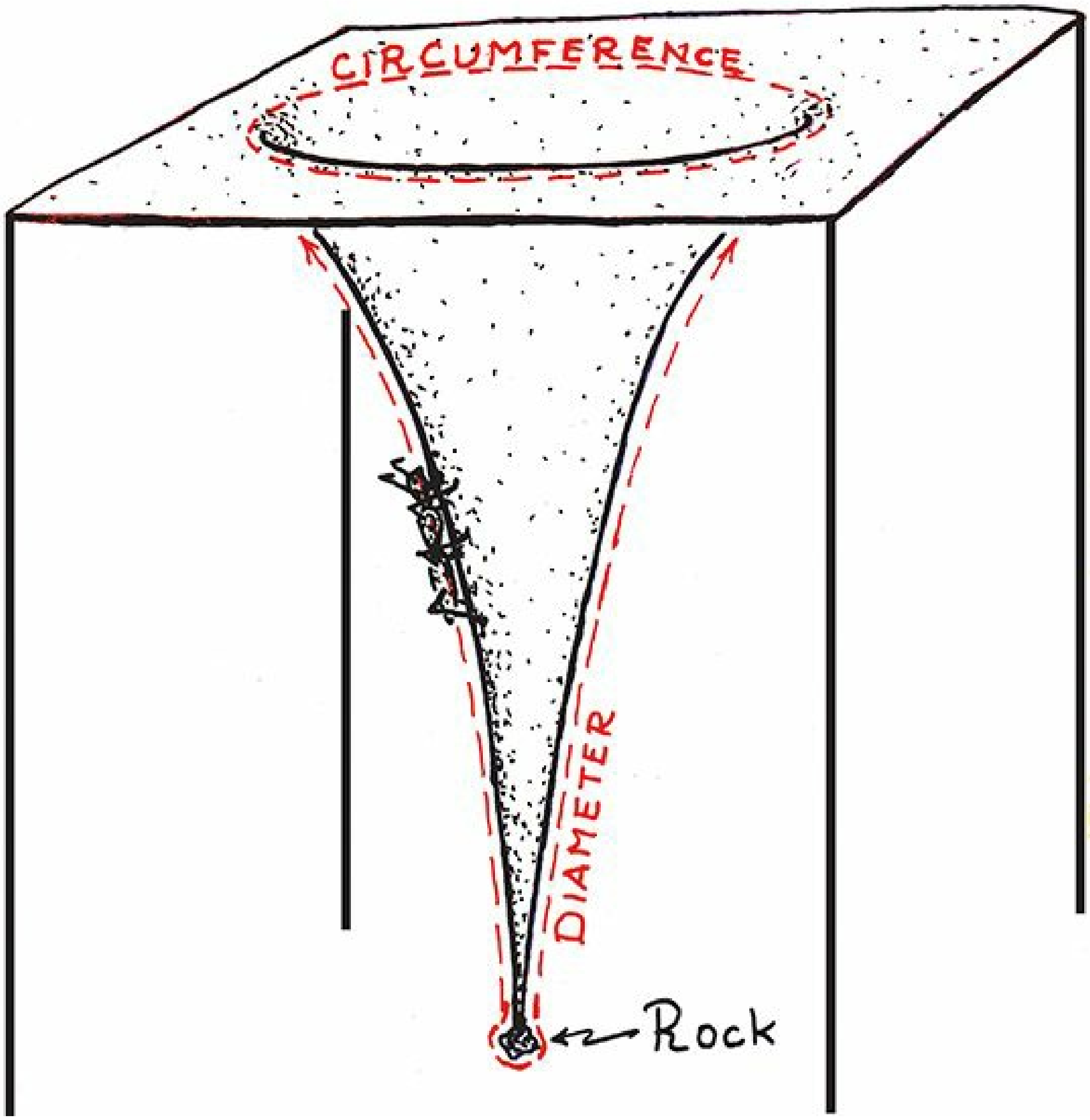

Fig. 5.1. An ant on a warped trampoline. *[My own hand sketch.]*

Space around a nonspinning black hole has the same warping as the trampoline: Take an equatorial slice through the black hole. This is a two-dimensional surface. As seen from the bulk, this surface is warped in the same manner as the trampoline. Figure 5.2 is the same as Figure 5.1, with the ant and poles removed and the rock replaced by a *singularity* at the black hole's center.

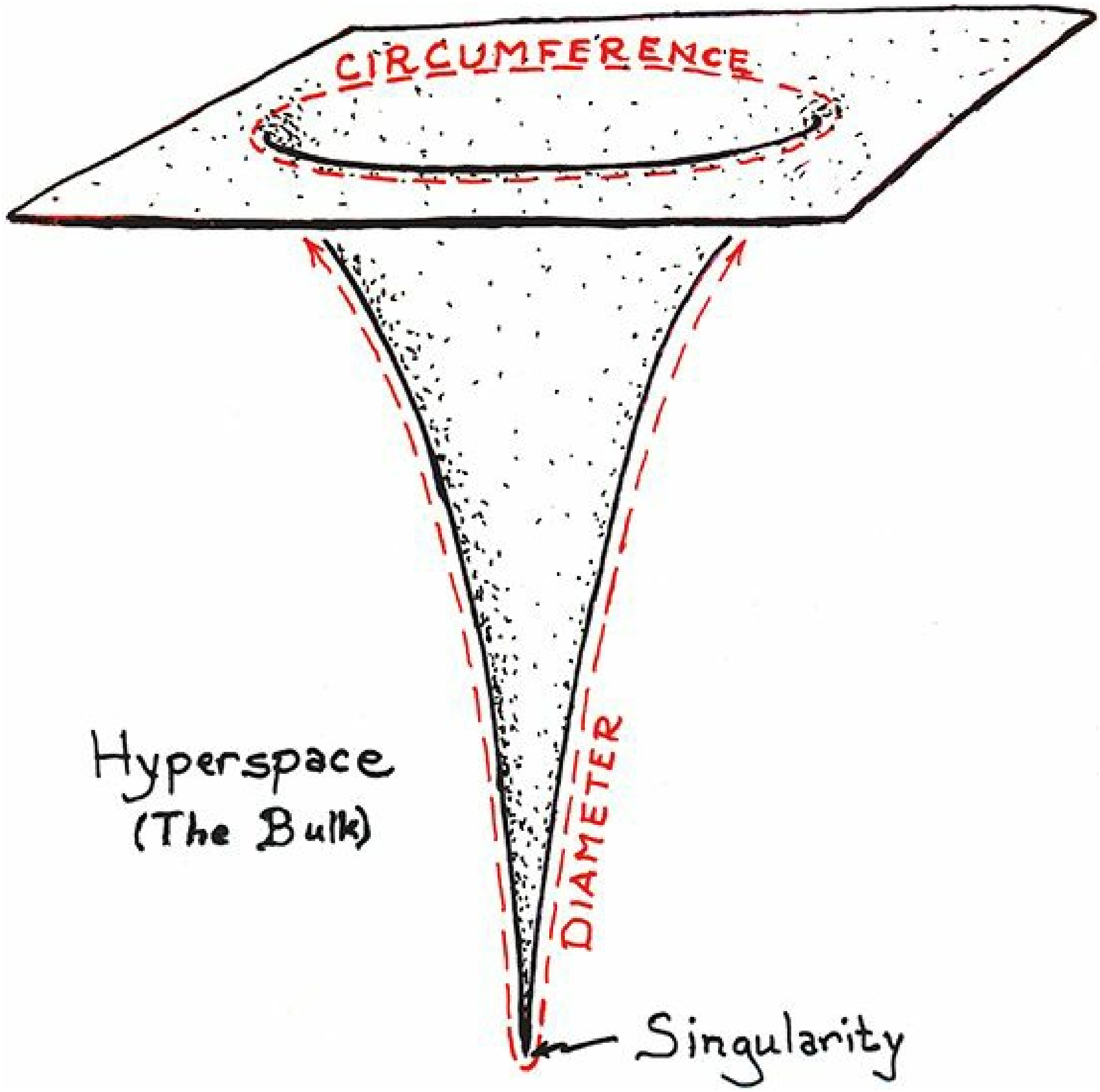

Fig. 5.2. The warped space inside and around a black hole, as seen from the bulk. *[My own hand sketch.]*

The singularity is a tiny region where the surface forms a point and thus is “infinitely warped,” and where, it turns out, tidal gravitational forces are infinitely strong, so matter as we know it gets stretched and squeezed out of existence. In chapters 26, 28, and 29, we see that Gargantua’s singularity is somewhat different from this one, and why.

For the trampoline, the warping of space is produced by the rock’s weight. Similarly, one might suspect, the black hole’s space warp is produced by the singularity at its center. Not so. In fact, the hole’s space is warped by the enormous energy of its warping. Yes, that’s what I meant to say. If this seems a bit circular to you, well, it is, but it has deep meaning.

Just as it requires a lot of energy to bend a stiff bow in preparation for shooting an arrow, so it requires a lot of energy to bend space; to warp it. And just as the bending energy is stored in the bent bow (until the string is released and feeds the bow’s energy into the arrow), so the warping energy is stored in the black hole’s warped space. And for a black hole, that energy of warping is so great that it generates the warping.

Warping begets warping in a nonlinear, self-bootstrapping manner. This is a fundamental feature of Einstein’s relativistic laws, and so different from everyday experience. It’s somewhat like a hypothetical science-fiction character who goes backward in time and gives birth to herself.

This warping-begets-warping scenario does not happen in our solar system hardly at all. Throughout our solar system the space warps are so weak that their energy is minuscule, far too small to produce much bootstrapped warping. Almost all the space warping in our solar system is produced directly by matter—the Sun's matter, the Earth's matter, the matter of the other planets—by contrast with a black hole where the warping is fully responsible for the warping.

Event Horizon and Warped Time

When you first hear mention of a black hole, you probably think of its trapping power as depicted in Figure 5.3, not its warped space.

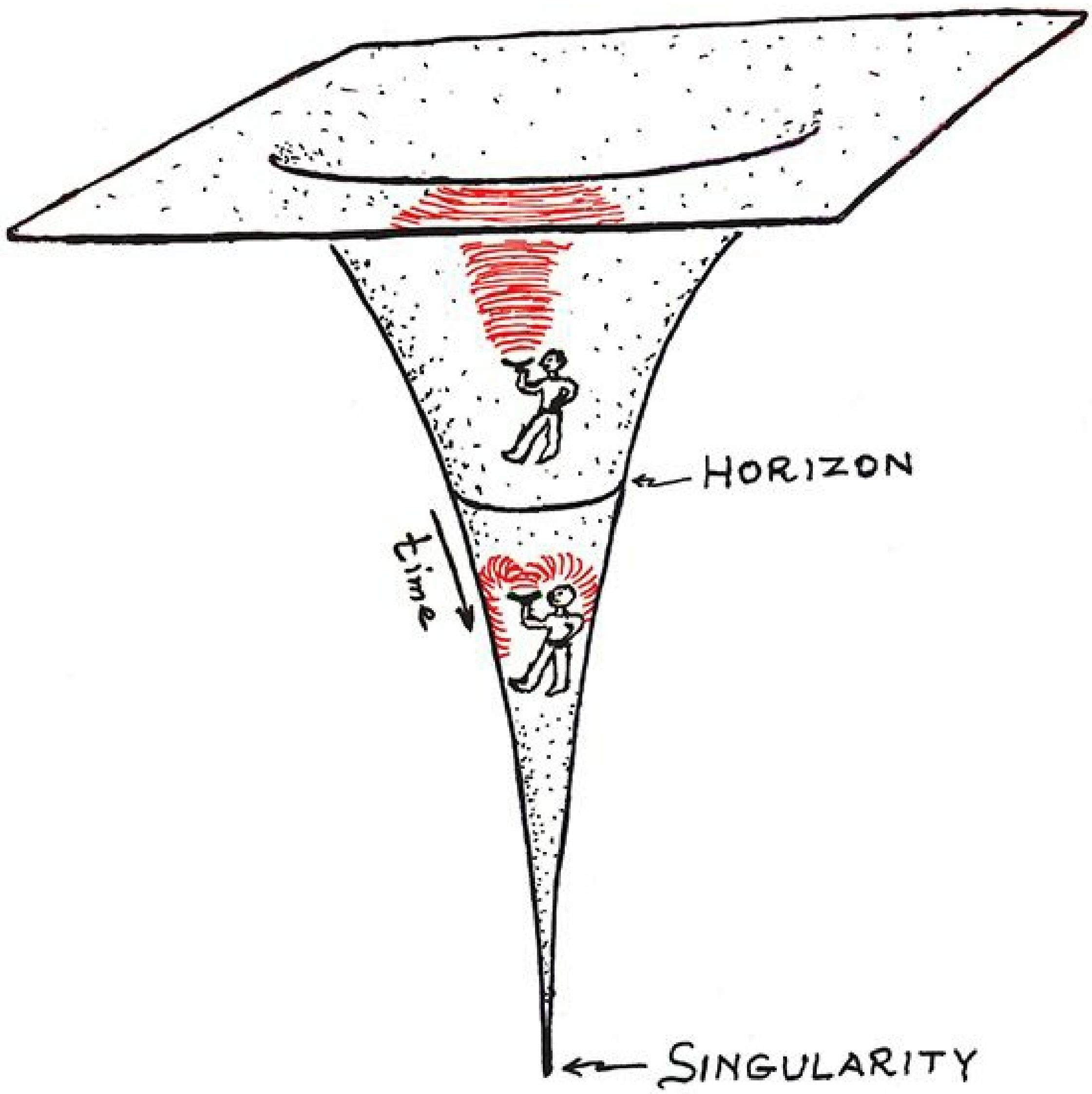

Fig. 5.3. Signals I send after crossing the event horizon can't get out. *Note:* Because one space dimension is removed from this diagram, I am a two-dimensional Kip, sliding down the warped two-dimensional surface, part of our brane. *[My own hand sketch.]*

If I fall into a black hole carrying a microwave transmitter, then once I pass through the hole's *event horizon*, I'm pulled inexorably on downward, into the hole's singularity. And any signals I try to transmit in any manner whatsoever get pulled down with me. Nobody above the horizon can ever see the signals I send after I cross the horizon. My signals and I are trapped inside the black hole. (See Chapter 28 for how this plays out in *Interstellar*.)

This trapping is actually caused by the hole's time warp. If I hover above the black hole, supporting myself by the blast of a rocket engine, then the closer I am to the horizon, the more slowly my time flows. At the horizon itself, time slows to a halt and, therefore, according to Einstein's law of time warps, I must experience an infinitely strong gravitational pull.

What happens inside the event horizon? Time is so extremely warped there that it flows in a direction you would have thought was spatial: it flows downward toward the singularity. That downward flow, in fact, is why nothing can escape from a black hole. Everything is drawn inexorably toward the future,[12] and since the future inside the hole is downward, away from the horizon, nothing can escape back upward, through the horizon.

Space Whirl

Black holes can spin, just as the Earth spins. A spinning hole drags space around it into a vortex-type, whirling motion (Figure 5.4). Like the air in a tornado, space whirls fastest near the hole's center, and the whirl slows as one moves outward, away from the hole. Anything that falls toward the hole's horizon gets dragged, by the whirl of space, into a whirling motion around and around the hole, like a straw caught and dragged by a tornado's wind. Near the horizon there is no way whatsoever to protect oneself against this whirling drag.

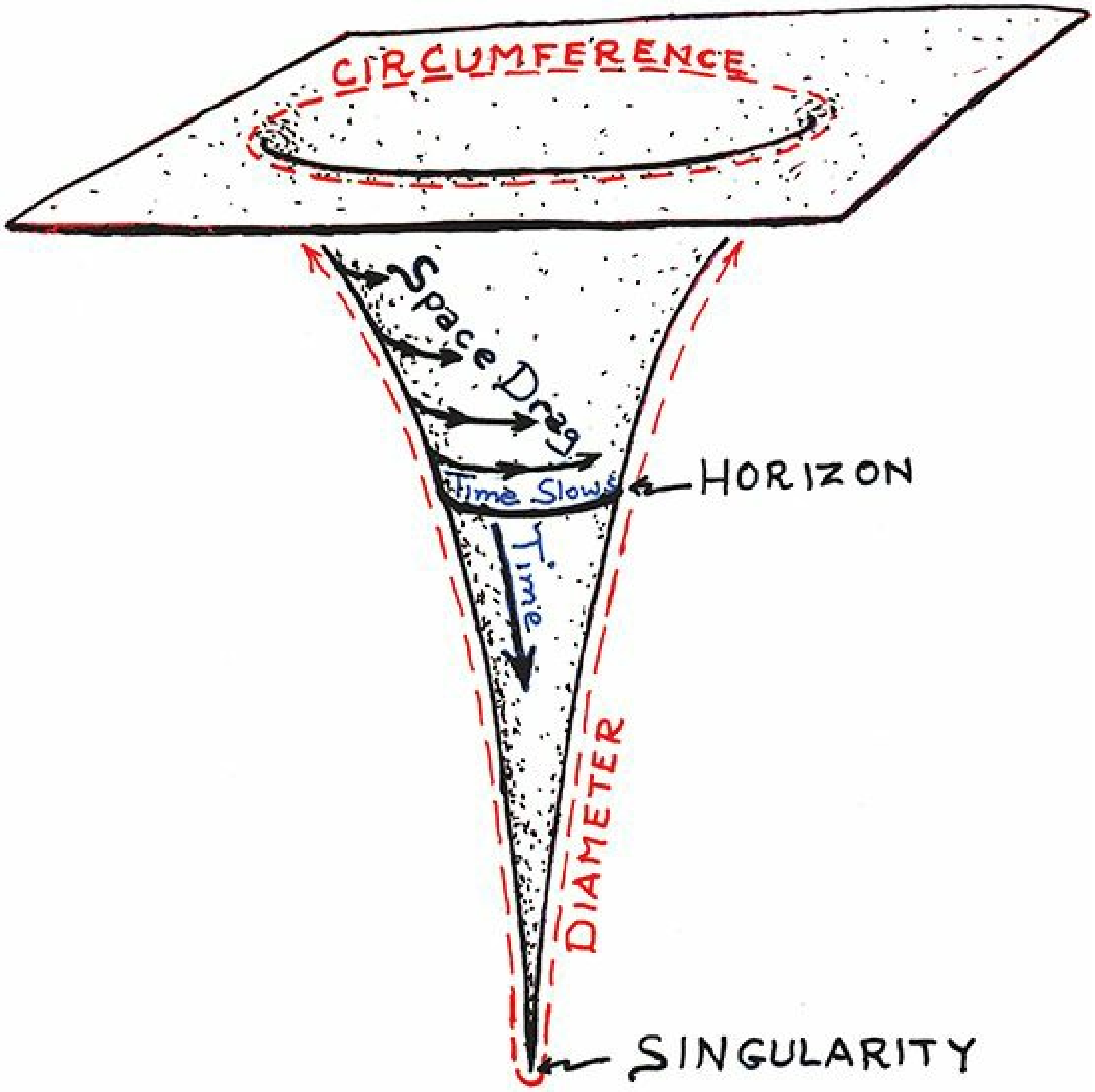

Fig. 5.4. Space around a spinnning black hole is dragged into whirling motion. *[My own hand sketch.]*

Precise Depiction of the Warped Space and Time Around a Black Hole

These three aspects of spacetime warping—the warp of space, the slowing and distortion of time, and the whirl of space—are all described by mathematical formulas. These formulas have been deduced from Einstein's relativistic laws, and their precise predictions are depicted quantitatively in Figure 5.5 (by contrast with Figures 5.1–5.4, which were only qualitative).

The warped shape of the surface in Figure 5.5 is precisely what we would see from the bulk, when looking at the hole's equatorial plane. The colors depict the slowing of time as measured by someone who hovers at a fixed height above the horizon. At the transition from blue to green, time flows 20 percent as fast as it flows far from the hole. At the transition from yellow to red, time is slowed to 10 percent of its normal rate far away. And at the black circle, the bottom of the surface, time slows to a halt. This is the event horizon. It is a circle, not a sphere, because we are looking only at the equatorial plane, only at two dimensions of our universe (of our brane). If we were to restore the third space dimension, the horizon would become a flattened sphere: a spheroid. The white arrows depict the rate at which space whirls around the black hole. The whirl is fast at the horizon, and decreases as we climb upward in a spacecraft.

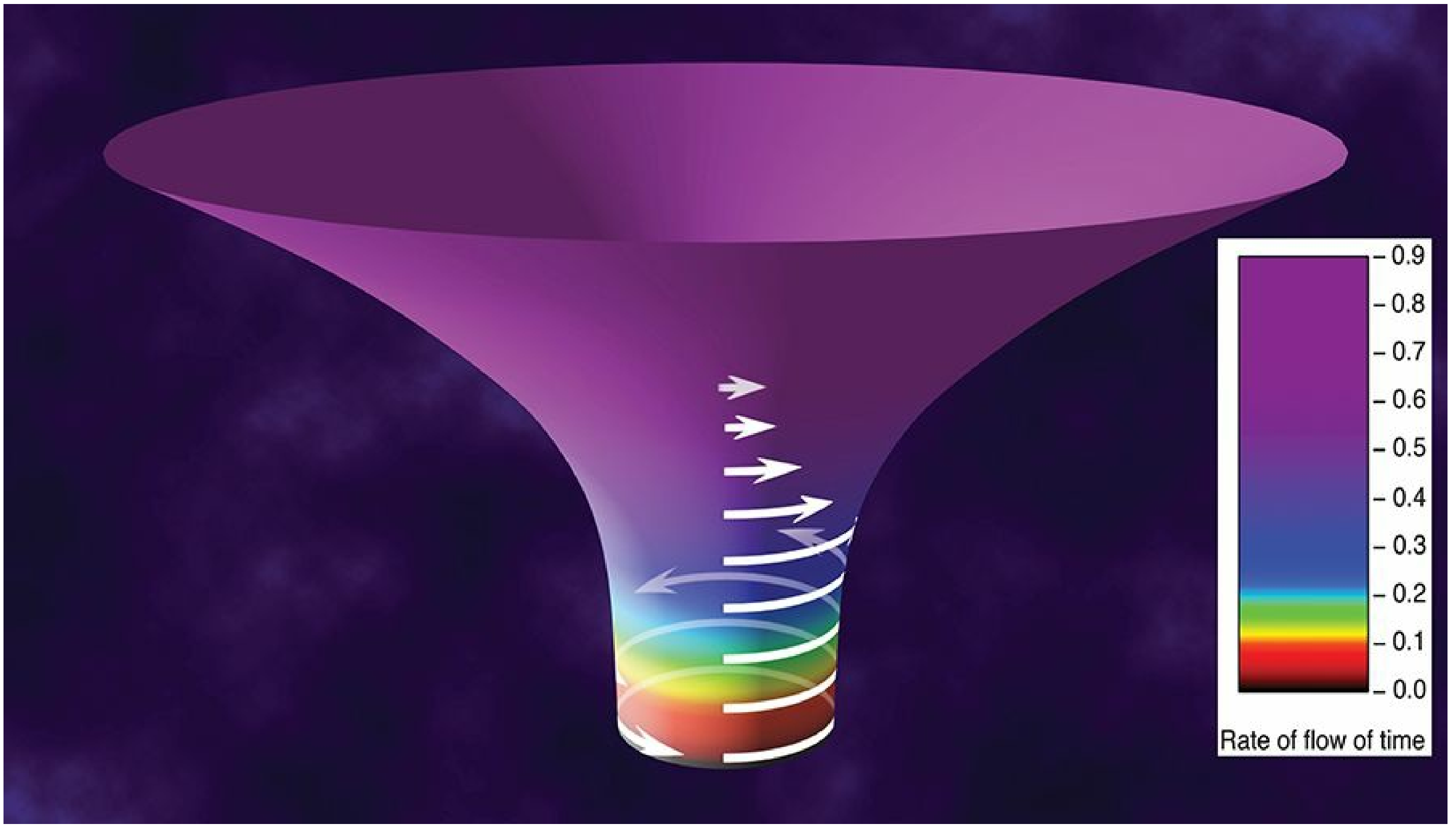

Fig. 5.5. Precise depiction of the warped space and time around a rapidly spinning black hole: one that spins at 99.8 percent of the maximum possible rate. *[Drawing by Don Davis based on a sketch by me.]*

In the fully accurate Figure 5.5, I don't depict the hole's interior. We'll get to that later, in Chapters 26 and 28.

The warping in Figure 5.5 is the essence of a black hole. From its details, expressed mathematically, physicists can deduce everything about the black hole, except the nature of the singularity at its center. For the singularity, they need the ill-understood laws of quantum gravity (Chapters 26).

A Black Hole's Appearance from Inside Our Universe

We humans are confined to our brane. We can't escape from it, into the bulk (unless an ultra-advanced civilization gives us a ride in a tesseract or some such vehicle, as they do for Cooper in *Interstellar*; see Chapter 29). Therefore, we can't see a black hole's warped space, as depicted in Figure 5.5. The black-hole funnels and whirlpools so often shown in movies, for example, Disney Studios' 1979 movie *The Black Hole*, would never be seen by any creature that lives in our universe.

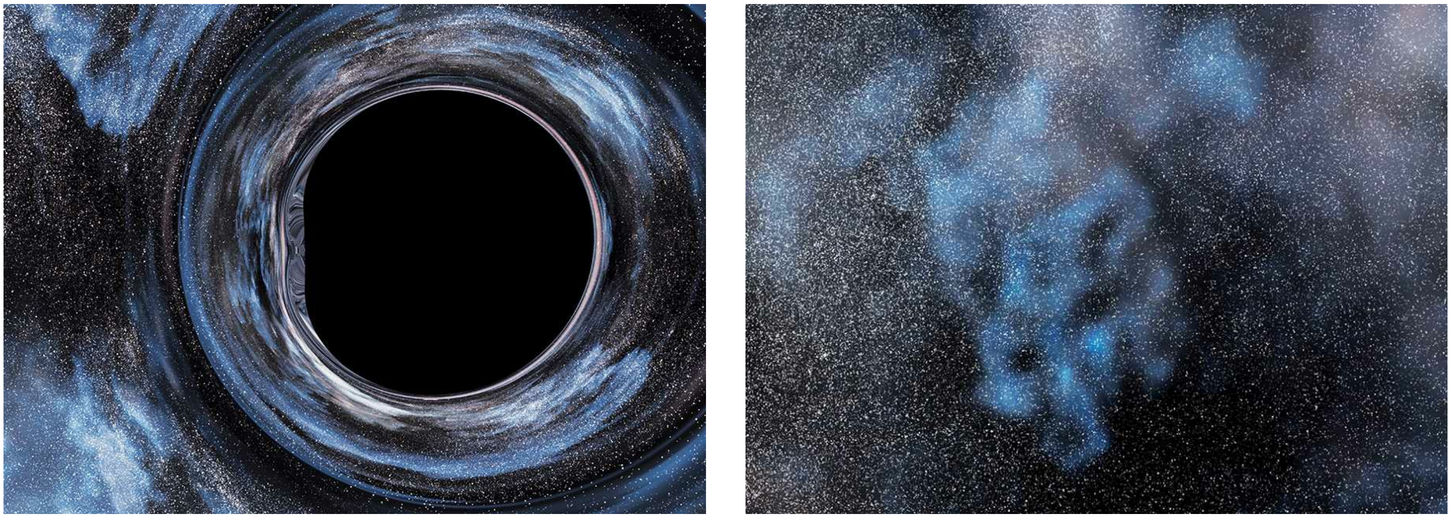

Fig. 5.6. A fast-spinning black hole (*left*) moving in front of the star field shown on the right. *[From a simulation for this book by the Double Negative visual-effects team.]*

Interstellar is the first Hollywood movie to depict a black hole correctly, in the manner that humans would actually see and experience it. Figure 5.6 is a example, not taken from the movie. The black hole casts a black shadow on the field of stars behind it. Light rays from the stars are bent by the hole's warped space; they are *gravitationally lensed*, producing a concentric pattern of distortion. Light rays coming to us from the shadow's left edge move in the same direction as the hole's whirling space. The space whirl gives them a boost, letting them escape from closer to the horizon than light rays on the shadow's right edge, which struggle against the whirl of space. That's why the shadow is flattened on the left and bulges out on the right. In Chapter 8 I talk more about this and other aspects of what a black hole really looks like, as seen up close in our universe, in our *brane*.

How Do We Know This Is *True*?

Einstein's relativistic laws have been tested to high precision. I'm convinced they are right, except when they confront quantum physics. For a big black hole like *Interstellar*'s Gargantua, quantum physics is relevant only near its center, in its singularity. So if black holes exist at all in our universe, they must have the properties that Einstein's relativistic laws dictate, the properties I described above.

These properties and others have been deduced from Einstein's equations by a large number of physicists standing intellectually on each others' shoulders (Figure 5.7); most importantly, Karl Schwarzschild, Roy Kerr, and Stephen Hawking. In 1915, shortly before his tragic death on World War I's German/Russian front, Schwarzschild deduced the details of the warped spacetime around a nonspinning black hole. In physicists' jargon, those details are called the "Schwarzschild metric." In 1963, Kerr (a New Zealand mathematician) did the same for a spinning black hole: he deduced the spinning hole's "Kerr metric." And in the early 1970s

Stephen Hawking and others deduced a set of laws that black holes must obey when they swallow stars, collide and merge, and feel the tidal forces of other objects.

Black holes surely do exist. Einstein's relativistic laws insist that, when a massive star exhausts the nuclear fuel that keeps it hot, then the star must implode. In 1939, J. Robert Oppenheimer and his student Hartland Snyder used Einstein's laws to discover that, if the implosion is precisely spherical, the imploding star *must* create a black hole around itself, and then create a singularity at the hole's center, and then get swallowed into the singularity. No matter is left behind. None whatsoever. The resulting black hole is made entirely from warped space and time. Over the decades since 1939, physicists using Einstein's laws have shown that if the imploding star is deformed and spinning, it will also produce a black hole. Computer simulations reveal the full details.

Astronomers have seen compelling evidence for many black holes in our universe. The most beautiful example is a massive black hole at the center of our Milky Way galaxy. Andrea Ghez of UCLA, with a small group of astronomers that she leads, has monitored the motions of stars around that black hole (Figure 5.8). Along each orbit, the dots are the star's position at times separated by one year. I marked the black hole's location by a white, five-pointed symbol. From the stars' observed motions, Ghez has deduced the strength of the hole's gravity. Its gravitational pull, at a fixed distance, is 4.1 million times greater than the Sun's pull at that distance. This means the black hole's mass is 4.1 million times greater than the Sun's!

Fig 5.7. Black-hole scientists. *Left to right*: Karl Schwarzschild (1873–1916), Roy Kerr (1934–), Stephen W. Hawking (1942–), J. Robert Oppenheimer (1904–1967), and Andrea Ghez (1965–).

Figure 5.9 shows where this black hole is on the night sky in summer. It is to the lower right of the constellation Sagittarius, the teapot, at the × labeled "Galactic Center."

A massive black hole inhabits the core of nearly every big galaxy in our universe. Many of these are as heavy as Gargantua (100 million Suns), or even heavier. The heaviest yet measured is 17 billion times more massive than the Sun; it resides at the center of a galaxy whose name is NGC1277, 250 million light-years from Earth—roughly a tenth of the way to the edge of the visible universe.

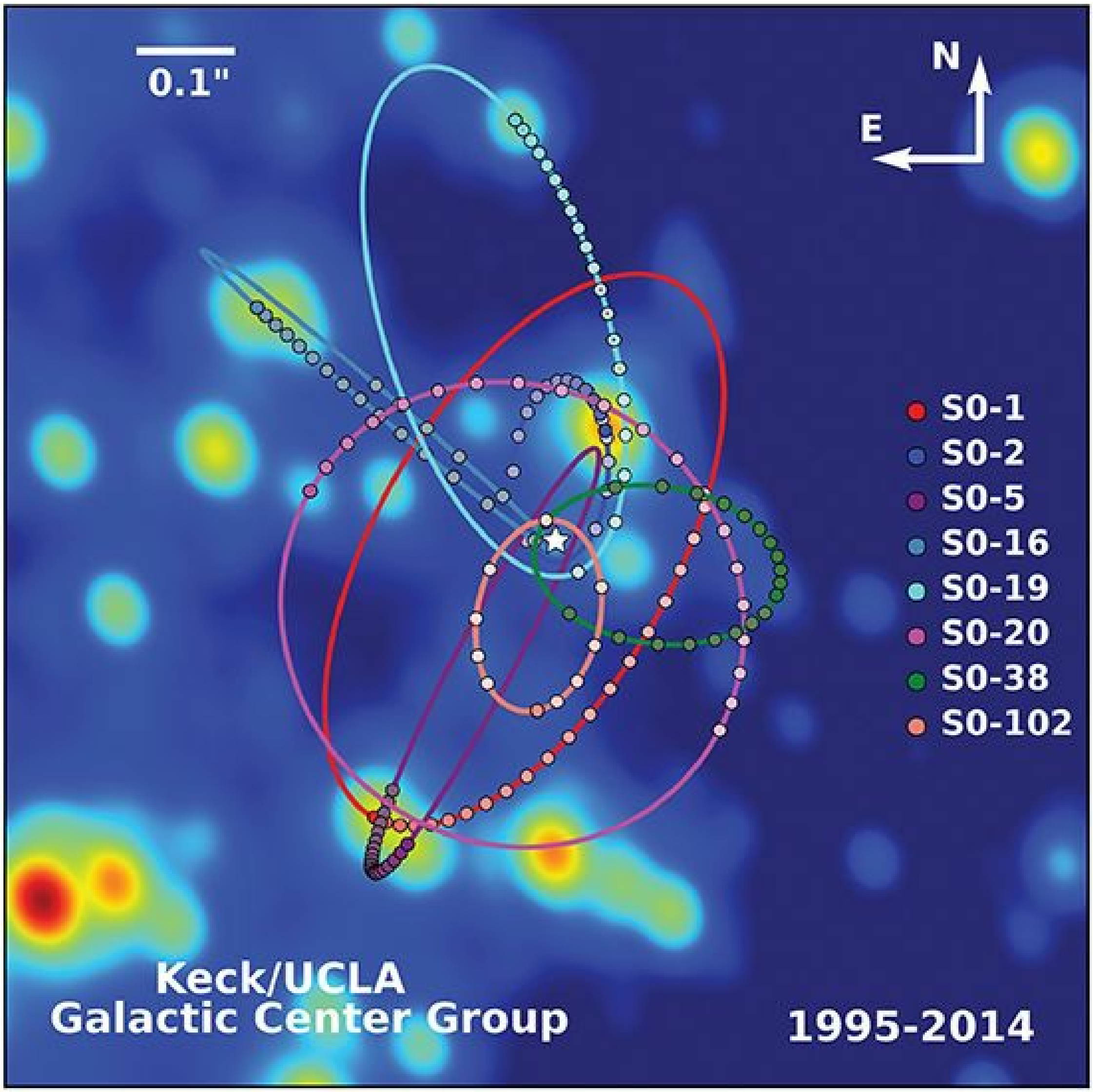

Fig. 5.8. Observed orbits of stars around the massive black hole at the center of our Milky Way galaxy, as measured by Andrea Ghez and colleagues.

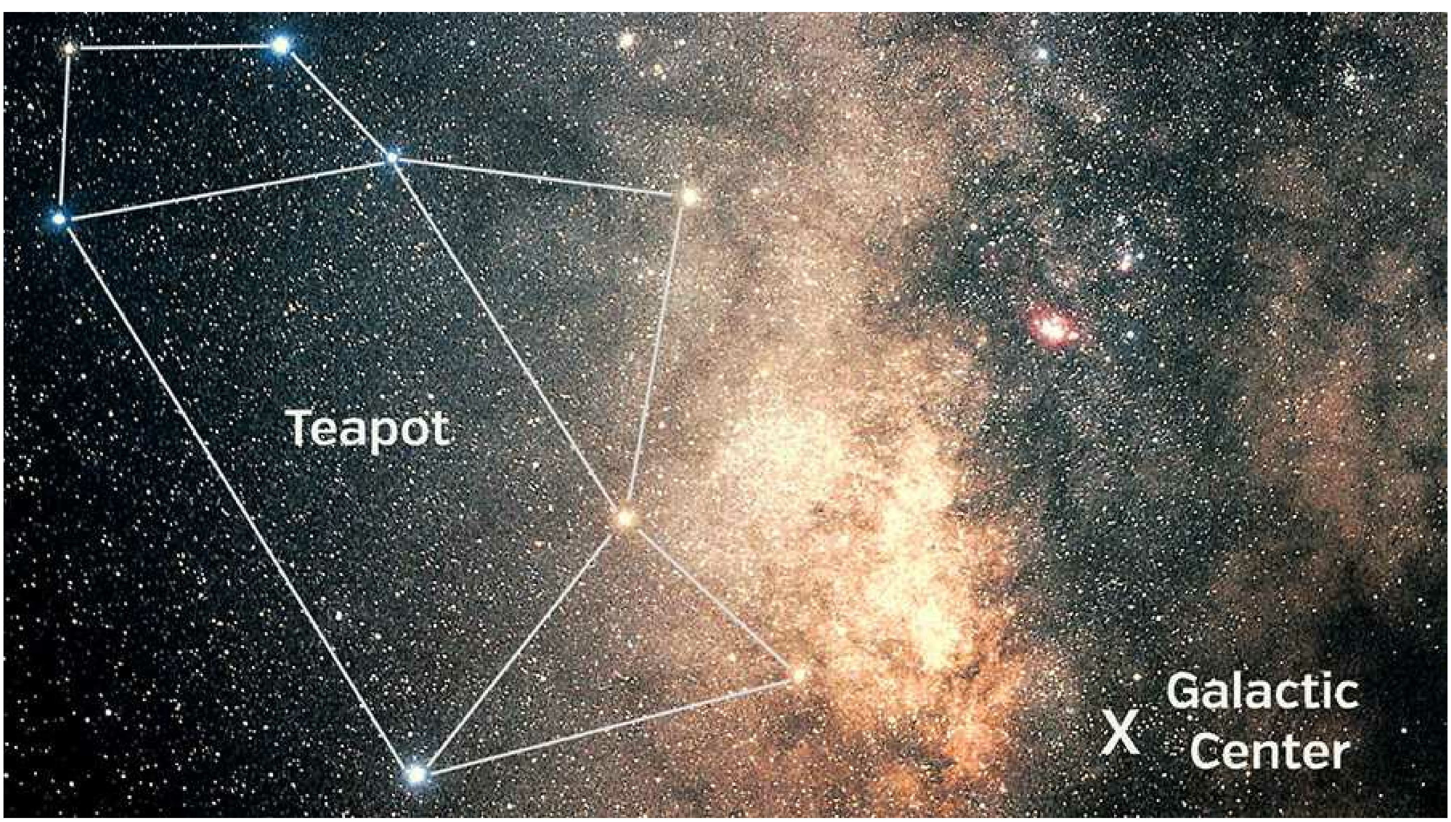

Fig. 5.9. The location of our galaxy's center on the sky. A giant black hole resides there.

Inside our own galaxy, there are roughly 100 million smaller black holes: holes that typically are between about three and thirty times as heavy as the Sun. We know this not because we've seen evidence for all these, but because astronomers have made a census of heavy stars that will become black holes when they exhaust their nuclear fuel. From that census, astronomers have inferred how many such stars have already exhausted their fuel and become black holes.

So black holes are ubiquitous in our universe. Fortunately, there are none in our solar system. If there were, the hole's gravity would wreak havoc with the Earth's orbit. The Earth would be thrown close to the Sun where it boils, or far from the Sun where it freezes, or even out of the solar system or into the black hole. We humans would survive for no more than a year or so!

Astronomers estimate that the nearest black hole to Earth is roughly 300 light-years away: a hundred times farther than the nearest star (other than the Sun), Proxima Centauri.

Now armed with a basic understanding of the universe, fields, warped time and space and especially black holes, we are ready, at last, to explore *Interstellar*'s Gargantua.

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12 If it is possible to go backward in time, you can only do so by traveling outward in space and then returning to your starting point before you left. You *cannot* go backward in time at some fixed location, while watching others go forward in time there. More on this in Chapter 30.

II

GARGANTUA

6

Gargantua's Anatomy

If we know the mass of a black hole and how fast it spins, then from Einstein's relativistic laws we can deduce all the hole's other properties: its size, the strength of its gravitational pull, how much its event horizon is stretched outward near the equator by centrifugal forces, the details of the gravitational lensing of objects behind it. Everything.

This is amazing. So different from everyday experience. It is as though knowing my weight and how fast I can run, you could deduce everything about me: the color of my eyes, the length of my nose, my IQ, . . .

John Wheeler (my mentor, who gave "black holes" their name) has described this by the phrase "A black hole has no hair"—no extra, *independent* properties beyond its mass and its spin. Actually, he should have said, "A black hole has only two hairs, from which you can deduce everything else about it," but that's not as catchy as "no hair," which quickly became embedded in black-hole lore and scientists' lexicon.[13]

From the properties of Miller's planet, as depicted in *Interstellar*, a physicist who knows Einstein's relativistic laws can deduce Gargantua's mass and spin, and thence all else about it. Let's see how this works.[14]

Gargantua's Mass

Ⓣ

Miller's planet (which I talk about at length in Chapter 17) is about as close to Gargantua as it can possibly be and still survive. We know this because the crew's extreme loss of time can only occur very near Gargantua.

At so close a distance, Gargantua's tidal gravitational forces (Chapter 4) are especially strong. They stretch Miller's planet toward and away from Gargantua and squeeze the planet's sides (Figure 6.1).

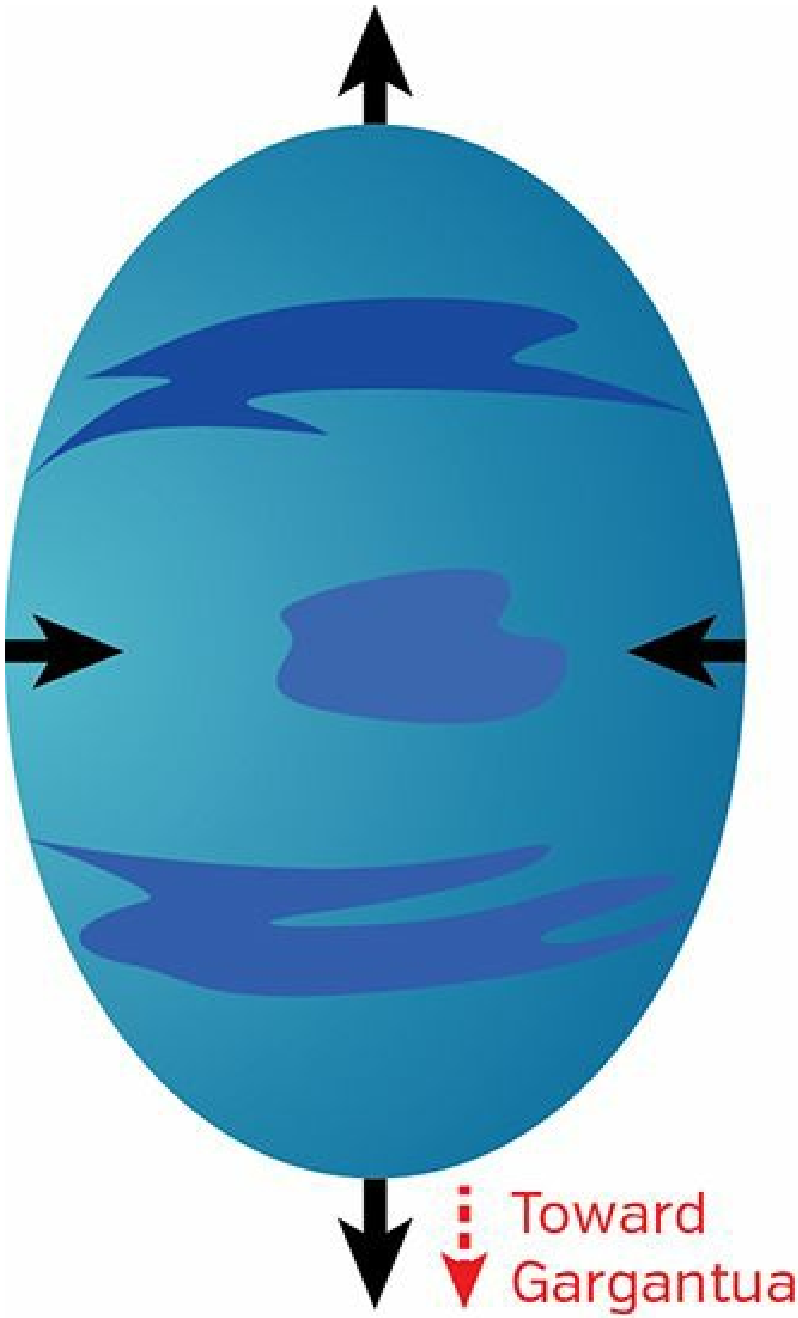

Fig. 6.1. Gargantua's tidal gravitational forces stretch and squeeze Miller's planet.

The strength of this stretch and squeeze is inversely proportional to the square of Gargantua's mass. Why? The greater Gargantua's mass, the greater its circumference, and therefore the more similar Gargantua's gravitational forces are on the various parts of the planet, which results in weaker tidal forces. (See Newton's viewpoint on tidal forces; Figure 4.8.) Working through the details, I conclude that Gargantua's mass must be at least 100 million times bigger than the Sun's mass. If Gargantua were less massive than that, it would tear Miller's planet apart!

In all my science interpretations of what happens in *Interstellar*, I assume that this actually *is* Gargantua's mass: 100 million Suns.[15] For example, I assume this mass in Chapter 17, when explaining how Gargantua's tidal forces could produce the giant water waves that inundate the Ranger on Miller's planet.

The circumference of a black hole's event horizon is proportional to the hole's mass. For Gargantua's 100 million solar masses, the horizon circumference works out to be approximately the same as the Earth's orbit around the Sun: about *1 billion kilometers*. That's big! After consulting with me, that's the circumference assumed by Paul Franklin's visual-effects team, when producing the images in *Interstellar*.

Physicists attribute to a black hole a radius equal to its horizon's circumference divided by 2π (about 6.28). Because of the extreme warping of space inside the black hole, this is not the hole's true radius. Not the true distance from the horizon to the hole's center, as measured in our universe. But it *is* the event horizon's radius (half its diameter) as measured in the bulk; see Figure 6.3 below. Gargantua's radius, in this sense, is about 150 million kilometers, the same as the radius of the Earth's orbit around the Sun.

Gargantua's Spin

When Christopher Nolan told me how much slowing of time he wanted on Miller's planet, *one hour there is seven years back on Earth*, I was shocked. I didn't think that possible and I told Chris so. "It's non-negotiable," Chris insisted. So, not for the first time and also not the last, I went home, thought about it, did some calculations with Einstein's relativistic equations, and found a way.

I discovered that, if Miller's planet is about as near Gargantua as it can get without falling in,[16] and if Gargantua is spinning fast enough, then Chris's one-hour-in-seven-years time slowing is possible. But Gargantua has to spin *awfully fast*.

There is a maximum spin rate that any black hole can have. If it spins faster than that maximum, its horizon disappears, leaving the singularity inside it wide open for all the universe to see; that is, making it *naked*—which is probably forbidden by the laws of physics (Chapter 26).

I found that Chris's huge slowing of time requires Gargantua to spin almost as fast as the maximum: less than the maximum by about *one part in 100 trillion*.[17] In most of my science interpretations of *Interstellar*, I assume this spin.

The crew of the *Endurance* could measure the spin rate directly by watching from far, far away as the robot TARS falls into Gargantua (Figure 6.2).[18] As seen from afar, TARS never crosses the horizon (because signals he sends after crossing can't get out of the black hole). Instead, TARS' infall appears to slow down, and he appears to hover just above the horizon. And as he hovers, Gargantua's whirling space sweeps him around and around Gargantua, as seen from afar. With Garantua's spin very near the maximum possible, TARS' orbital period is about one hour, as seen from afar.

You can do the math yourself: the orbital distance around Gargantua is a billion kilometers and TARS covers that distance in one hour, so his speed as measured from afar is about a billion kilometers per hour, which is approximately the speed of light! If Gargantua were spinning faster than the maximum, TARS would whip around faster than the speed of light, which violates Einstein▮s speed limit. This is a heuristic way to understand why there is a maximum possible spin for any black hole.

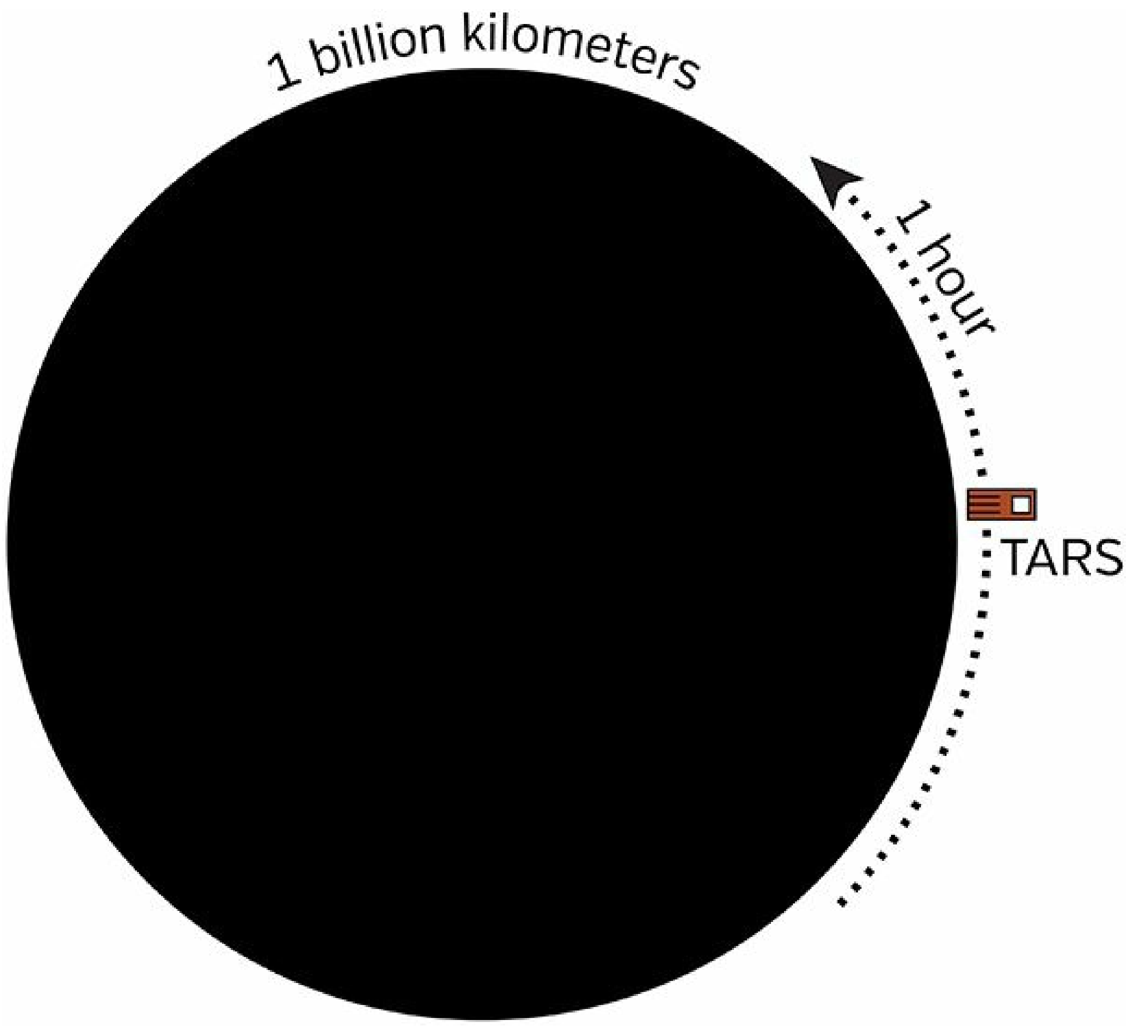

Fig. 6.2. TARS, falling into Gargantua, is dragged around the hole's billion-kilometer circumference once each hour, as seen from afar.

In 1975, I discovered a mechanism by which Nature protects black holes from spinning faster than the maximum: When it gets close to the maximum spin, a black hole has difficulty capturing objects that orbit in the same direction as the hole rotates and that therefore, when captured, increase the hole's spin. But the hole easily captures things that orbit opposite to its spin and that, when captured, slow the hole's spin. Therefore, the spin is easily slowed, when it gets close to the maximum.

In my discovery, I focused on a disk of gas, somewhat like Saturn's rings, that orbits in the same direction as the hole's spin: an *accretion disk* (Chapter 9). Friction in the disk makes the gas gradually spiral into the black hole, spinning it up. Friction also heats the gas, making it radiate photons. The whirl of space around the hole grabs those photons that travel in the same direction as the hole spins and flings them away, so they can't get into the hole. By contrast, the whirl grabs photons that are trying to travel opposite to the spin and sucks them into the hole, where they slow the spin. Ultimately, when the hole's spin reaches 0.998 of the maximum, an equilibrium is reached, with spin-down by the captured photons precisely counteracting spin-up by the accreting gas. This equilibrium appears to be somewhat robust. In most astrophysical environments I expect black holes to spin no faster than about 0.998 of the maximum.

However, I can imagine situations—very rare or never in the real universe, but possible nevertheless—where the spin gets much closer to the maximum, even as close as Chris requires to produce the slowing of time on Miller's planet, a spin one part in 100 trillion less than the maximum spin. Unlikely, but possible.

This is common in movies. To make a great film, a superb filmmaker often pushes things to the extreme. In science fantasy films such as *Harry Potter*, that extreme is far beyond the bounds of the scientifically possible. In science fiction, it's generally kept in the realm of the possible. That's the main distinction between science fantasy and science fiction. *Interstellar* is science fiction, not fantasy. Gargantua's ultrafast spin is scientifically possible.

Gargantua's Anatomy

Having determined Gargantua's mass and spin, I used Einstein's equations to compute its anatomy. As in the previous chapter, here we focus solely on the external anatomy, leaving the interior (especially Gargantua's singularities) for Chapters 26 and 28.

In the top picture in Figure 6.3, you see the shape of Gargantua's equatorial plane as viewed from the bulk. This is like Figure 5.5, but because Gargantua's spin is much closer to the maximum possible (one part in 100 trillion contrasted with two parts in a thousand in Figure 5.5), Gargantua's throat is far longer. It extends much farther downward before reaching the horizon. The region near the horizon, as seen from the bulk, looks like a long cylinder. The length of the cylindrical region is about two horizon circumferences, that is, 2 billion kilometers.

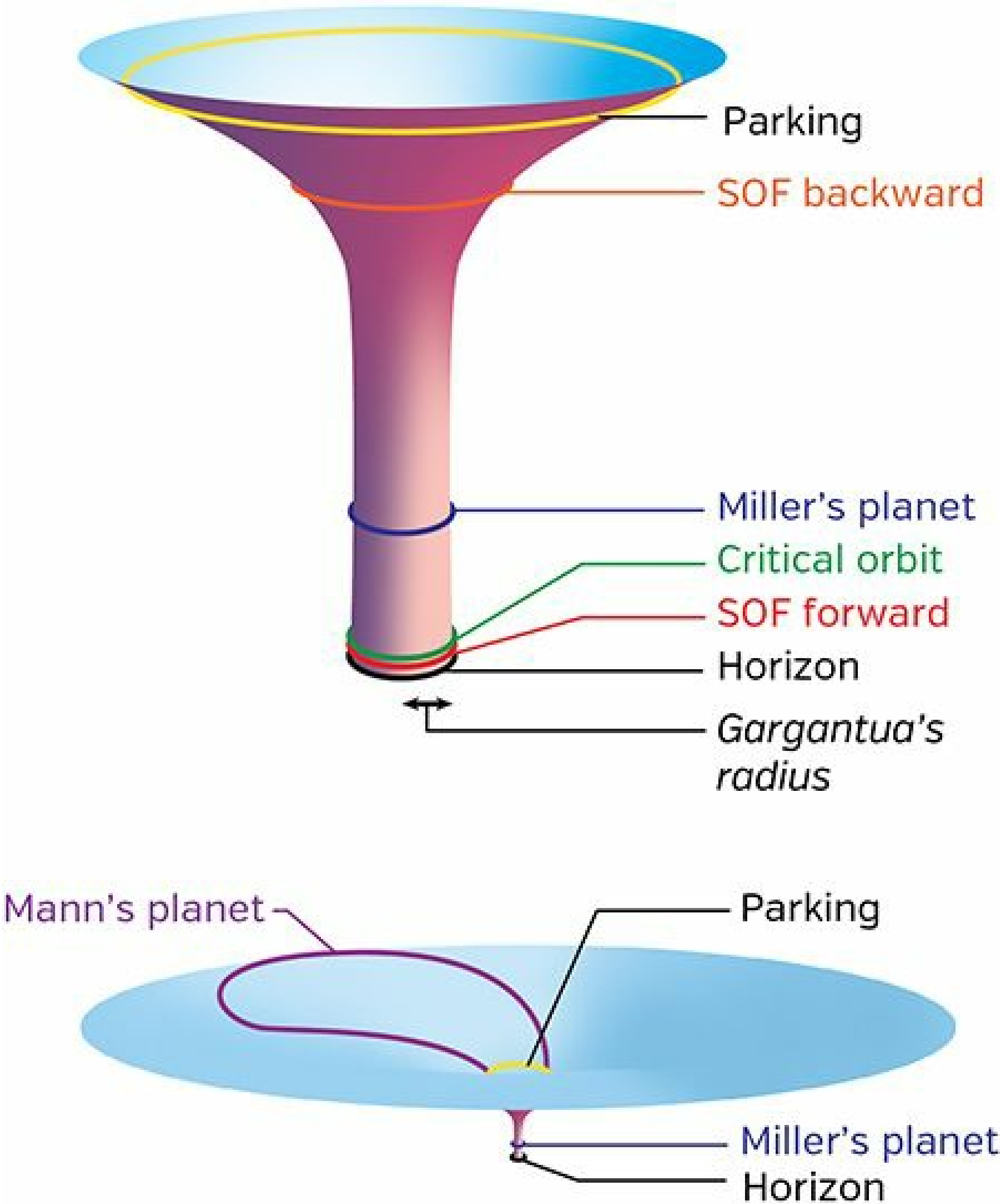

Fig. 6.3. Gargantua's anatomy, when its spin is only one part in 100 trillion smaller than the maximum possible, as is required to get the extreme slowing of time on Miller's planet.

The cylinder's cross sections are circles in the diagram, but if we were to restore the third dimension of our brane by moving out of Gargantua's equatorial plane, the cross sections would become flattened spheres (spheroids).

On Gargantua's equatorial plane I marked several special locations that occur in my science interpretations of *Interstellar*: Gargantua's event horizon (black circle), the critical orbit from which Cooper and TARS fall into Gargantua near the end of the movie (green circle; Chapter 27), the orbit of Miller's planet (blue circle; Chapter 17), the orbit in which the *Endurance* is parked while the crew visit Miller's planet (yellow circle), and a segment of the nonequatorial orbit of Mann's planet, projected into the equatorial plane (purple circle). The outer part of Mann's orbit is so far away from Gargantua (600 Gargantua radii or more; Chapter 19) that I had to redraw the picture on a much larger scale to fit it in (bottom picture), and, even so, I didn't do it honestly: I only put the outer part at 100 Gargantua radii instead of 600 as I should. The red circles are labeled "SOF" for "shell of fire"; see below.

How did I come up with these locations? I use the parking orbit as an illustration here and discuss the others later. In the movie, Cooper describes the parking orbit this way: "So we track a wider orbit of Gargantua, parallel with Miller's planet but a little further out." And he wants it to be far enough from Gargantua to be "out of the time shift," that is, far enough from Gargantua that the slowing of time compared to Earth is very modest. This motivated my choice of five Gargantua radii (yellow circle in Figure 6.3). The time for the Ranger to travel from this parking orbit to Miller's planet, two and a half hours, reinforced my choice.

But there was a problem with this choice. At this distance, Gargantua would look huge; it would subtend about 50 degrees on the *Endurance*'s sky. Truly awe inspiring, but undesirable for so early in the movie! So Chris and Paul chose to make Gargantua look much smaller at the parking orbit: about two and a half degrees, which is five times the size of the Moon as seen from Earth—still impressive but not overwhelmingly so.

The Shell of Fire

Gravity is so strong near Gargantua, and space and time are so warped, that light (photons) can be trapped in orbits outside the horizon, traveling around and around the hole many times before escaping. These trapped orbits are *unstable* in the sense that the photons always escape from them, eventually. (By contrast, photons caught inside the horizon can never get out.)

I like to call this temporarily trapped light the "shell of fire." This fire shell plays an important role in the computer simulations (Chapter 8) that underlie Gargantua's visual appearance in *Interstellar*.

For a *non*spinning black hole, the shell of fire is a sphere, one with circumference 1.5 times larger than the horizon's circumference. The trapped light travels around and around this sphere on great circles (like the lines of constant longitude on the Earth); and some of it leaks into the black hole, while the rest leaks outward, away from the hole.

When a black hole is spun up, its shell of fire expands outward and inward, so it occupies a finite volume rather than just the surface of a sphere. For Gargantua, with its huge spin, the shell of fire in the equatorial plane extends from the bottom red circle of Figure 6.3 to the upper red circle. The shell of fire has expanded to encompass Miller's planet and the critical orbit, and much, much more! The bottom red circle is a light ray (a photon orbit) that moves around and around Gargantua in the same direction as Gargantua spins (the *forward* direction). The upper red circle is a photon orbit that moves in the opposite direction to Gargantua's spin (the *backward* direction). Evidently, the whirl of space enables the forward light to be much closer to the horizon without falling in than the backward light. What a huge effect the space whirl has!

The region of space occupied by the shell of fire above and below the equatorial plane is depicted in Figure 6.4. It is a large, annular region. I omit the warping of space from this picture; it would get in the way of showing the shell of fire's full three dimensions.

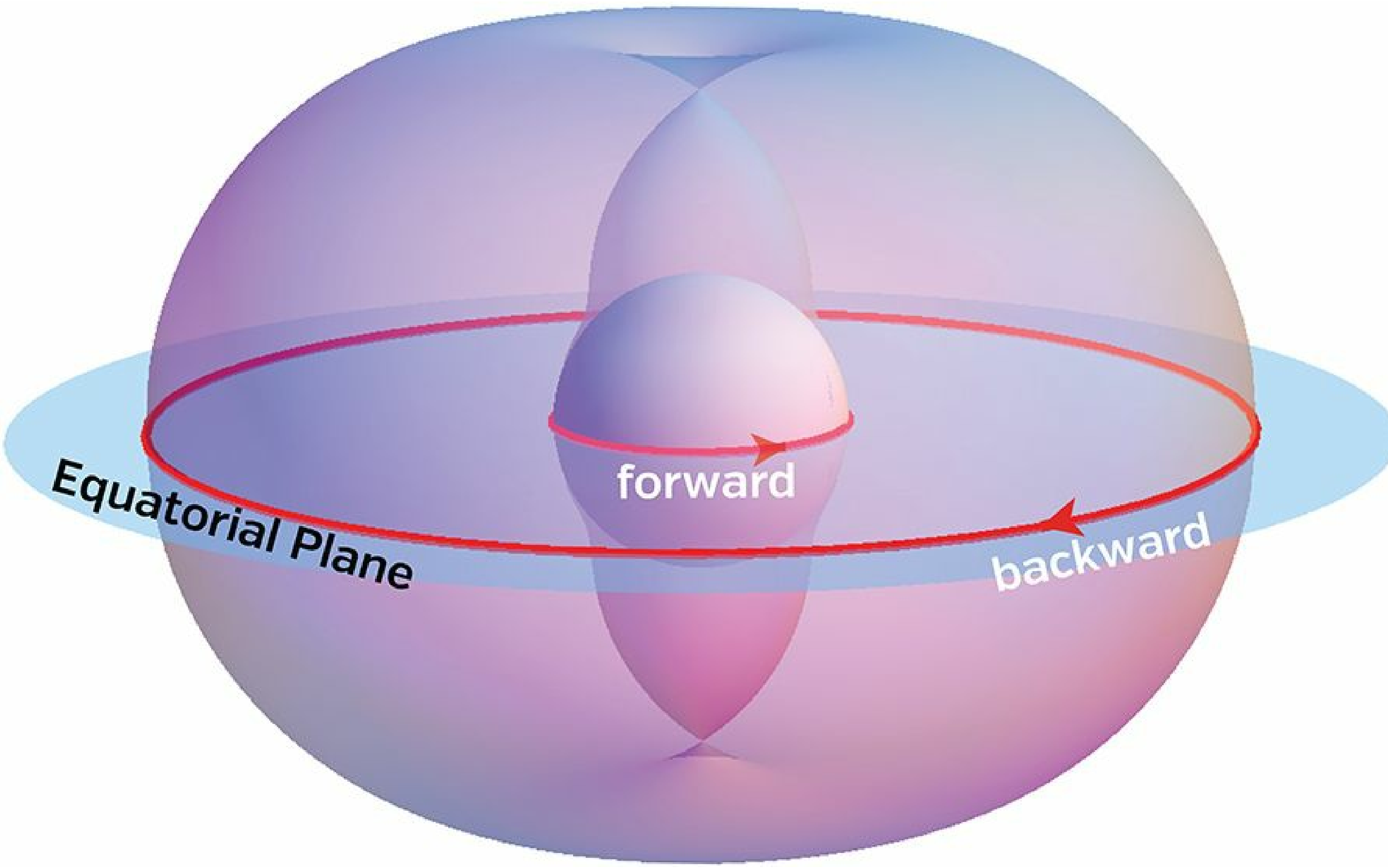

Fig. 6.4. The annular region around Gargantua, occupied by the shell of fire.

Figure 6.5 shows some examples of photon orbits (light rays) trapped, temporarily, in the shell of fire.

The black hole is at the center of each of these orbits. The leftmost orbit winds around and around the equatorial region of a small sphere, traveling always forward, in the same direction as Gargantua's spin. It is nearly the same as the bottom (inner) red orbit in Figures 6.3 and 6.4. The next orbit in Figure 6.5 winds around a slightly larger sphere, in a nearly polar and slightly forward direction. The third orbit is larger still, but backward and nearly polar. The fourth is very nearly equatorial and backward, that is, nearly the upper (outer) red equatorial orbit of Figures 6.3 and 6.4. These orbits are actually inside each other; I pulled them apart so they are easier to see.

Some photons that are temporarily trapped in the shell of fire escape outward; they spiral away from Gargantua. The rest escape spiraling inward; they spiral toward Gargantua and plunge through its horizon. The nearly trapped but escaping photons have a big impact on Gargantua's visual appearance in *Interstellar*. They mark the edge of Gargantua's shadow as seen by the *Endurance*'s crew, and they produce a thin bright line along the shadow's edge: a "ring of fire" (Chapter 8).

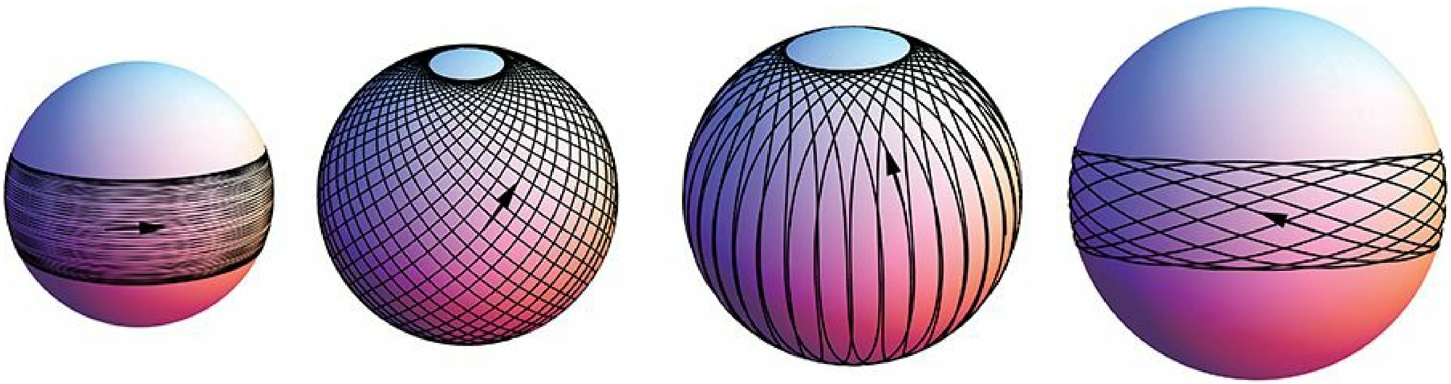

Fig. 6.5. Examples of light rays (photon orbits) temporarily trapped in the shell of fire, as computed using Einstein's relativistic equations.

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13 The literal French translation of "a black hole has no hair" is so obscene that French publishers resisted it vigorously, to no avail.

14 For some quantitative details, see *Some Technical Notes*, at the end of this book.

15 A more reasonable value might be 200 million times the Sun's mass, but I want to keep the numbers simple and there's a lot of slop in this one, so I chose 100 million.

16 See Figure 17.2 and the discussion of it in Chapter 17.

17 In other words, its spin is the maximum minus 0.00000000000001 of the maximum.

18 When TARS falls in, the *Endurance* is not far, far away, but rather is on the critical orbit, quite near the horizon, whirling around the hole nearly as fast as TARS; so Amelia Brand, in the *Endurance*, does not see TARS swept around at high speed. For more on this, see Chapter 27.

7

Gravitational Slingshots

Navigating a spacecraft near Gargantua is hard because the speeds are very high. To survive, a planet or star or spacecraft must counteract Gargantua's huge gravity with a comparably huge centrifugal force. This means it must move at very high speed. Near the speed of light, it turns out. In my science interpretation of *Interstellar*, the *Endurance*, parked at ten Gargantua radii while the crew visit Miller's planet, moves at one-third the speed of light: $c/3$, where c represents the speed of light. Miller's planet moves at 55 percent the speed of light, $0.55c$.

To reach Miller's planet from the parking orbit in my interpretation (Figure 7.1), the Ranger must slow its forward motion from $c/3$ to far less than that, so Gargantua's gravity can pull it downward. And when it reaches the vicinity of the planet, the Ranger must turn from downward to forward. And, having picked up far too much speed while falling, it must slow by about $c/4$ to reach the planet's $0.55c$ speed and rendezvous with it.

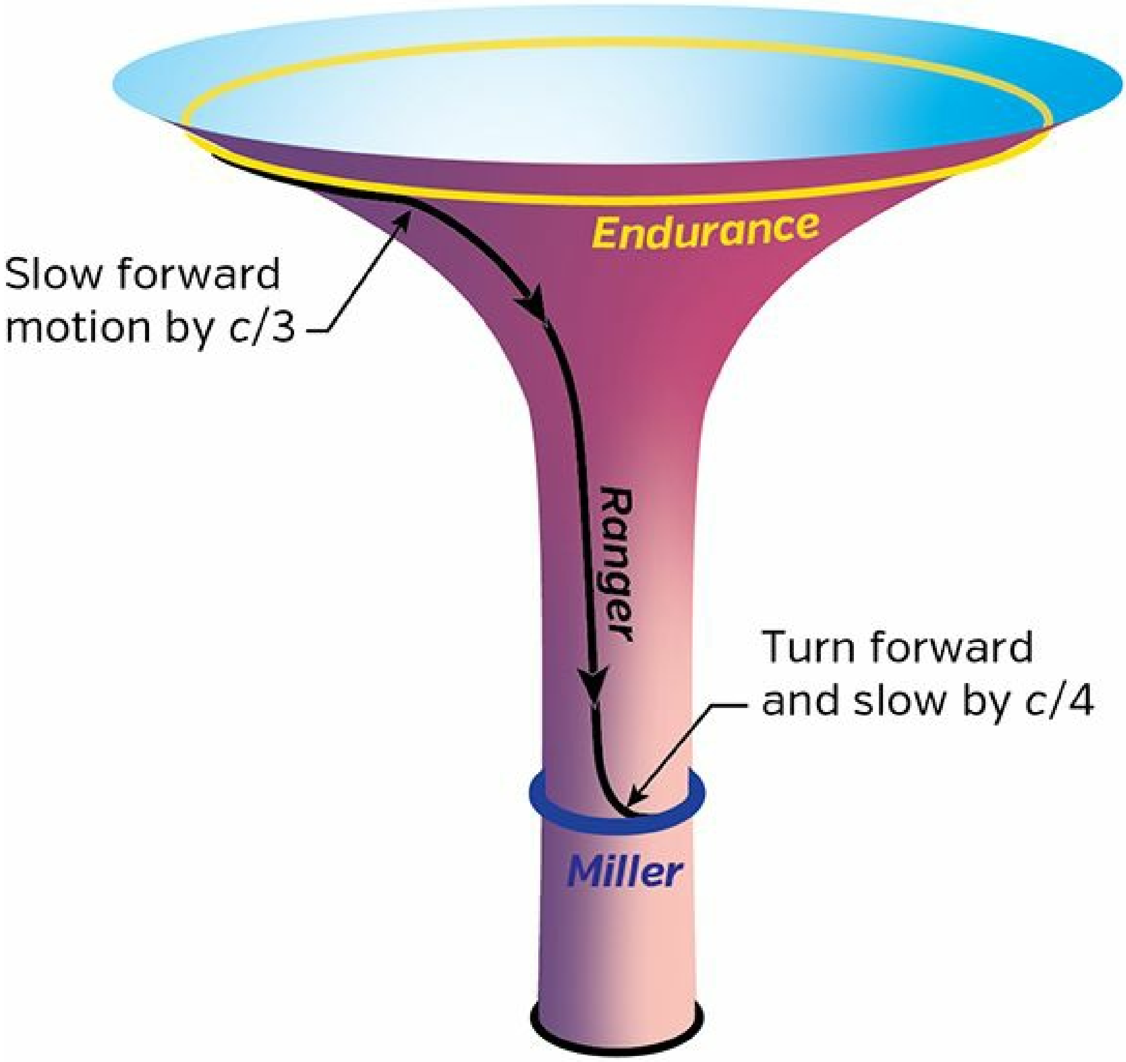

Fig. 7.1. The Ranger's trip to Miller's planet, in my interpretation of *Interstellar*.

What mechanism can Cooper, the Ranger's pilot, possibly use to produce these huge velocity changes?

Twenty-First-Century Technology

The required changes of velocity, roughly *c*/3, are 100,000 kilometers per second (per *second,* not per hour!).

By contrast, the most powerful rockets we humans have today can reach 15 kilometers per second: seven thousand times too slow. In *Interstellar*, the *Endurance* travels from Earth to Saturn in two years at an average speed of 20 kilometers per second, five thousand times too slow. The fastest that human spacecraft are likely to achieve in the twenty-first century, I think, is 300 kilometers per second. That would require a major R&D effort on nuclear rockets, but it is still three hundred times too slow for *Interstellar*'s needs.

Fortunately, Nature provides a way to achieve the huge speed changes, *c*/3, required in *Interstellar:* gravitational slingshots around black holes far smaller than Gargantua.

Slingshot Navigation to Miller's Planet

Stars and small black holes congregate around gigantic black holes like Gargantua (more on this in the next section). In my science interpretation of the movie, I imagine that Cooper and his team make a survey of all the small black holes orbiting Gargantua. They identify one that is well positioned to gravitationally deflect the Ranger from its near circular orbit and send it plunging downward toward Miller's planet (Figure 7.2). This gravity-assisted maneuver is called a "gravitational slingshot," and has often been used by NASA in the solar system—though with the gravity coming from planets rather than a black hole (see the end of the chapter).

This slingshot maneuver is not seen or discussed in *Interstellar*, but the next one *is* mentioned, by Cooper: "Look, I can swing around that *neutron star* to decelerate," he says. Deceleration is necessary because, having fallen under Gargantua's huge gravitational pull, from the *Endurance*'s orbit to Miller's orbit, the Ranger has acquired too much speed; it is moving $c/4$ faster than Miller's planet. In Figure 7.3, the neutron star, traveling leftward relative to Miller's planet, deflects and slows the Ranger's motion so it can rendezvous gently with the planet.

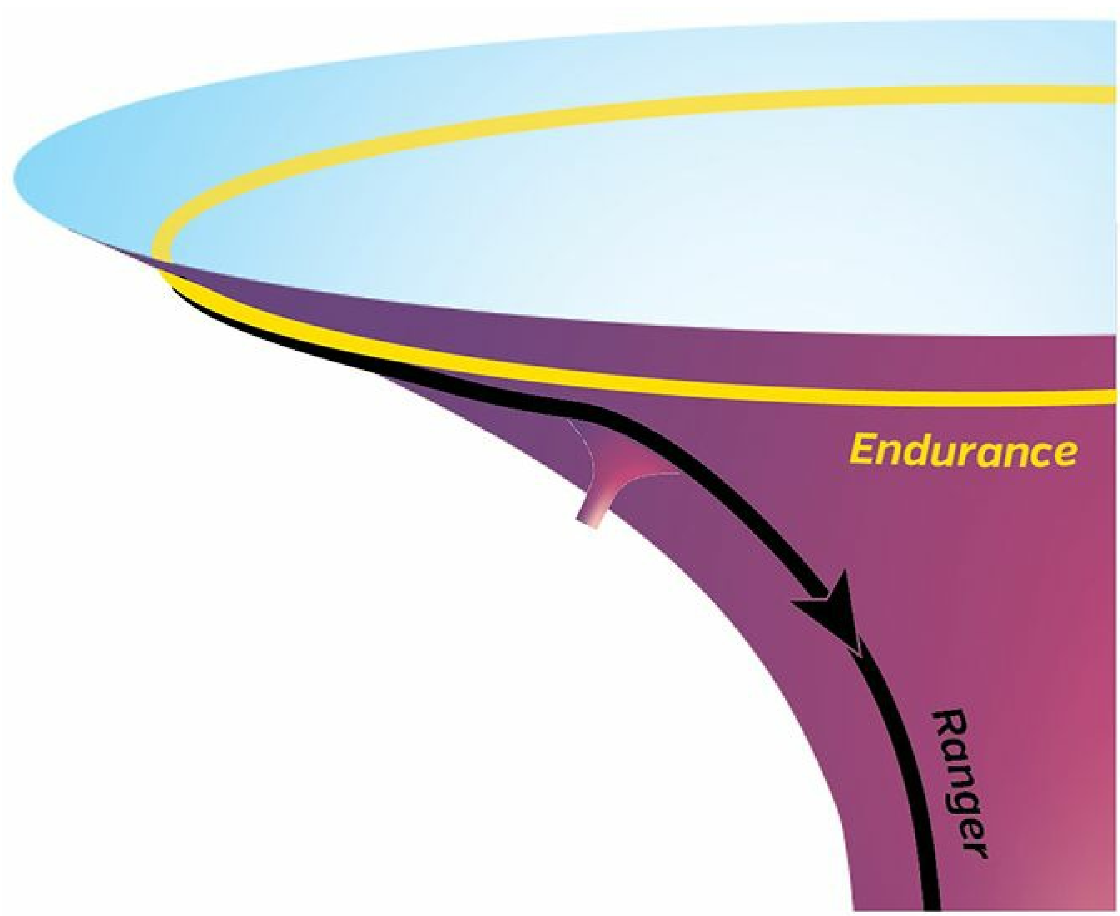

Fig. 7.2. The Ranger performs a slingshot maneuver around a small black hole, deflecting it downward, toward Miller's planet.

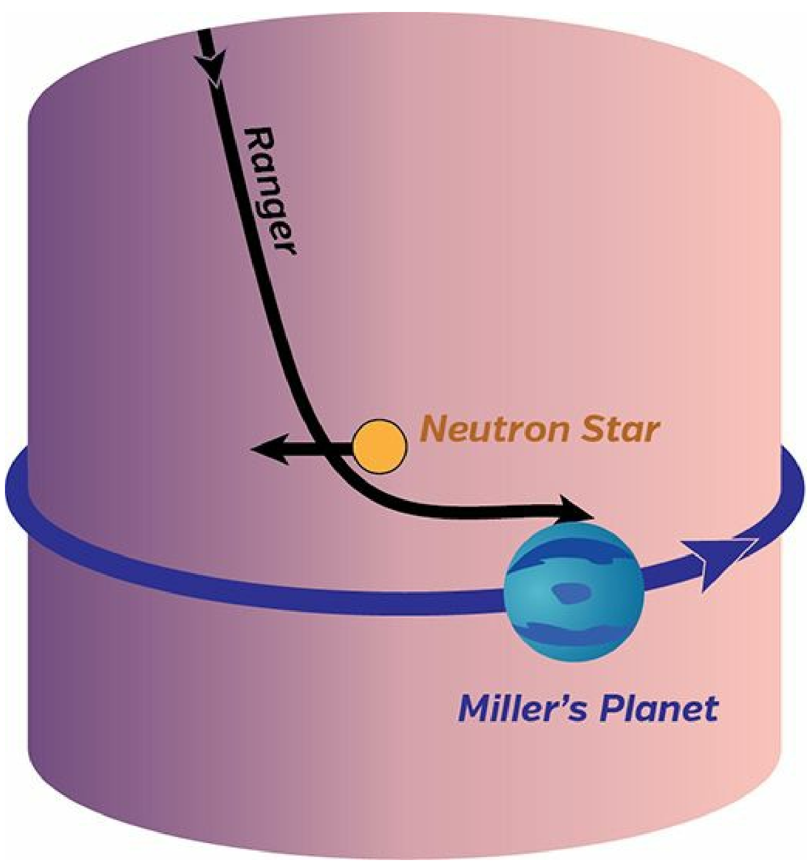

Fig. 7.3. Slingshot around a neutron star enables the lander to rendezvous with Miller's planet.

Now, there is a feature of these slingshots that could be very unpleasant. Indeed, deadly: tidal forces (Chapter 4).

To change velocities by as much as *c*/3 or *c*/4, the Ranger must come close enough to the small black hole and neutron star to feel their intense gravity. At those close distances, if the deflector is a neutron star or is a black hole with radius less than 10,000 kilometers, the humans and the Ranger will be torn apart by tidal forces (Chapter 4). For the Ranger and humans to survive, the deflector must be a black hole at least 10,000 kilometers in size (about the size of the Earth).

Now, black holes that size *do* occur in Nature. They are called intermediate-mass black holes, or IMBHs, and despite their big size, they are tiny compared to Gargantua: ten thousand times smaller.

So Christopher Nolan should have used an Earth-sized IMBH to slow down the Ranger, not a neutron star. I discussed this with Chris early in his rewrites of Jonah's screenplay. After our discussion, Chris chose the neutron star. Why? Because he didn't want to confuse his mass audience by having more than one black hole in the movie. One black hole, one wormhole, and also a neutron star, along with *Interstellar*'s other rich science, all to be absorbed in a fast-paced two-hour film; that was all Chris thought he could get away with. Recognizing that strong gravitational slingshots *are* needed to navigate near Gargantua, Chris included one slingshot in Cooper's dialog, at the price of using a scientifically implausible deflector: the neutron star instead of a black hole.

Intermediate-Mass Black Holes in Galactic Nuclei

A 10,000-kilometer IMBH weighs about 10,000 solar masses. That's ten thousand times less than Gargantua, but a thousand times heavier than typical black holes. These are the deflectors Cooper needs.

Some IMBHs are thought to form in the cores of dense clusters of stars called globular clusters, and some of them are likely to find their way into the nuclei of galaxies, where gigantic black holes reside.

An example is Andromeda, the nearest large galaxy to our own (Figure 7.4), in whose nucleus lurks a Gargantua-sized black hole: 100 million solar masses. Huge numbers of stars are drawn into the vicinity of such gigantic black holes; as many as a thousand stars per cubic light-year. When an IMBH passes through such a dense region, it gravitationally deflects the stars, creating a wake with enhanced density behind itself (Figure 7.4). The wake pulls on the IMBH gravitationally, slowing the IMBH down, a process called "dynamical friction." As the IMBH very gradually slows, it sinks deeper into the vicinity of the gigantic black hole. In this manner, Nature could provide Cooper, in my interpretation of *Interstellar*, with the IMBHs that he needs for his slingshots.[19]

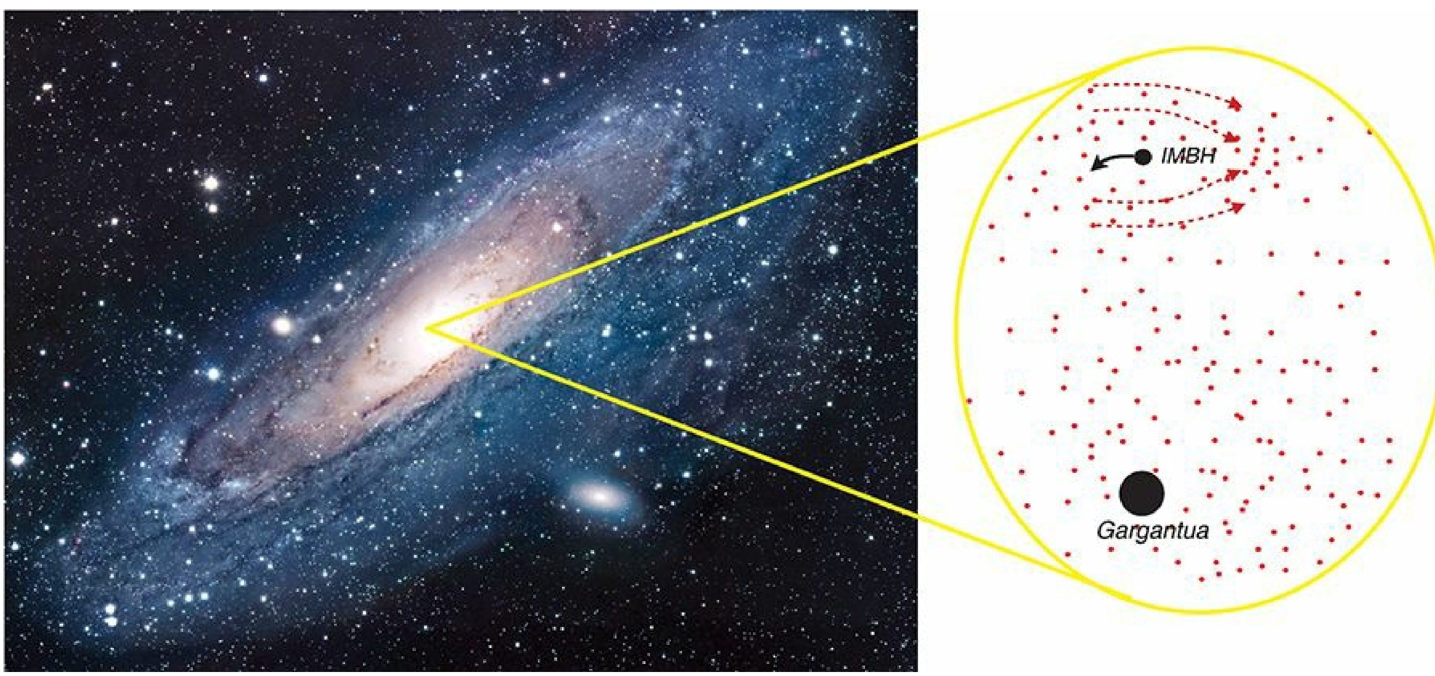

Fig. 7.4. *Left*: The Andromeda galaxy, which harbors a Gargantua-sized black hole. *Right*: The dynamical friction by which an IMBH will gradually slow down and sink into the vicinity of the gigantic black hole.

Orbital Navigation by Ultra-Advanced Civilizations: A Digression

The orbits of planets and comets in our solar system are all ellipses to very high accuracy (Figure 7.5). Newton's laws of gravity guarantee and enforce this.

By contrast, around a gigantic, spinning black hole such as Gargantua, where Einstein's relativistic laws hold sway, the orbits are far more complex. Figure 7.6 is an example. For this orbit, each trip around Gargantua would require a few hours to a few days, so the entire pattern in Figure 7.6 would be swept out in about a year. After a few years, the orbit would pass near most any destination you might wish, though the speed at which you arrive might not be right. A slingshot might be needed to change speed and make a rendezvous.

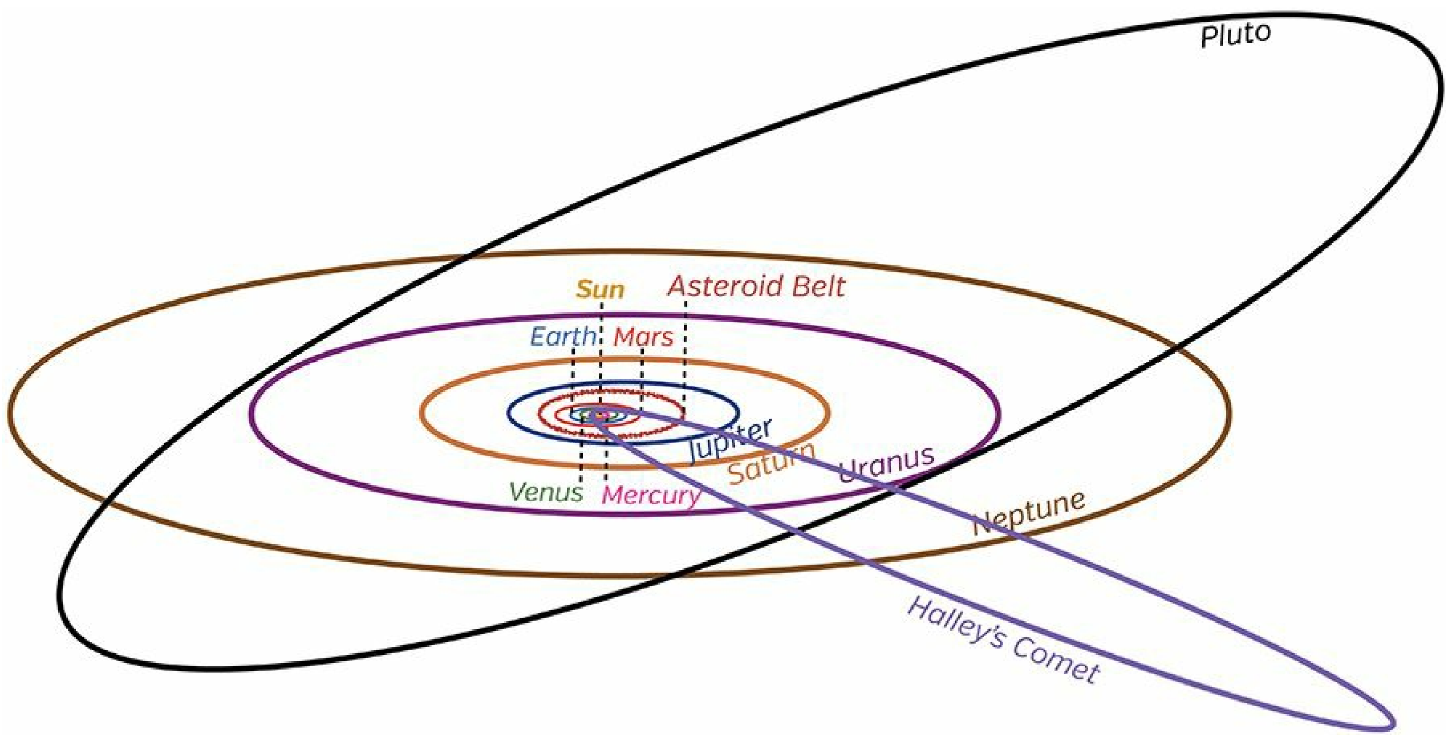

Fig. 7.5. The orbits of planets, Pluto, and Halley's comet in our solar system are all ellipses.

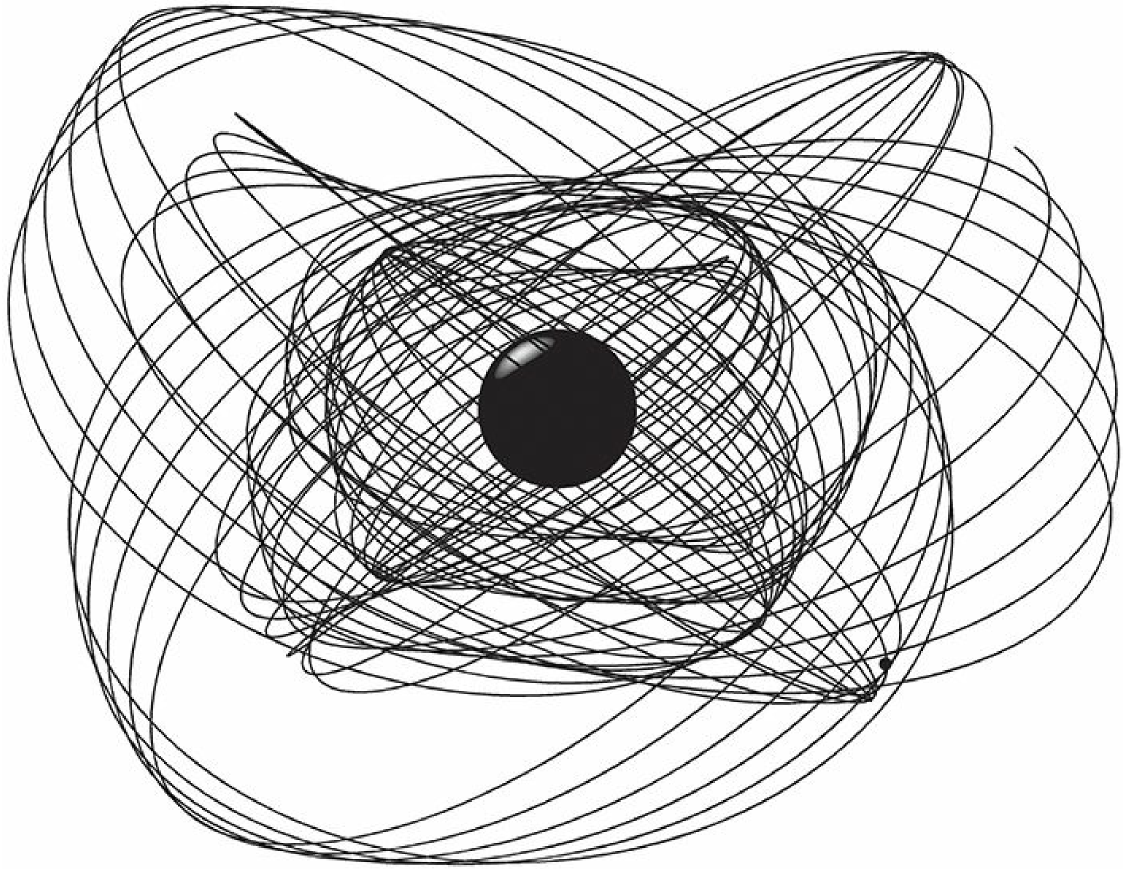

Fig. 7.6. A single orbit of a spacecraft or planet or star around a gigantic, fast-spinning black hole such as Gargantua. *[From a simulation by Steve Drasco.]*

I'll let *you* imagine how an ultra-advanced civilization might use such complex orbits. In my science interpretations of the movie, for simplicity I mostly eschew them and focus primarily on circular, equatorial orbits (those of the parked *Endurance*, Miller's planet, and the critical orbit), and on simple trajectories for the *Endurance* as it travels from one circular equatorial orbit to another. An exception is the orbit of Mann's planet, discussed in Chapter 19.

NASA's Gravitational Slingshots in the Solar System

Let's return from the world of the possible (what the laws of physics allow) to hard-nosed, real-life gravitational slingshots in the comfy confines of our solar system (what humans have actually achieved as of 2014).

You may be familiar with NASA's *Cassini* spacecraft (Figure 7.7). It was launched from Earth on October 15, 1997, with too little fuel to reach its destination, Saturn. The deficit was dealt with by slingshots: around Venus on April 26, 1998; a second slingshot around Venus on July 24, 1999; around Earth on August 18, 1999; and around Jupiter on December 30, 2000. Arriving at Saturn on July 1, 2004, *Cassini* slowed down with the aid of a slingshot around Saturn's closest moon, Io.

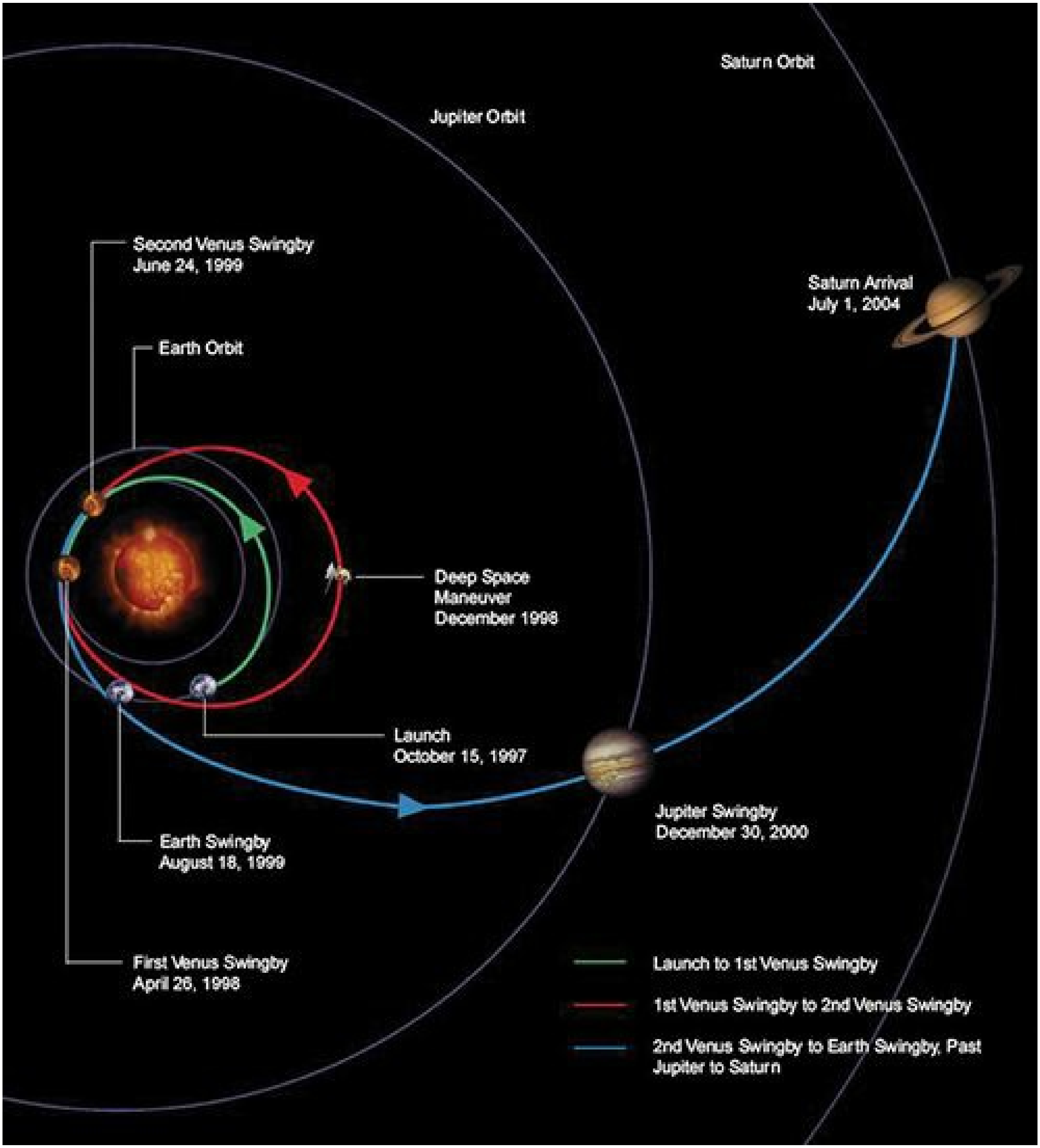

Fig. 7.7. The trajectory of *Cassini* from Earth to Saturn.

None of these slingshots looked like the ones I described above. Instead of strongly deflecting the spacecraft's direction of motion, Venus, Earth, Jupiter, and Io deflected it only mildly. Why?

The deflectors' gravity was too weak to produce a strong deflection. For Venus, Earth, and Io, the deflection was inevitably small because their gravity is intrinsically weak. Jupiter has much stronger gravity, but a large deflection would have sent *Cassini* in the wrong direction; reaching Saturn required a small deflection.

Despite the small deflections, *Cassini* got substantial kicks from the flybys, big enough to compensate for inadequate fuel. In each flyby (except Io), *Cassini* traveled behind the deflecting planet but at an angle, so the planet's gravity optimally pulled *Cassini* forward, speeding it up. In *Interstellar*, the *Endurance* does a similar slingshot around Mars.

Cassini has been exploring Saturn and Saturn's moons for the past ten years, sending back amazing images and information—a treasure trove of beauty and science. For a glimpse, see http://www.nasa.gov/mission_pages/cassini/main/.

By contrast with these weak slingshots in the solar system, Gargantua's intense gravity can grab even objects moving at ultrahigh speeds and throw them around on strongly bent slingshots. Even a light ray. This produces gravitational lensing, the key to seeing Gargantua.

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19 The probability of finding IMBH's at the needed locations and times is small, but in the spirit of science fiction, since it is within the bounds of physical law, we can utilize them.

8

Imaging Gargantua

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Black holes emit no light, so the only way to see Gargantua is by its influence on light from other objects. In *Interstellar* the other objects are an accretion disk (Chapter 9) and the galaxy in which it lives including nebulae and a rich field of stars. For the sake of simplicity, let's include only the stars for now.

Gargantua casts a black shadow on the field of stars and it also deflects the light rays from each star, distorting the stellar pattern that the camera sees. This distortion is the gravitational lensing discussed in Chapter 3.

Figure 8.1 shows a rapidly spinning black hole (let's call it Gargantua) in front of a field of stars, as it would appear to you if you were in Gargantua's equatorial plane. Gargantua's shadow is the totally black region. Immediately outside the shadow's edge is a very thin ring of starlight called the "ring of fire" that I intensified by hand to make the edge of the shadow more distinct. Outside that ring we see a dense sprinkling of stars with a pattern of concentric shells, a pattern produced by the gravitational lensing.

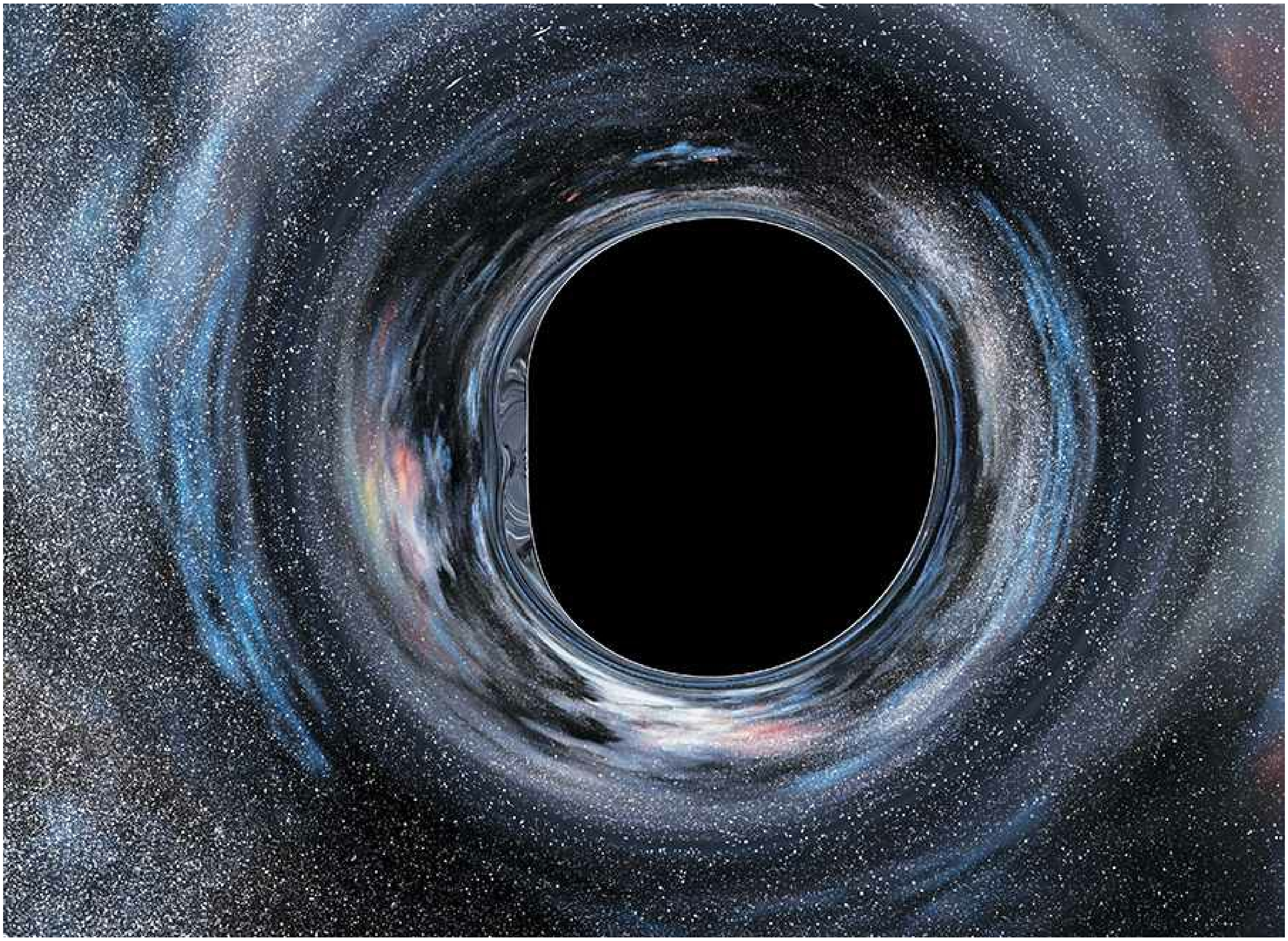

Fig. 8.1. The gravitationally lensed pattern of stars around a rapidly spinning black hole such as Gargantua. When seen from far away, the shadow's angular diameter, measured in radians, is 9 Gargantua radii divided by the observer's distance from Gargantua. *[From a simulation by the Double Negative visual-effects team.]*

As the camera orbits around Gargantua, the field of stars appears to move. This motion combined with the lensing produces dramatically changing patterns of light. The stars stream at high speed in some regions, they float gently in others, and they're frozen in still other regions; see the film clip on this book's page at Interstellar.withgoogle.com.

In this chapter I explain all these features, beginning with the shadow and its ring of fire. Then I describe how the black-hole images in *Interstellar* were actually produced.

When imaging Gargantua in this chapter, I treat it as a fast-spinning black hole, as it must be to produce the extreme loss of time that the *Endurance*'s crew experience relative to Earth (Chapter 6). However, for fast spin, a mass audience could be confused by the flattening of the left edge of Gargantua's shadow (Figure 8.1) and by some peculiar features of the star streaming and the accretion disk, so Christopher Nolan and Paul Franklin chose a smaller spin, 60 percent of the maximum, for their Gargantua images in the movie. See the last section in Chapter 9.

Warning: The explanations in the following three sections may require a lot of thought; you can skip them without losing pace with the rest of the book. Not to worry!

The shell of fire (Chapter 6) plays a key role in producing Gargantua's shadow and the thin ring of fire alongside it. The shell of fire is the purple region surrounding Gargantua in Figure 8.2, and it contains nearly trapped photon orbits (light rays) such as the one in the upper right inset.[20]

Suppose you are at the location of the yellow dot. The white light rays A and B and others like them bring you the image of the ring of fire, and the black light rays A and B bring you the image of the shadow's edge. For example, the white ray A originates at some star far from Gargantua, it travels inward and gets trapped on the inner edge of the shell of fire in Gargantua's equatorial plane, where it flies round and round, driven by the whirl of space, and then escapes and comes to your eyes. The black ray also labeled A originates on Gargantua's event horizon, it travels outward and gets trapped on that same inner edge of the shell of fire, where it goes round and round, then escapes and reaches your eyes alongside the white ray A. The white ray brings you an image of a bit of the thin ring; the black ray, an image of a bit of the shadow's edge. The shell of fire is responsible for merging the rays side by side and directing them toward your eyes.

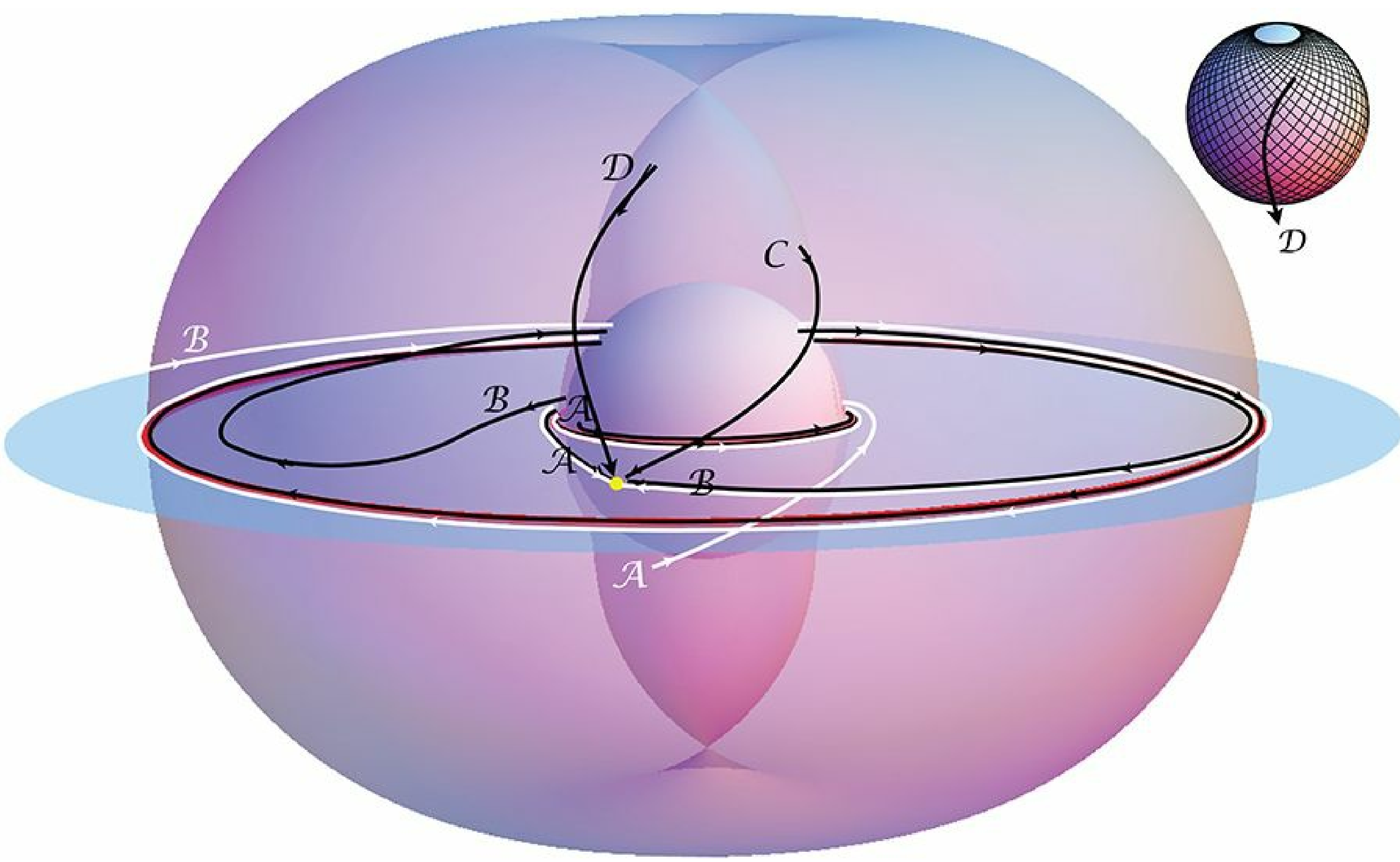

Fig. 8.2. Gargantua (*central spheroid*), its equatorial plane (blue), its shell of fire (*purple and violet*), and black and white light rays that bring you images of the shadow's edge and the thin ring alongside it.

Similarly for the white and black rays B, except they get trapped on the outer edge of the shell of fire going clockwise (struggling against the whirl of space), while rays A are trapped on the inner edge going counterclockwise (and driven by the whirl of space). The flattening of the shadow's left edge in Figure 8.1 and rounding of its right edge are due to rays A (left edge) coming from the inner edge of the shell of fire, very close to the horizon, and rays B (right edge) from the outer edge of the shell of fire, much further out.

Black rays C and D in Figure 8.2 begin on the horizon, travel outward and get trapped on nonequatorial orbits in the shell of fire, and then escape from their trapped orbits and come to your eyes, bringing images of bits of the shadow edge that lie outside the equatorial plane. The trapped orbit for ray D is shown in the upper right inset. White rays C and D (not shown), coming from distant stars, get trapped alongside black rays C and D, and then travel to your eyes alongside C and D, bringing images of bits of the ring of fire alongside bits of the shadow edge.

Lensing by a Nonspinning Black Hole

To understand the pattern of gravitationally lensed stars outside the shadow and their streaming as the camera moves, let's begin with a nonspinning black hole and with light rays that emerge from a single star (Figure 8.3). Two light rays travel from the star to the camera. They each travel along the straightest line they can in the hole's warped space, but because of the warping, each ray gets bent.

One bent ray travels to the camera around the hole's left side; the other, around its right side. Each ray brings the camera its own image of the star. The two images, as seen by the camera, are shown in the inset of Figure 8.3. I put red circles around them to distinguish them from all the other stars the camera sees. Note that the right image is much closer to the hole's shadow than the left image. This is because its bent ray passed closer to the hole's event horizon.

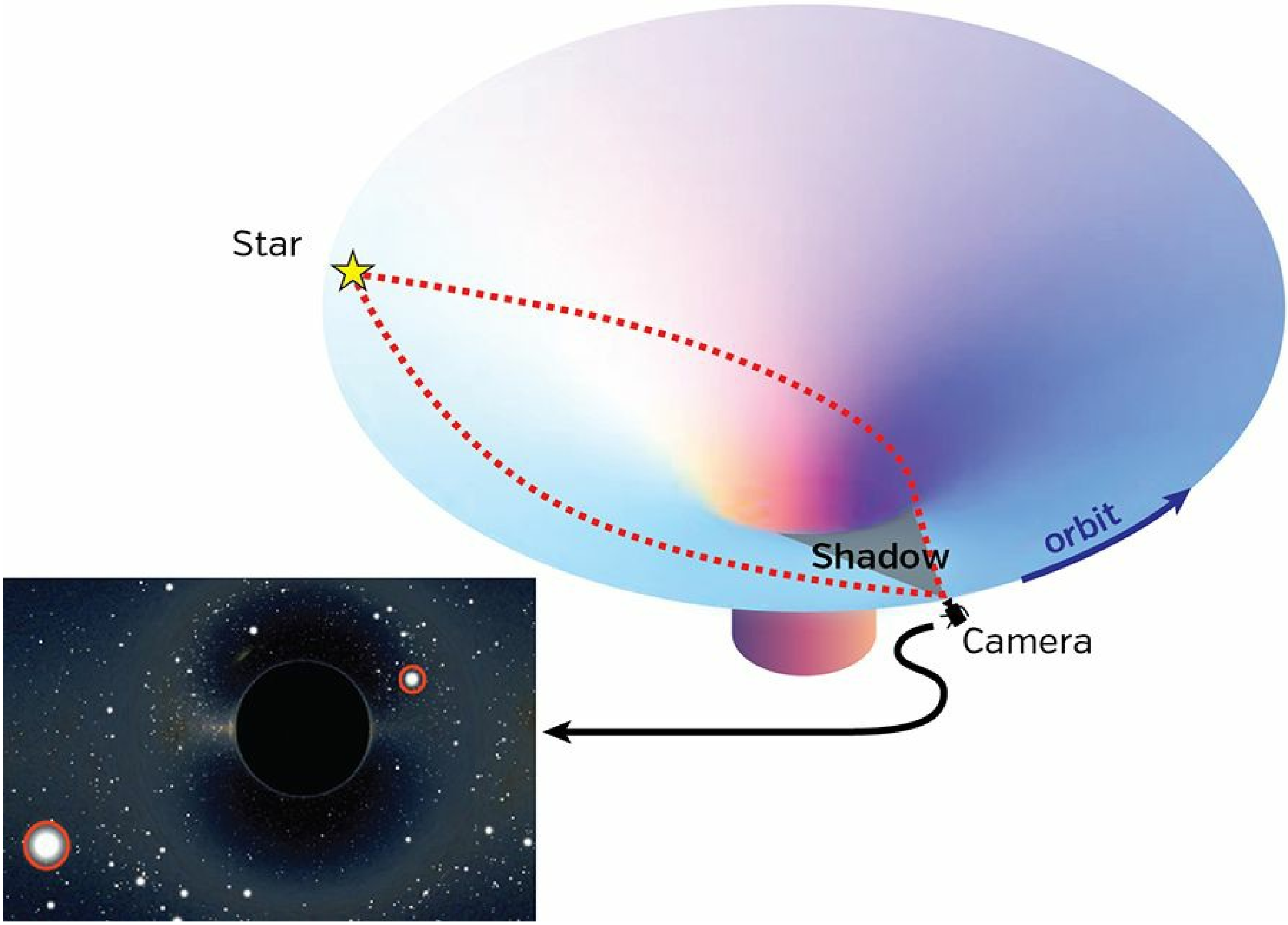

Fig. 8.3. *Top*: The warped space around a nonspinning black hole as seen from the bulk, and two light rays that travel through the warped space from a star to the camera. *Bottom*: The gravitationally lensed pattern of stars that is seen by the camera. *[From a simulation by Alain Riazuelo; for a film clip of his simulation, see www2.iap.fr/users/riazuelo/interstellar .]*

Each of the other stars appears twice in the picture, on opposite sides of the hole's shadow. Can you identify some of the pairs? The black hole's shadow, in the picture, consists of directions from which no rays can come to the camera; see the triangular shaped region labeled "shadow" in the upper diagram. All the rays that "want to be" in the shadow got caught and swallowed by the black hole.

As the camera moves rightward in its orbit (Figure 8.3), the pattern of stars seen by the camera changes as shown in Figure 8.4.

This figure highlights two particular stars. One is circled in red (the same star circled in Figure 8.3). The other is inside a yellow diamond. We see two images of each star: one image is outside the pink circle; the other is inside the pink circle. This pink circle is called the "Einstein ring."

As the camera moves rightward, the images move along the yellow and red curves.

The star images outside the Einstein ring (the primary images, let's call them) move in the way one might expect: smoothy from left to right, but deflecting away from the black hole as they move. (Can you figure out why the deflection is *away* from the hole instead of toward it?)

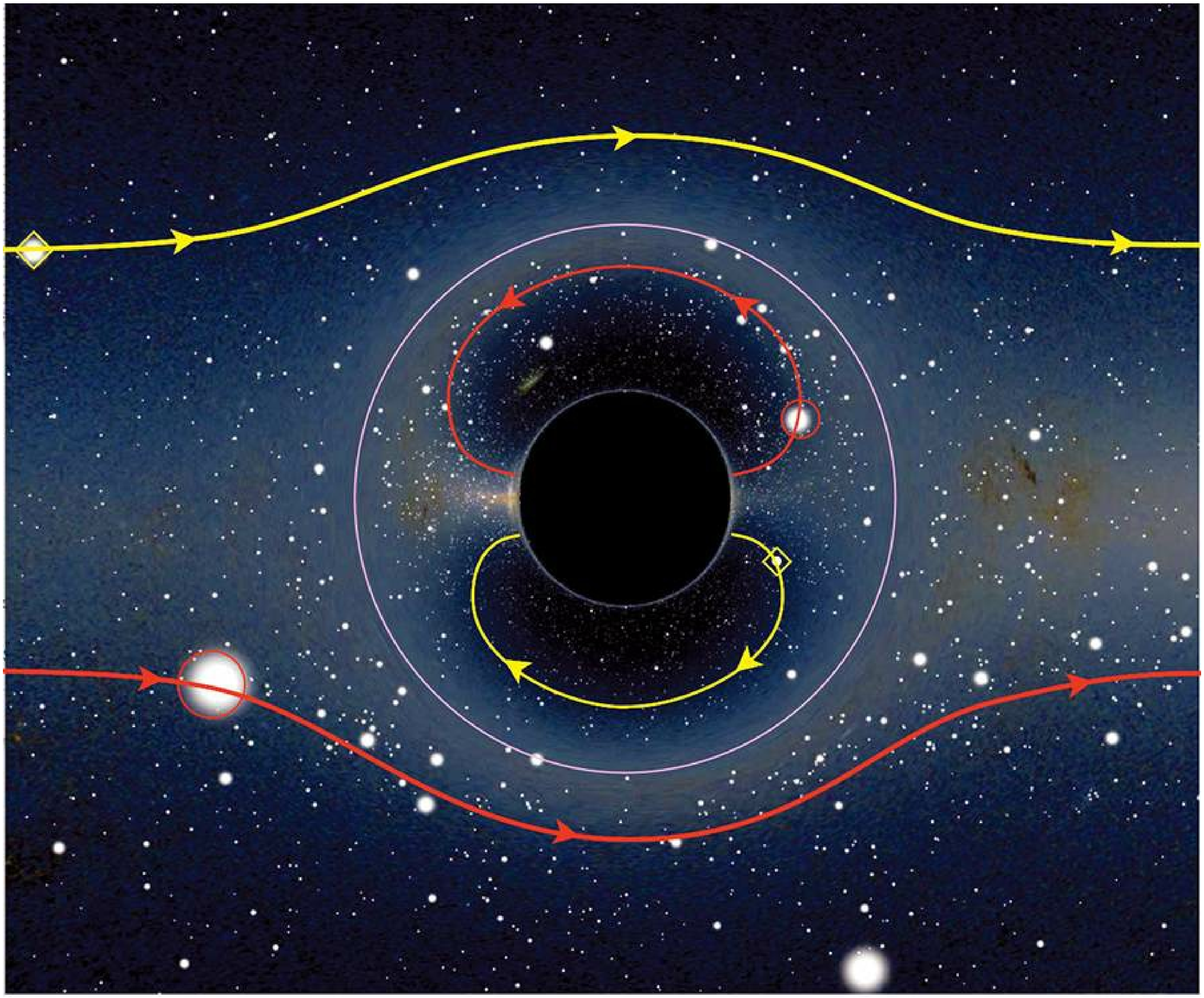

Fig. 8.4. The changing star pattern seen by the camera as it moves rightward in its orbit in Figure 8.3. *[From the simulation by Alain Riazuelo; see www2.iap.fr/users/riazuelo/interstellar .]*

However the secondary images, inside the Einstein ring, move in an unexpected manner: They appear to emerge from the right edge of the shadow, move outward into the annulus between the shadow and the Einstein ring, swing leftward around the shadow, and descend back toward the shadow's edge.

You can understand this by going back to the upper drawing in Figure 8.3. The right ray passes near the black hole, so the right stellar image is near its shadow. Earlier in time, when the camera was further leftward, the right ray had to pass even closer to the black hole in order to bend more strongly and reach the camera, so the right image was very close to the edge of the shadow. By contrast, earlier in time, the left ray passed rather far from the hole and so was nearly straight and produced an image rather far from the hole.

Now, if you're ready, think through the subsequent motions of the images, depicted in Figure 8.4.

Lensing by a Rapidly Spinning Black Hole: Gargantua

The whirl of space generated by Gargantua's very fast spin changes the gravitational lensing. The star patterns in Figure 8.1 (Gargantua) look somewhat different from those in Figure 8.4 (a nonspinning black hole), and the streaming patterns differ even more.

For Gargantua the streaming (Figure 8.5) reveals two Einstein rings, shown as pink curves. Outside the outer ring, the stars stream rightward (for example, along the two red curves), as they did for a nonspinning black hole in Figure 8.4. However, the whirl of space has concentrated the stream into narrowed high-speed strips along the back edge of the hole's shadow, strips that bend somewhat sharply at the equator. The whirl has also produced eddies in the streaming (the closed red curves).

The secondary image of each star appears between the two Einstein rings. Each secondary image circulates along a closed curve (for example, the two yellow curves), and it circulates in the opposite direction to the red streaming motions outside the outer ring.

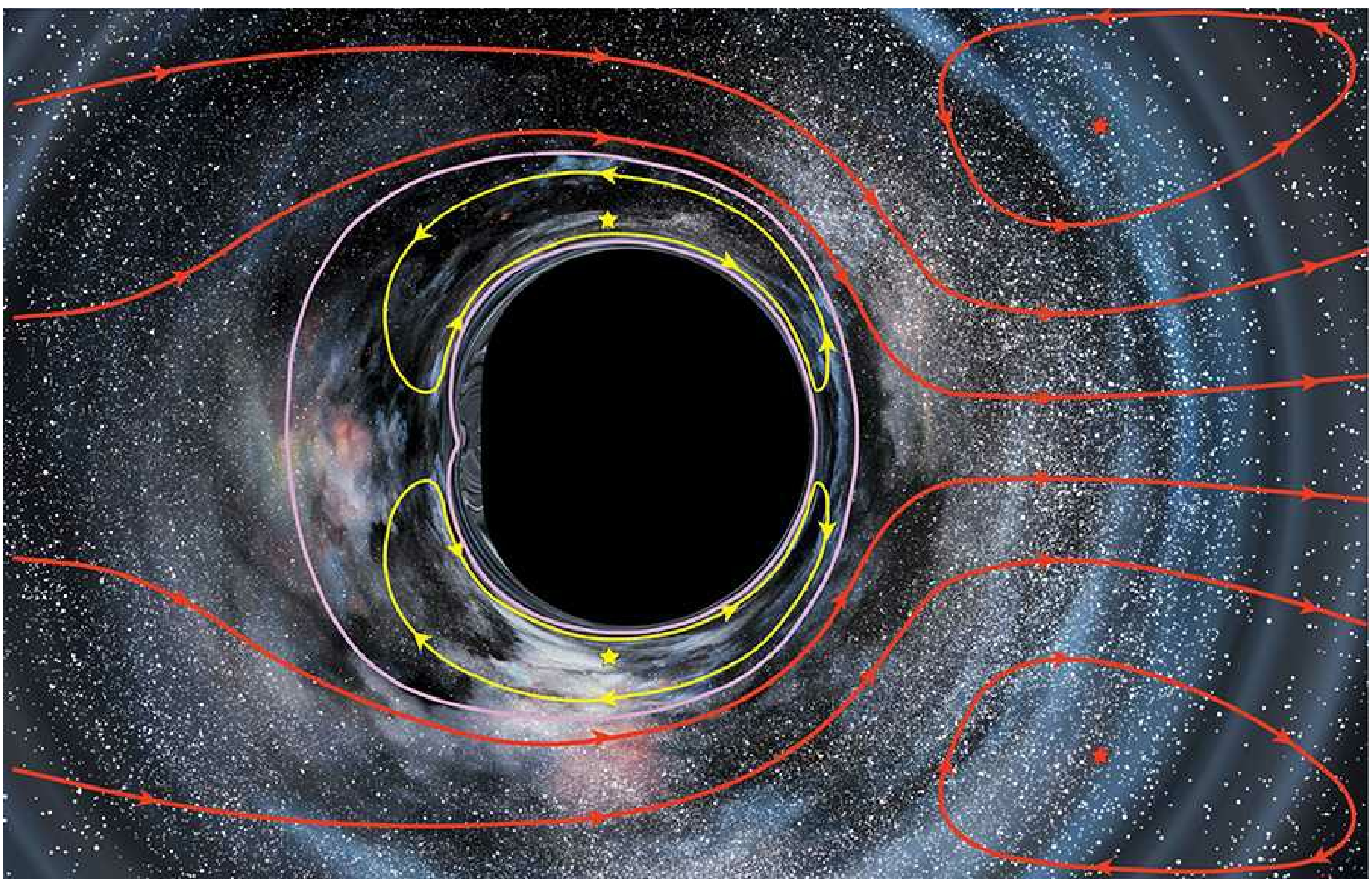

Fig. 8.5. The star streaming patterns as seen by a camera near a rapidly spinning black hole such as Gargantua. In this simulation by the Double Negative visual-effects team, the hole spins at 99.9 percent of the fastest possible, and the camera is in a circular, equatorial orbit with circumference six times larger than the horizon's circumference. For a film clip of this simulation, see this book's page at Interstellar.withgoogle.com.

There are two very special stars in Gargantua's sky with gravitational lensing turned off. One lies directly above Gargantua's north pole; the other directly below its south pole. These are analogs of the star Polaris, which resides directly above the Earth's north pole. I placed five-pointed stars at the primary (red) and secondary (yellow) images of Gargantua's pole stars. All the stars on the Earth's sky appear to circulate around Polaris as we humans are carried around by the Earth's rotation. Similarly, all of Gargantua's primary stellar images circulate around the red pole-star images as the camera orbits the hole, but their circulation paths (for example, the two red eddy curves) are highly distorted by the whirl of space and gravitational lensing. Similarly, all the secondary stellar images circulate around the yellow pole-star images (for example, along the two distorted yellow curves).

Why, for a nonspinning hole (Figure 8.4), did the secondary images appear to emerge from the black hole's shadow, swing around the hole, and descend back into the shadow, instead of circulating around a closed curve as for Gargantua (Figure 8.5)? They actually *do* circulate around closed curves for a nonspinning hole. However, the inner edge of the closed curve is so close to the shadow's edge that it can't be seen. Gargantua's spin makes space whirl, and that whirl moves the inner Einstein ring outward, revealing the secondary images' full circulatory pattern (yellow curves in Figure 8.5), and revealing the inner Einstein ring.

Inside the inner Einstein ring, the streaming pattern is more complicated. The stars in this region are tertiary and higher-order images of all the stars in the universe—the same stars as appear as primary images outside the outer Einstein ring and secondary images between the Einstein rings.

In Figure 8.6, I show five small pictures of Gargantua's equatorial plane, with Gargantua itself in black, the camera's orbit in dashed purple, and a light ray in red. The light ray brings to the camera the stellar image that is at the tip of the blue arrow. The camera is moving counterclockwise around Gargantua.

You can get a lot of insight into the gravitational lensing by walking yourself through these pictures, one by one. Take note: The actual direction to the star is upward and rightward (see outer ends of the red rays). The camera and beginning of each ray point toward the stellar image. The tenth image is very near the left edge of the shadow and the right secondary image is near the right edge; comparing the directions of the camera for these images, we see that the shadow subtends about 150 degrees in the upward direction. This despite the fact that the actual direction from camera to center of Gargantua is leftward and upward. The lensing has moved the shadow relative to Gargantua's actual direction.

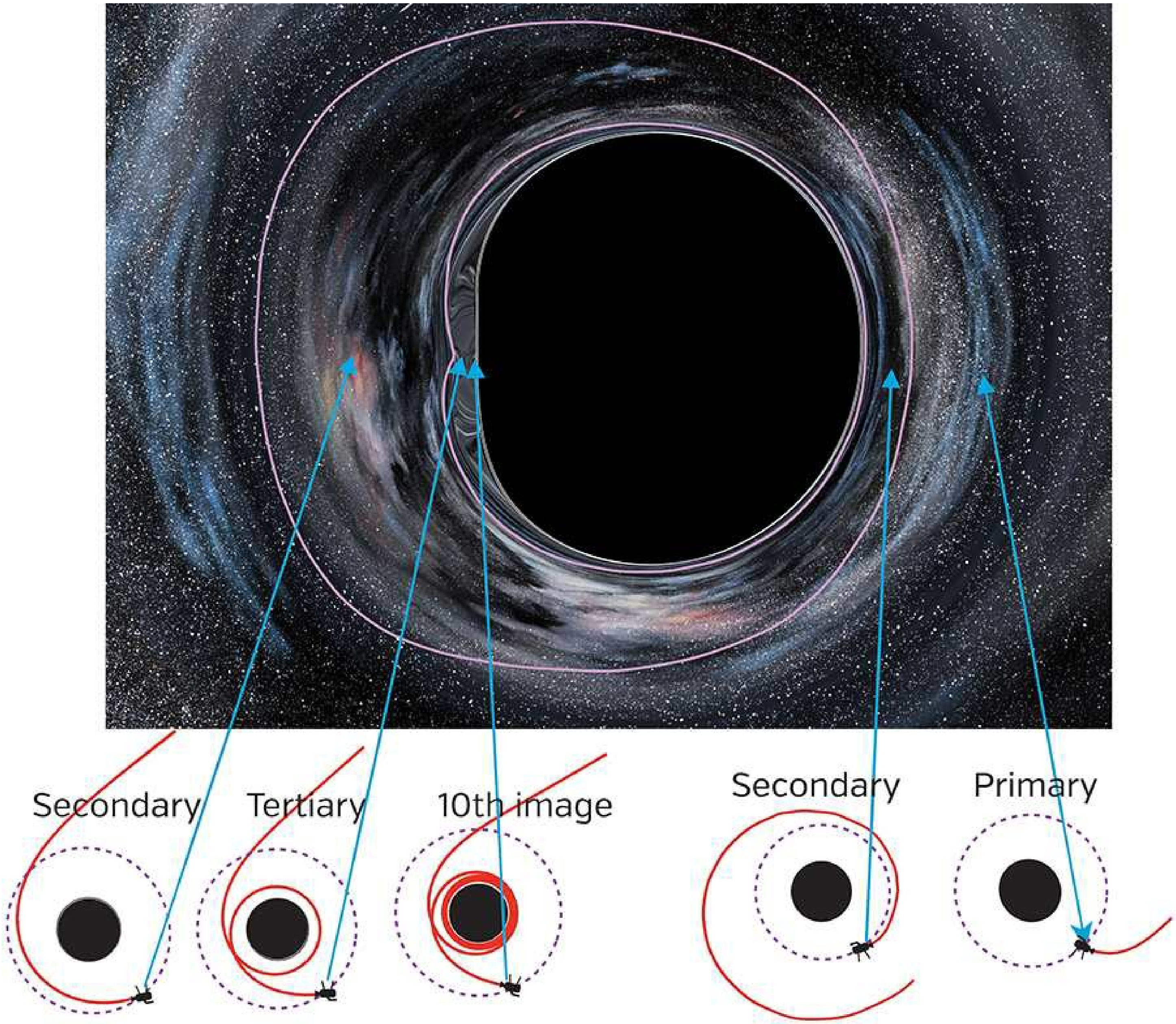

Fig. 8.6. Light rays that bring images of the stars at the tips of the blue arrows. *[From the same Double Negative simulation as Figures 8.1 and 8.5.]*

Creating *Interstellar*'s Black-Hole and Wormhole Visual Effects

Chris wanted Gargantua to look like what a spinning black hole *really* looks like when viewed up close, so he asked Paul to consult with me. Paul put me in touch with the *Interstellar* team he had assembled at his London-based visual-effects studio, Double Negative.

I wound up working closely with Oliver James, the chief scientist. Oliver and I talked by phone and Skype, exchanged e-mails and electronic files, and met in person in Los Angeles and at his London office. Oliver has a college degree in optics and atomic physics and understands Einstein's relativity laws, so we speak the same technical language.

Several of my physicist colleagues had already done computer simulations of what one would see when orbiting a black hole and even falling into one. The best experts were Alain Riazuelo, at the Institut d'Astrophysique in Paris, and Andrew Hamilton, at the University of Colorado in

Boulder. Andrew had generated black-hole movies shown in planetariums around the world, and Alain had simulated black holes that spin very, very fast, like Gargantua.

So initially I planned to put Oliver in touch with Alain and Andrew and ask them to provide him the input he needed. I lived uncomfortably with that decision for several days, and then changed my mind.

During my half century physics career I put great effort into making new discoveries myself and mentoring students as they made new discoveries. Why not, for a change, do something just because it's fun, I asked myself, even though others have done it before me? And so I went for it. And it *was* fun. And to my surprise, as a byproduct, it produced (modest) new discoveries.

Using Einstein's relativistic laws of physics and leaning heavily on prior work by others (especially Brandon Carter at the Laboratoire Univers et Théories in France and Janna Levin at Columbia University), I worked out the equations Oliver needed. These equations compute the trajectories of light rays that begin at some light source, for example, a distant star, and travel inward through Gargantua's warped space and time to the camera. From those light rays, my equations then compute the images the camera sees, taking account not only of the light's sources and Gargantua's warping of space and time, but also the camera's motion around Gargantua.

Having derived the equations, I implemented them myself, using user-friendly computer software called Mathematica. I compared images produced by my Mathematica computer code with Alain Riazuelo's images, and when they agreed, I cheered. I then wrote up detailed descriptions of my equations and sent them to Oliver in London, along with my Mathematica code.

My code was very slow and had low resolution. Oliver's challenge was to convert my equations into computer code that could generate the ultra-high-quality IMAX images needed for the movie.

Oliver and I did this in steps. We began with a nonspinning black hole and a nonmoving camera. Then we added the black hole's spin. Then we added the camera's motion: first motion in a circular orbit, and then plunging into a black hole. And then we switched to a camera around a wormhole.

At this point, Oliver hit me with a minibombshell: To model some of the more subtle effects, he would need not only equations describing the trajectory of a ray of light, but also equations describing how the cross section of a beam of light changes its size and shape during its journey past the black hole.

I knew more or less how to do this, but the equations were horrendously complicated and I feared making mistakes. So I searched the technical literature and found that in 1977 Serge Pineault and Rob Roeder at the University of Toronto had derived the necessary equations in almost the form I needed. After a three-week struggle with my own stupidities, I brought their equations into precisely the needed form, implemented them in Mathematica, and wrote them up for Oliver, who incorporated them into his own computer code. At last his code could produce the quality images needed for the movie.

At Double Negative, Oliver's computer code was just the beginning. He handed it over to an artistic team led by Eugénie von Tunzelmann, who added an accretion disk (Chapter 9) and created the background galaxy with its stars and nebulae that Gargantua would lens. Her team then added the *Endurance* and Rangers and landers and the camera animation (its changing motion, direction, field of view, etc.), and molded the images into intensely compelling forms: the fabulous scenes that actually appear in the movie. For further discussion, see Chapter 9.

In the meantime, I puzzled over the high-resolution film clips that Oliver and Eugénie sent me, struggling to extract insights into why the images look like they look, and why the star fields stream as they stream. For me, those film clips are like experimental data: they reveal things I never could have figured out on my own, without those simulations—for example, the things I described in the previous section (Figures 8.5 and 8.6). We plan to publish one or more technical papers, describing the new things we learned.

Imaging a Gravitational Slingshot

Although Chris chose not to show any gravitational slingshots in *Interstellar*, I wondered what they would look like to Cooper as he piloted the Ranger toward Miller's planet. So I used my equations and Mathematica to simulate them and produce images. (My images have far lower resolution than Oliver's and Eugénie's due to my code's slowness.)

Figure 8.7 shows a sequence of images, as Cooper's Ranger swings around an intermediate-mass black hole (IMBH) to initiate its descent toward Miller's planet—in my scientist's interpretation of *Interstellar*. This is the slingshot described in Figure 7.2.

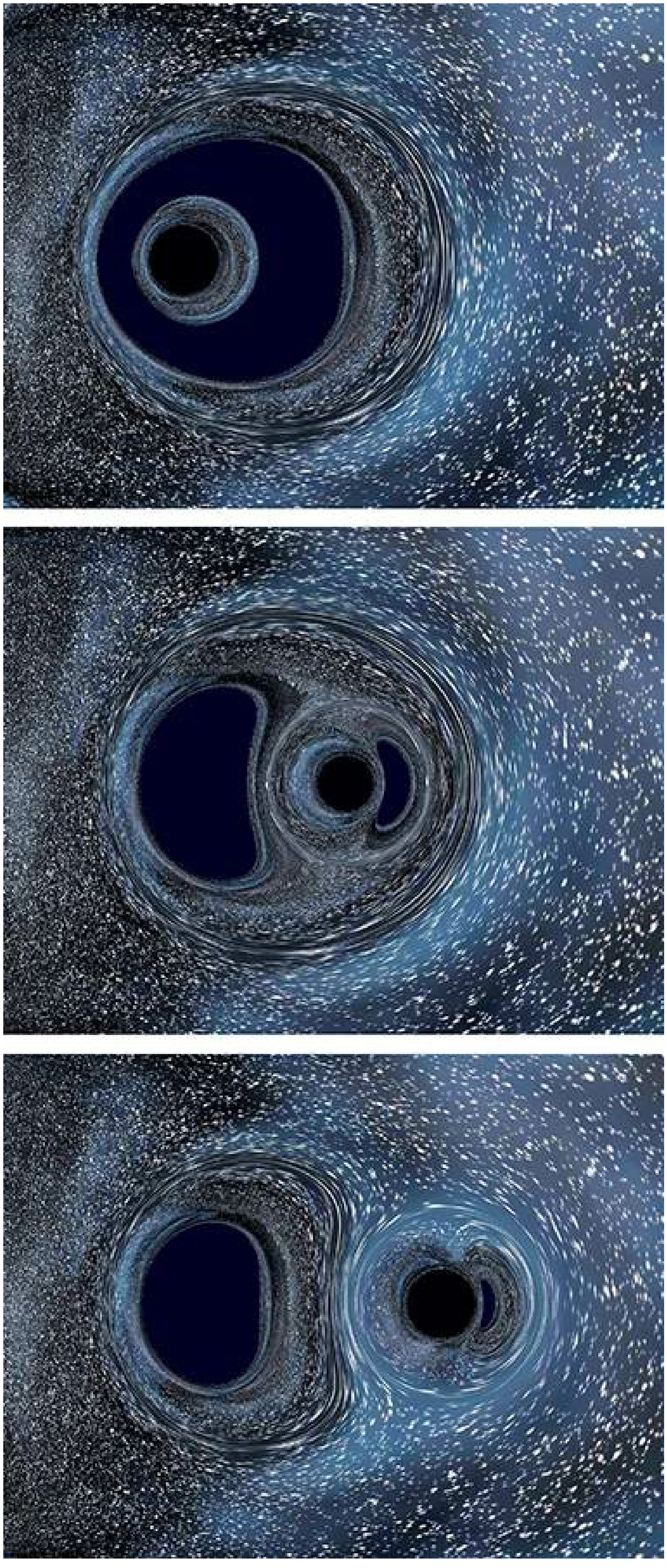

Fig. 8.7. Gravitational slingshot around an IMBH, with Gargantua in the background. *[My own simulation and visualization.]*

In the top image, Gargantua is in the background with the IMBH passing in front of it. The

IMBH grabs light rays from distant stars that are headed toward gargantua, swings the rays around itself, and ejects them toward the camera. This explains the donut of starlight that surrounds the IMBH's shadow. Although the IMBH is a thousand times smaller than Gargantua, it is far closer to the Ranger than is Gargantua, so it looks only modestly smaller.

As the IMBH appears to move rightward, as seen by the slingshot-moving camera, it leaves Gargantua's primary shadow behind itself (middle picture in Figure 8.7), and it pushes a secondary image of Gargantua's shadow ahead of itself. These two images are completely analogous to the primary and secondary images of a star gravitationally lensed by a black hole; but now it is Gargantua's shadow that is being lensed, by the IMBH. In the bottom picture, the secondary shadow is shrinking in size, as the IMBH moves onward. By this time the slingshot is nearly complete, and the camera, on board the Ranger, is headed downward, toward Miller's planet.

As impressive as these images may be, they can be seen only up close to the IMBH and Gargantua, not from the great distance of Earth. To astronomers on Earth, the most visually impressive things about gigantic black holes are jets that stick out of them and the light from brilliant disks of hot gas that orbit them. To these we'll now turn.

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20 See Figures 6.4 and 6.5.

9

Disks and Jets

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Quasars

Most of the objects seen by radio telescopes are huge clouds of gas, clouds far larger than any star. But in the early 1960s a few tiny objects were found. Astronomers named these objects *quasars* for “quasi-stellar radio sources.”

In 1962 the Caltech astronomer Maarten Schmidt, looking through the world’s largest optical telescope on Palomar Mountain, discovered light coming from a quasar called 3C273. It looked like a bright star with a faint jet shooting out of it (Figure 9.1). This was weird!

When Schmidt split 3C273’s light into its various colors (as is sometimes done by sending light through a prism), he saw the set of spectral lines in the bottom of Figure 9.1. At first sight, these were unlike any spectral lines he had ever seen. But in February 1963, after a few months’ struggle, he realized the lines were unfamiliar simply because their wavelengths were 16 percent larger than normal. This is called the Doppler shift; it was caused by the quasar’s moving away from Earth at 16 percent the speed of light, about $c/6$. What could cause that ultrafast motion? The least crazy explanation Schmidt could find was the expansion of the universe.

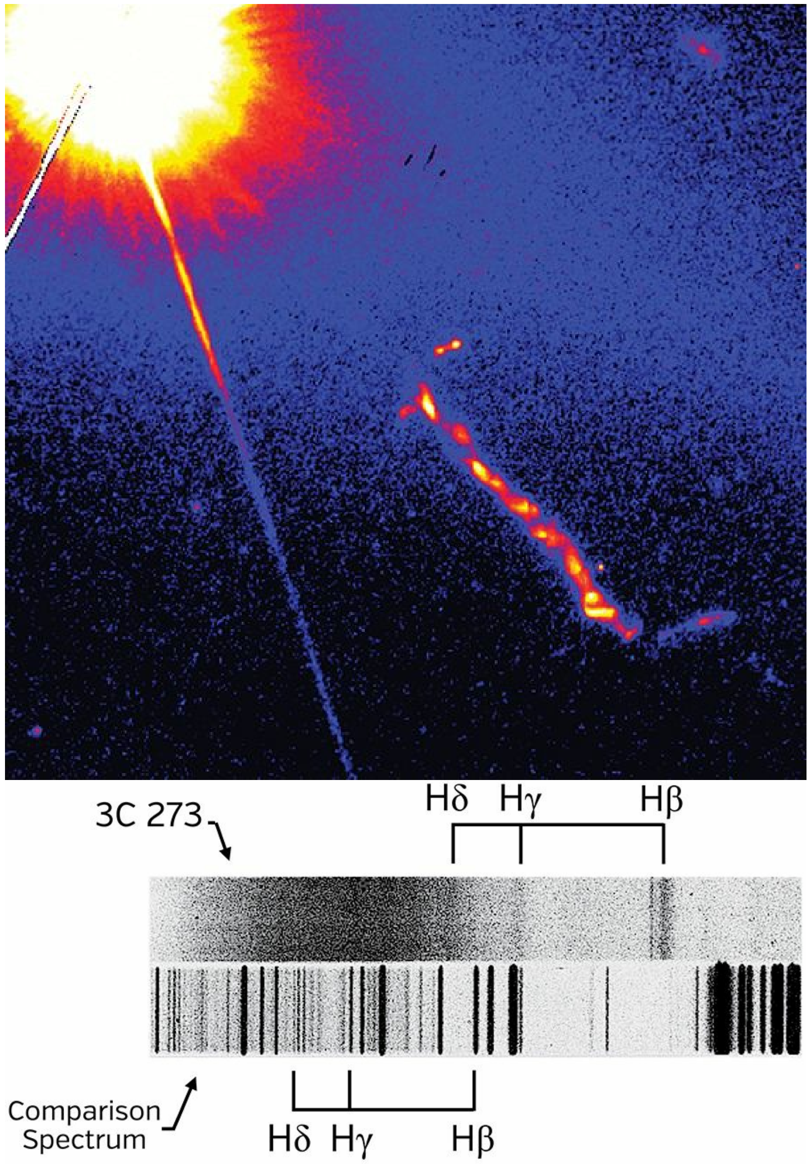

Fig. 9.1. *Top*: Photograph of 3C273 taken by NASA's Hubble Space Telescope. The star (*upper left*) looks big only because the photo is overexposed in order to see the faint jet (*lower right*). It is actually so small that its size cannot be measured. *Bottom*: Maarten Schmidt's spectral lines from 3C273 (*upper panel*) compared with spectral lines of hydrogen measured in an Earth laboratory. The quasar's three lines are the same as hydrogen's lines called Hβ, Hγ, and Hδ, but with wavelengths increased by 16 percent. (The images of the spectral lines are photographic negatives: black lines are really bright.)

As the universe expands, objects far from Earth move apart from us at very high speed, and objects nearer move away more slowly. 3C273's enormous speed, one-sixth that of light, meant that 3C273 was 2 billion light-years from Earth, nearly the farthest object that had ever been seen at that time. From its brightness and its distance, Schmidt concluded that 3C273 puts out 4 trillion times more power in light than the Sun, and a hundred times more power than the brightest galaxies!

This prodigious power fluctuated on times as short as a month, so most of the light must be coming from an object so small that the light can travel across it in one month's time—far smaller than the distance from Earth to the nearest star, Proxima Centauri. And other quasars with almost as much power fluctuated on times of a few hours, so they had to be not much larger than our solar system. *One hundred times the power of a bright galaxy, coming from a region the size of our solar system; that was phenomenal!*

Black Holes and Accretion Disks

How could so much power come out of a region so small? When we think about the fundamental forces in Nature, there are three possibilities: chemical energy, nuclear energy, or gravitational energy.

Chemical energy is the energy released when molecules combine together to make new kinds of molecules. An example is burning gasoline, which combines oxygen from the air with gasoline molecules to make water and carbon dioxide, and a lot of heat. The power from that would be far, far, far too little though.

Nuclear energy results when atomic nuclei combine together to make new atomic nuclei. Examples are an atomic bomb, a hydrogen bomb, and the burning of nuclear fuel inside a star. Though this can be far more powerful than chemical energy (think of the difference between a gasoline fire and a nuclear bomb), astrophysicists couldn't see any plausible way for nuclear energy to power quasars. It was still too puny.

So the only possibility left was *gravitational energy*, the same kind of energy we were driven to, when navigating the *Endurance* around Gargantua. For the *Endurance*, gravitational energy was harnessed by a slingshot around an intermediate-mass black hole (Chapter 7). The black hole's intense gravity was key. For quasars, similarly, the power must come from a black hole.

For several years, astrophysicists struggled to figure out how a black hole could do the job. The answer was found in 1969, by Donald Lynden-Bell at the Royal Greenwich Observatory in England. A quasar, Lynden-Bell hypothesized, is a gigantic black hole surrounded by a disk of hot gas (an accretion disk) that is threaded by a magnetic field (Figure 9.2).

Hot gas in our universe is almost always threaded by magnetic fields (Chapter 2). These fields are locked into the gas; the gas and fields move together, in lockstep.

When threading an accretion disk, a magnetic field becomes a catalyst for converting gravitational energy into heat and then light. The field provides ultrastrong friction[21] that slows the gas's circumferential motion, reducing the centrifugal force that holds it out against the pull of gravity, so the gas moves inward, toward the black hole. As the gas moves inward, the hole's gravity speeds up its orbital motion by even more than the friction slowed it. In other words, gravitational energy is converted into kinetic energy (energy of motion). Magnetic friction then converts half that new kinetic energy into heat and light, and the process repeats.

The energy comes from the black hole's gravity. The agents for extracting it are magnetic friction and the disk's gas.

The quasar's bright light, seen by astronomers, comes from the disk's heated gas, Lynden-Bell concluded. Moreover, the magnetic field accelerates some of the gas's electrons to high energies; and the electrons then spiral around the magnetic force lines, emitting the quasar's observed radio waves.

Lynden-Bell worked out the details of all this using a combination of the Newtonian, relativistic, and quantum laws of physics. He easily explained everything about quasars that astronomers had seen, except their jets. His technical article describing his reasoning and his calculations (Lynden-Bell 1979) is one of the great astrophysics articles of all time.

The Jets: Extracting Power from Whirling Space

Over the next few years, astronomers discovered many more jets sticking out of quasars and studied them in great detail. It soon became clear that they are streams of hot, magnetized gas ejected from the quasar itself: from the black hole and its accretion disk (Figure 9.2). And the ejection is extremely powerful: the gas travels out the jets at nearly the speed of light. As it travels, and when it plows into material far from the quasar, the gas emits power in light, in radio waves, in X-rays, and even in gamma rays. The jets are sometimes as bright as the quasar itself, a hundred times brighter than the brightest galaxies.

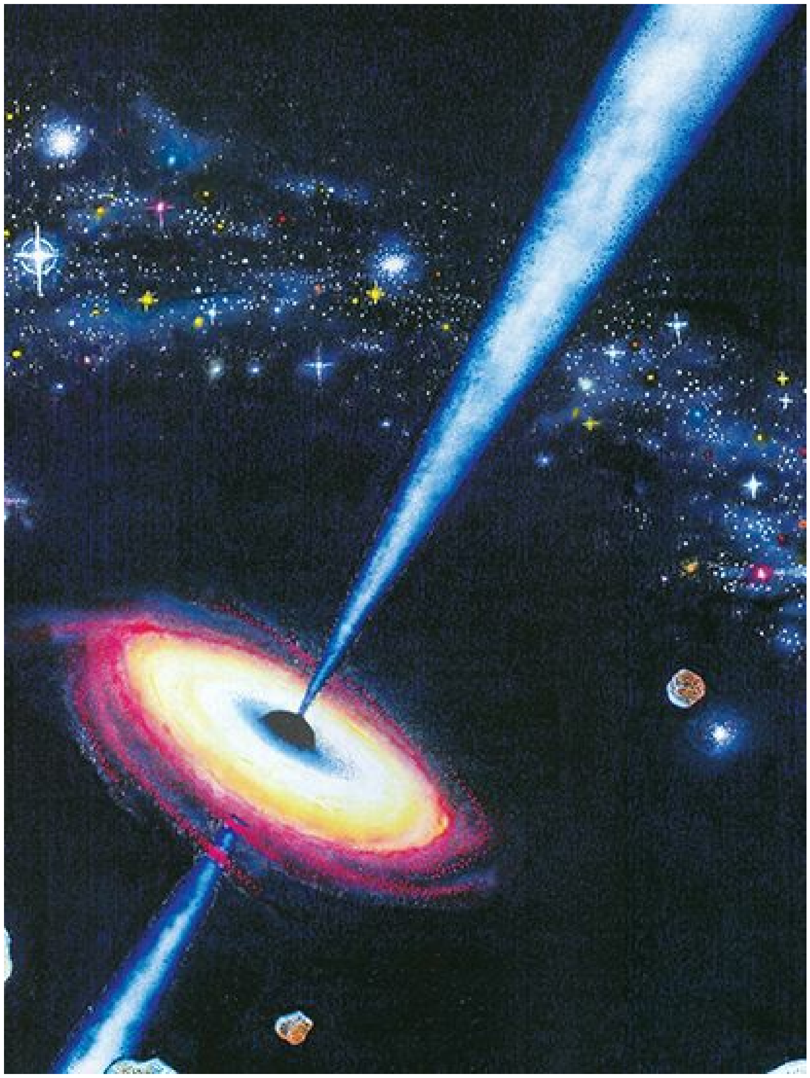

Fig. 9.2. Artist's conception of an accretion disk around a black hole, and jets emerging from near the hole's poles. *[Drawing by Matt Zimet based on a sketch by me; from my book* Black Holes & Time Warps: Einstein's Outrageous Legacy.*]*

Astrophysicists struggled for nearly a decade to explain how the jets are powered and what makes them so fast, so narrow, and so straight. The answers came in several variants, with the most interesting in 1977 from Roger Blandford at the University of Cambridge, England, and his student Roman Znajek, building on foundations laid by the Oxford physicist Roger Penrose; see Figure 9.3.

The accretion disk's gas gradually spirals into the black hole. When crossing the hole's event horizon, each bit of gas deposits its bit of magnetic field onto the horizon, and then the surrounding disk holds it there, Blandford and Znajek concluded. As the black hole spins, it drags space into whirling motion (Figures 5.4 and 5.5), and the whirling space makes the magnetic field whirl (Figure 9.3). The whirling magnetic field generates an intense electric field like in a dynamo at a hydroelectric power station. The electric field and the whirling magnetic field together fling plasma (hot, ionized gas) upward and downward at near light speed, creating and powering two jets. The jets' directions are held steady (when averaged over years) by the black hole's spin, which is steady due to gyroscopic action.

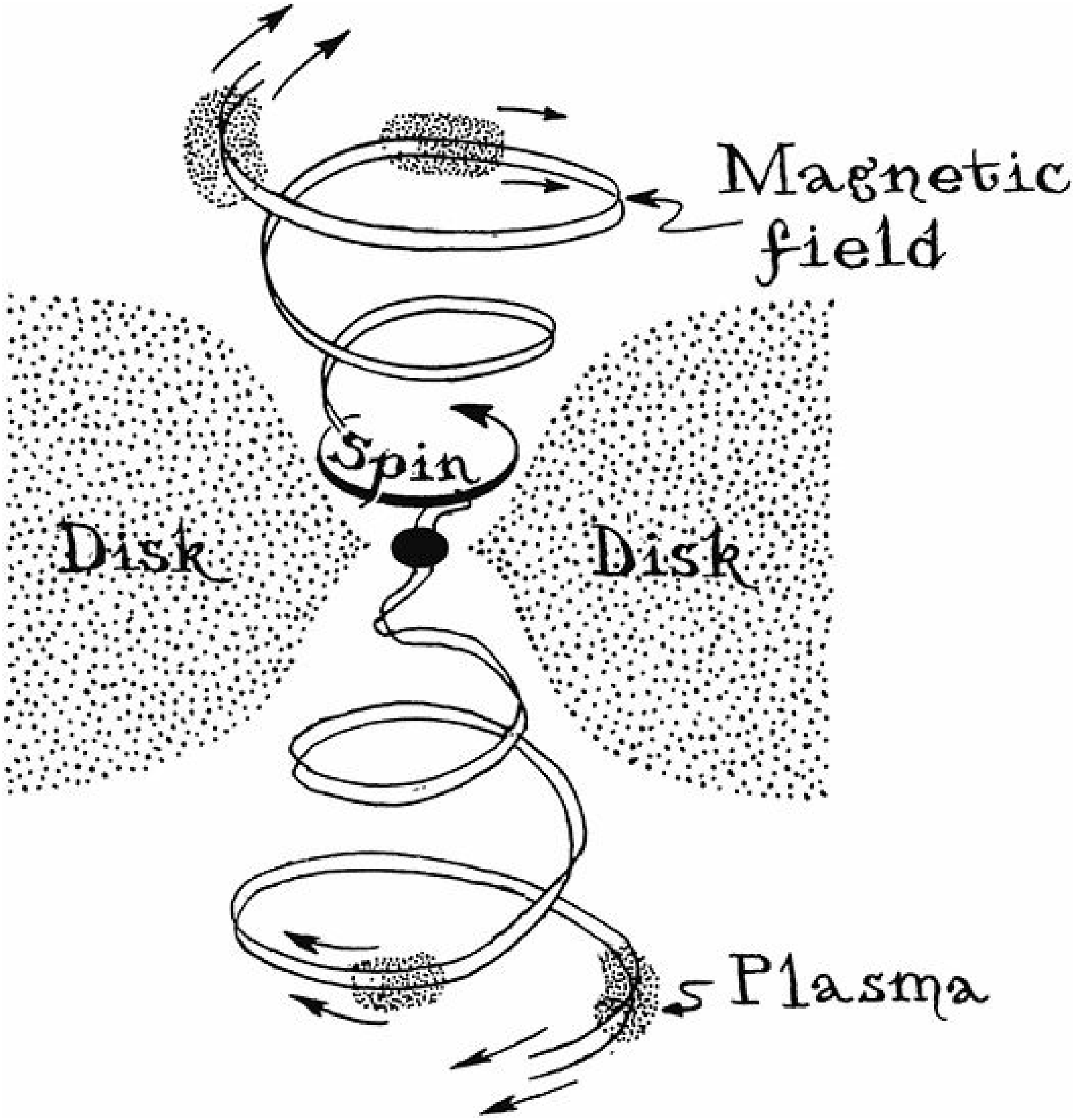

Fig. 9.3. Blandford-Znajek mechanism for generating jets. *[Drawing by Matt Zimet based on a sketch by me; from my book* Black Holes & Time Warps: Einstein's Outrageous Legacy.*]*

In 3C273 only one jet was bright enough to see (Figure 9.1), but in many other quasars both are seen.

Blandford and Znajek worked out the full details, relying heavily on Einstein's relativistic laws. They were able to explain most everything about the jets that astronomers see.

In a second variant of the explanation (Figure 9.4), the whirling magnetic field is anchored in the accretion disk instead of the hole, and is dragged around by the disk's orbital motion. Otherwise, the story is the same: dynamo action; plasma flung out. This variant works well even if the black hole isn't spinning. But we're pretty sure that most black holes spin fast, so I suspect the Blandford-Znajek mechanism (Figure 9.3) is the most common one in quasars. However, I may be prejudiced. I spent much time in the 1980s exploring aspects of the Blandford-Znajek ideas and even coauthored a technical book about them.

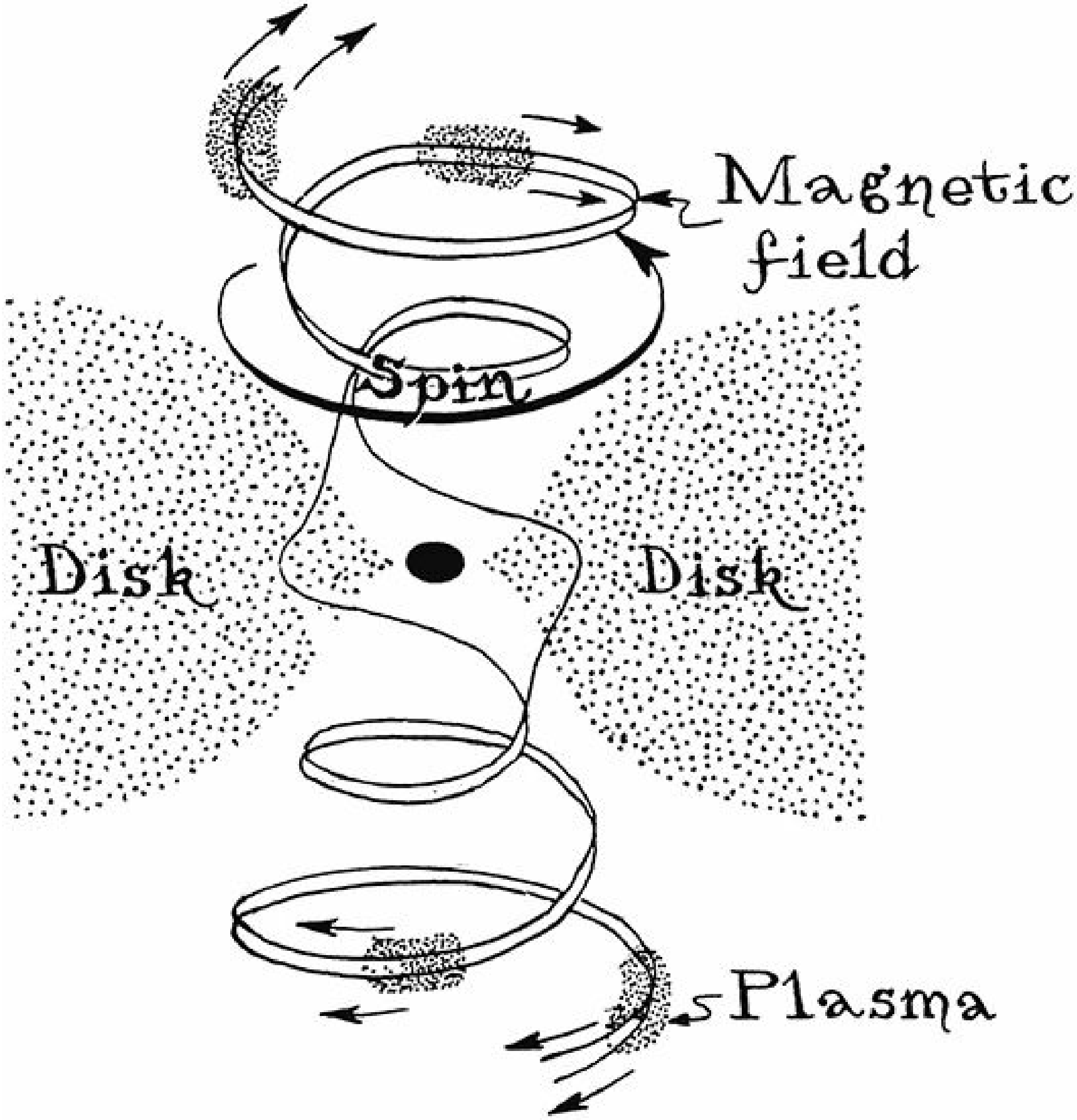

Fig. 9.4. Like Figure 9.3 but with magnetic field anchored in the accretion disk. *[Drawing by Matt Zimet based on a sketch by me; from my book* Black Holes & Time Warps: Einstein's Outrageous Legacy.*]*

Whence Comes the Disk? Tidal Forces Tear Stars Apart

Lynden-Bell, in 1969, speculated that quasars live at the centers of galaxies. We don't see a quasar's host galaxy, he said, because its light is so much fainter than the quasar's light. The quasar drowns the galaxy out. In the decades since then, with improving technology, astronomers have found the galaxy's light around many quasars, confirming Lynden-Bell's speculation.

In those recent decades we also learned where most of the disk's gas comes from. Occasionally a star strays so close to the quasar's black hole that the hole's tidal gravity (Chapter 4) tears the star apart. Much of the shredded star's gas is captured by the black hole and forms an accretion disk, but some of the gas escapes.

In recent years, thanks to improving computer technology, astrophysicists simulated this. Figure 9.5 is from a recent simulation by James Guillochon, Enrico Ramirez-Ruiz, and Daniel Kasen (University of California at Santa Cruz) and Stephan Rosswog (University of Bremen).[22] At time zero (not shown) the star was headed almost precisely toward the black hole and the hole's tidal gravity was beginning to stretch the star toward the hole and squeeze it from the sides, as in Figure 6.1. Twelve hours later the star is strongly deformed and at the location shown in Figure 9.5. Over the next few hours, it swings around the hole along the blue gravitational-slingshot orbit and deforms further as shown. By twenty-four hours the star is flying apart; its own gravity can no longer hold it together.

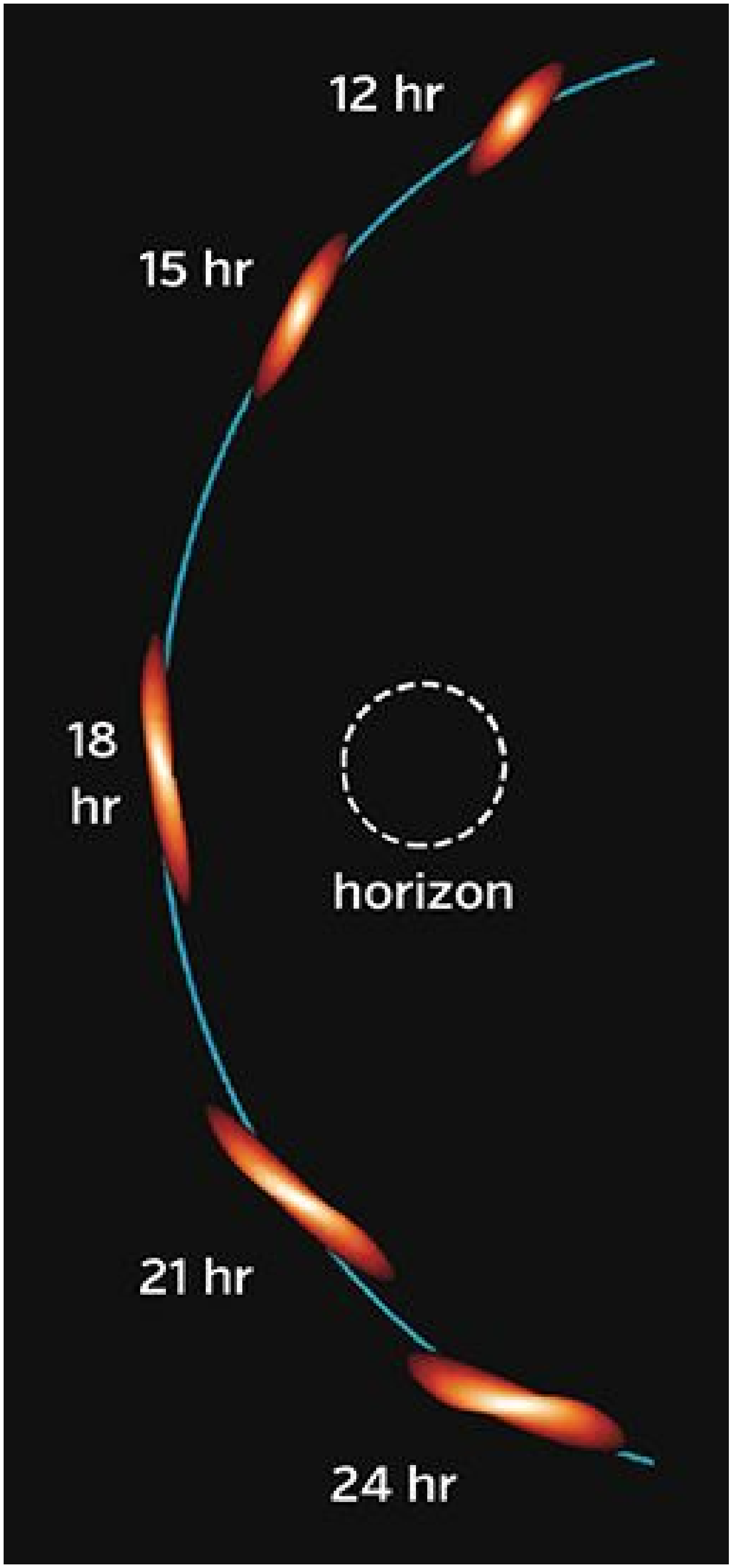

Fig. 9.5. Tidal disruption of a red giant star by a black hole similar to Gargantua.

The star's subsequent fate is shown in Figure 9.6, from a different simulation by James Guillochon together with Suvi Gezari (Johns Hopkins University). For a movie of this simulation, see http://hubblesite.org /newscenter /archive /releases /2012 /18 /video /a/.

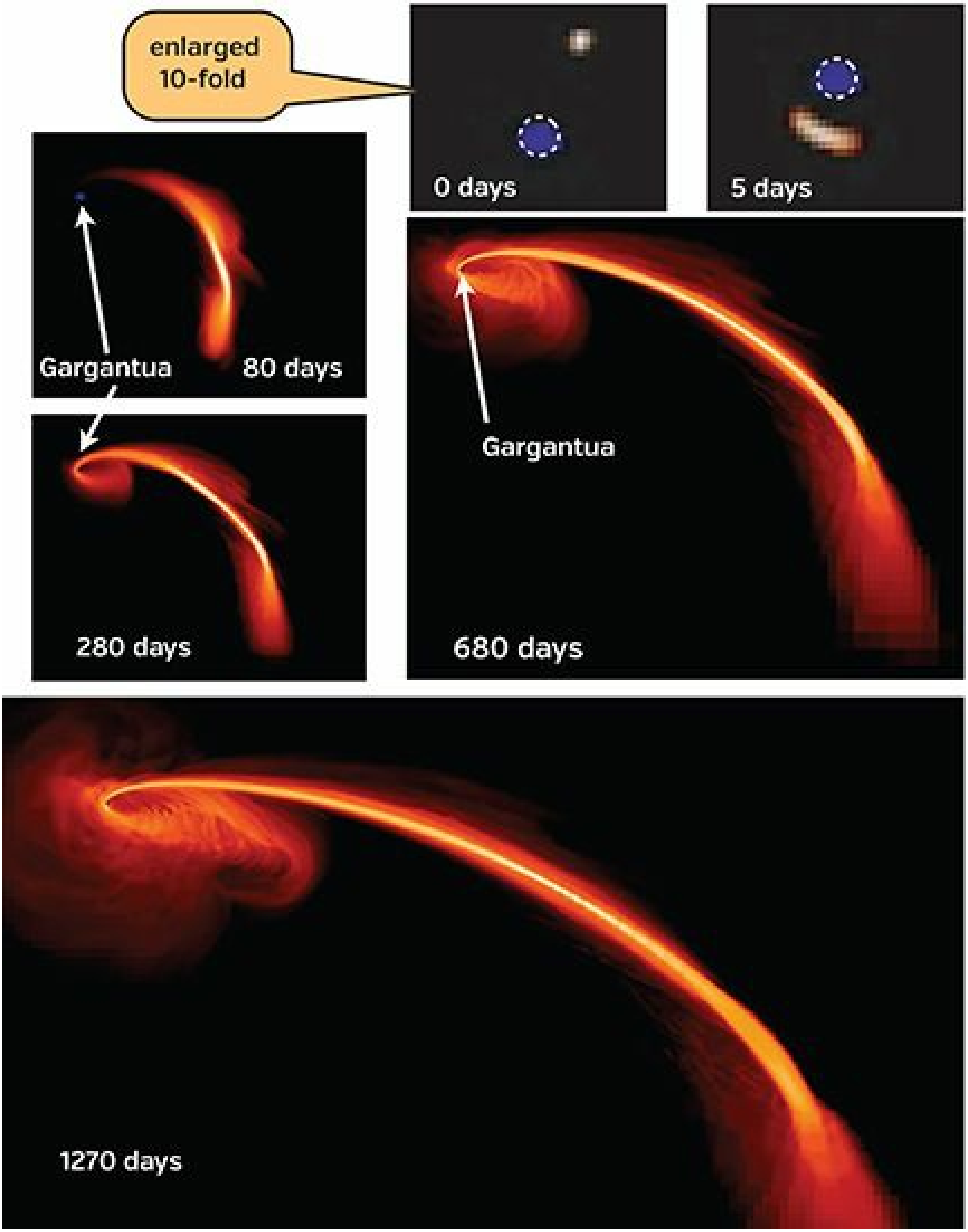

Fig. 9.6. Subsequent fate of the star in Figure 9.5.

The top two images are shortly before the beginning and shortly after the end of Figure 9.5; I enlarged these two images tenfold compared to the others, to make the hole and the disrupting star visible.

As the whole set of images shows, over the subsequent several years much of the star's matter is captured into orbit around the black hole, where it begins to form an accretion disk. And the remaining matter escapes from the hole's gravitational pull along a streaming, jetlike trajectory.

Gargantua's Accretion Disk and Missing Jet

A typical accretion disk and its jet emit radiation—X-rays, gamma rays, radio waves, and light—radiation so intense that it would fry any human nearby. To avoid frying, Christopher Nolan and Paul Franklin gave Gargantua an exceedingly anemic disk.

Now, "anemic" doesn't mean anemic by human standards; just by the standards of typical quasars. Instead of being a hundred million degrees like a typical quasar's disk, Gargantua's disk is only a few thousand degrees, like the Sun's surface, so it emits lots of light but little to no X-rays or gamma rays. With gas so cool, the atoms' thermal motions are too slow to puff the disk up much. The disk is thin and nearly confined to Gargantua's equatorial plane, with only a little puffing.

Disks like this might be common around black holes that have not torn a star apart in the past millions of years or more—that have not been "fed" in a long time. The magnetic field, originally confined by the disk's plasma, may have largely leaked away. And the jet, previously powered by the magnetic field, may have died. Such is Gargantua's disk: jetless and thin and relatively safe for humans. Relatively.

Gargantua's disk looks quite different from the pictures of thin disks that you see on the web or in astrophysicists' technical publications, because those pictures omit a key feature: the gravitational lensing of the disk by its black hole. Not so in *Interstellar*, where Chris insisted on visual accuracy.

Eugénie von Tunzelmann was charged with putting an accretion disk into Oliver James' gravitational lensing computer code, the code I described in Chapter 8. As a first step, just to see what the lensing does, Eugénie inserted a disk that was truly infinitesimally thin and lay precisely in Gargantua's equatorial plane. For this book she has provided a more pedagogical version of that disk, made of equally spaced color swatches (Inset in Figure 9.7).

If there had been no gravitational lensing, the disk would have looked like the inset. The lensing produced huge changes from this (body of Figure 9.7). You might have expected the back portion of the disk to be hidden behind the black hole. Not so. Instead, it is gravitationally lensed to produce two images, one above Gargantua and the other below; see Figure 9.8. Light rays emitted from the disk's top face, behind Gargantua, travel up and over the hole to the camera, producing the disk image that wraps over the top of Gargantua's shadow in Figure 9.7; and similarly for the disk image that wraps under the bottom of Gargantua's shadow.

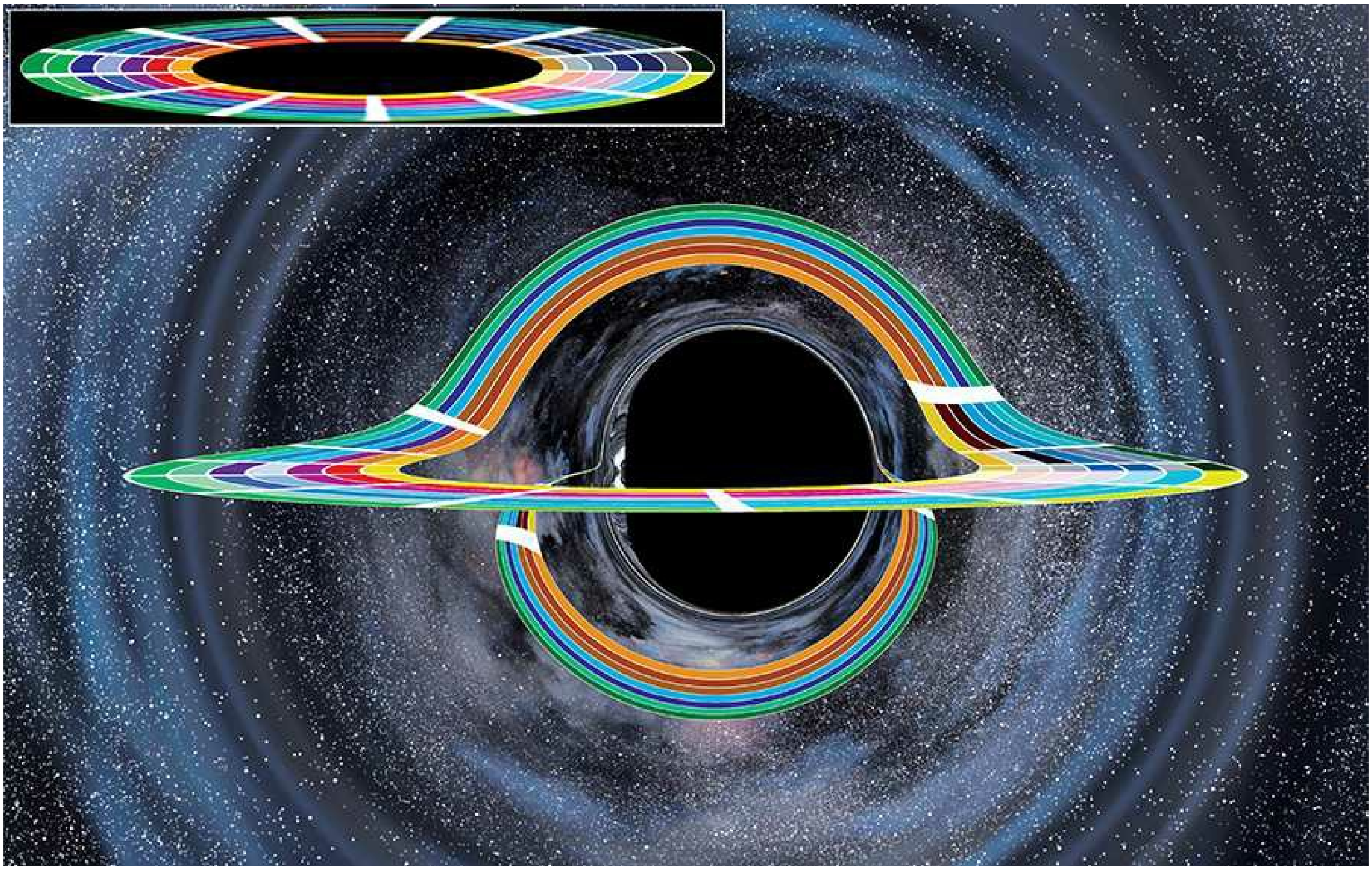

Fig. 9.7. An infinitesimally thin disk in Gargantua's equatorial plane, gravitationally lensed by Gargantua's warped space and time. Here Gargantua spins very fast. *Inset*: The disk in the absence of the black hole. *[From Eugénie von Tunzelmann's artistic team at Double Negative.]*

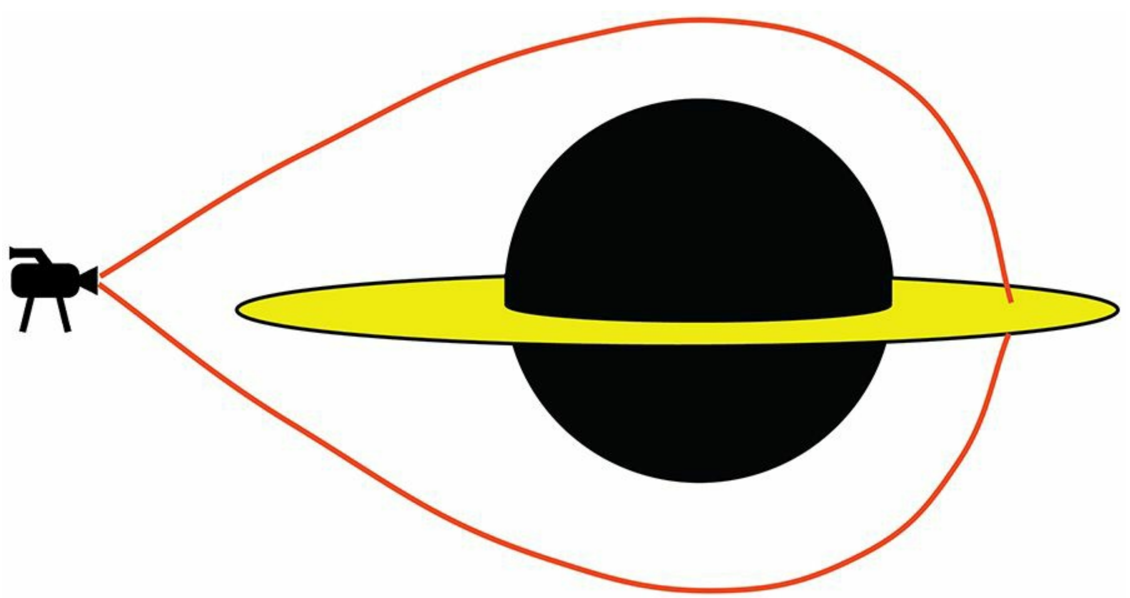

Fig. 9.8. Light rays (*red*) bring to the camera images of the back part of the accretion disk, behind Gargantua: one image above the hole's shadow, the other below the hole's shadow.

Inside these primary images, we see thin secondary images of the disk, wrapping over and under the shadow, near the shadow's edge. And if the picture were made much larger, you would see tertiary and higher-order images, closer and closer to the shadow.

Can you figure out why the lensed disk has the form you see? Why is the primary image wrapping under the shadow attached to the thin secondary image wrapping over it? Why are the paint swatches on the over-wrapping and under-wrapping images widened so greatly, and those on the sides squeezed? . . .

Gargantua's space whirl (space moving toward us on the left and away on the right) distorts the disk images. It pushes the disk away from the shadow on the left and toward the shadow on the right, so the disk looks a bit lopsided. (Can you explain why?)

To get further insight, Eugénie von Tunzelmann and her team replaced their variant of the color-swatch disk (Figure 9.7) with a more realistic thin accretion disk: Figure 9.9. This was much more beautiful, but it raised problems. Chris did not want his mass audience to be confused by the lopsidedness of the disk and black-hole shadow, and the shadow's flat left edge, and the complicated star-field patterns near that edge (discussed in Chapter 8). So he and Paul slowed Gargantua's spin to 0.6 of the maximum, making these weirdnesses more modest. (Eugénie had already omitted the Doppler shift caused by the disk's motion toward us on the left and away on the right. It would have made the disk far more lopsided: bright blue on the left and dim red on the right—totally confusing to a mass audience!)

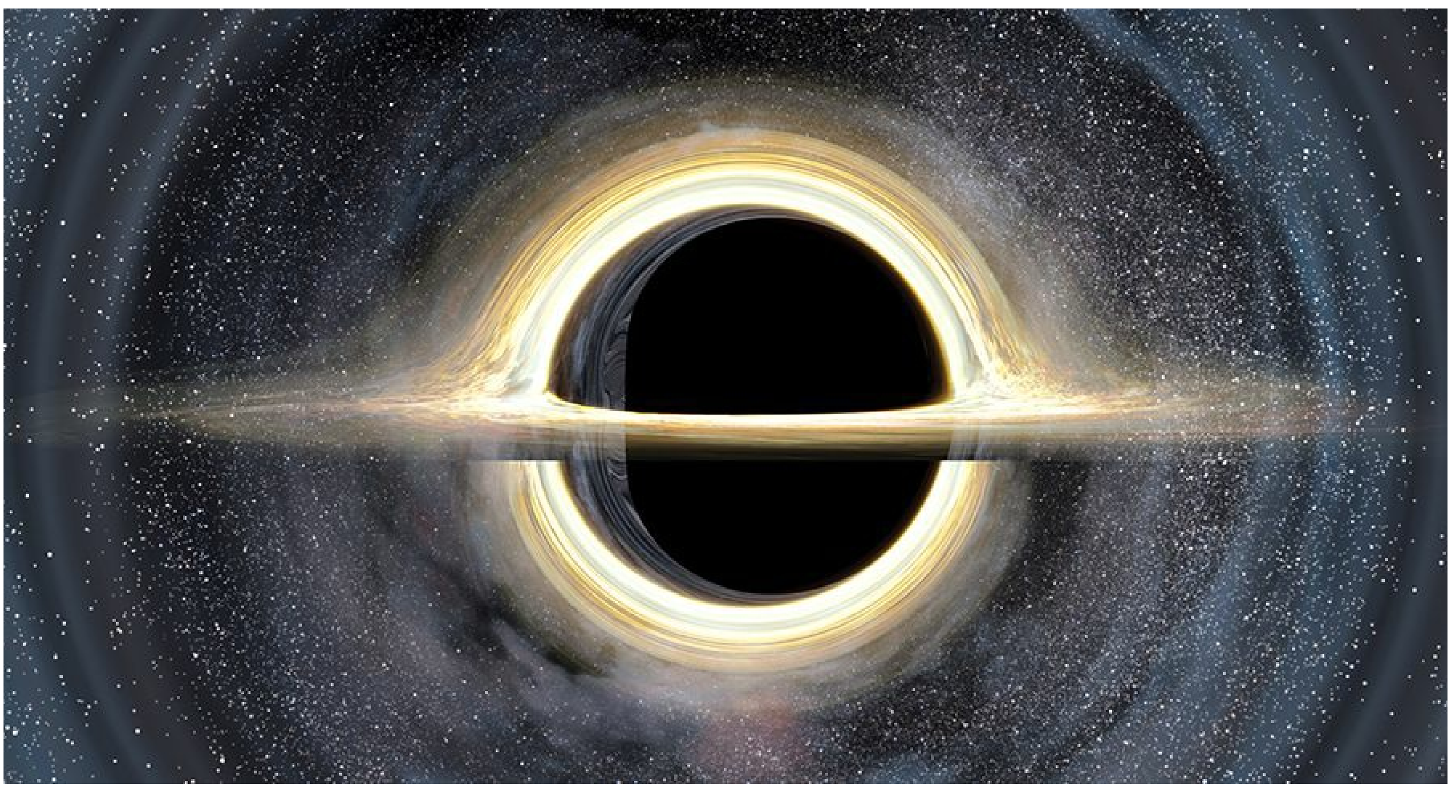

Fig. 9.9 Gargantua with the infinitesimally thin paint-swatch disk (Fig. 9.7) replaced by a more realistic, infinitesimally thin accretion disk. *[From Eugénie von Tunzelmann's artistic team at Double Negative.]*

The artistic team at Double Negative then gave the disk the texture and surface relief that we expect a real, anemic accretion disk to have, puffing it up a bit in a manner that varied from place to place. They made the disk hotter (brighter) near Gargantua and cooler (dimmer) at larger distances. They made it thicker at larger distances because it is Gargantua's tidal gravity that squeezes the disk into the equatorial plane, and tidal gravity is much weaker farther from the black hole. They added the background galaxy: many layers of artwork (dust, nebulae, stars). And they added lens flare—the haze and glare and streaks of light that would arise from scattering of the disk's bright light in a camera lens. The results were the wonderful and compelling images in the movie (Figures 9.10 and 9.11).

Fig. 9.10. Gargantua and its accretion disk, with Miller's planet above the disk's left edge. The disk is so bright that the stars and nebulae are barely visible. *[From* Interstellar*, used courtesy of Warner Bros. Entertainment Inc.]*

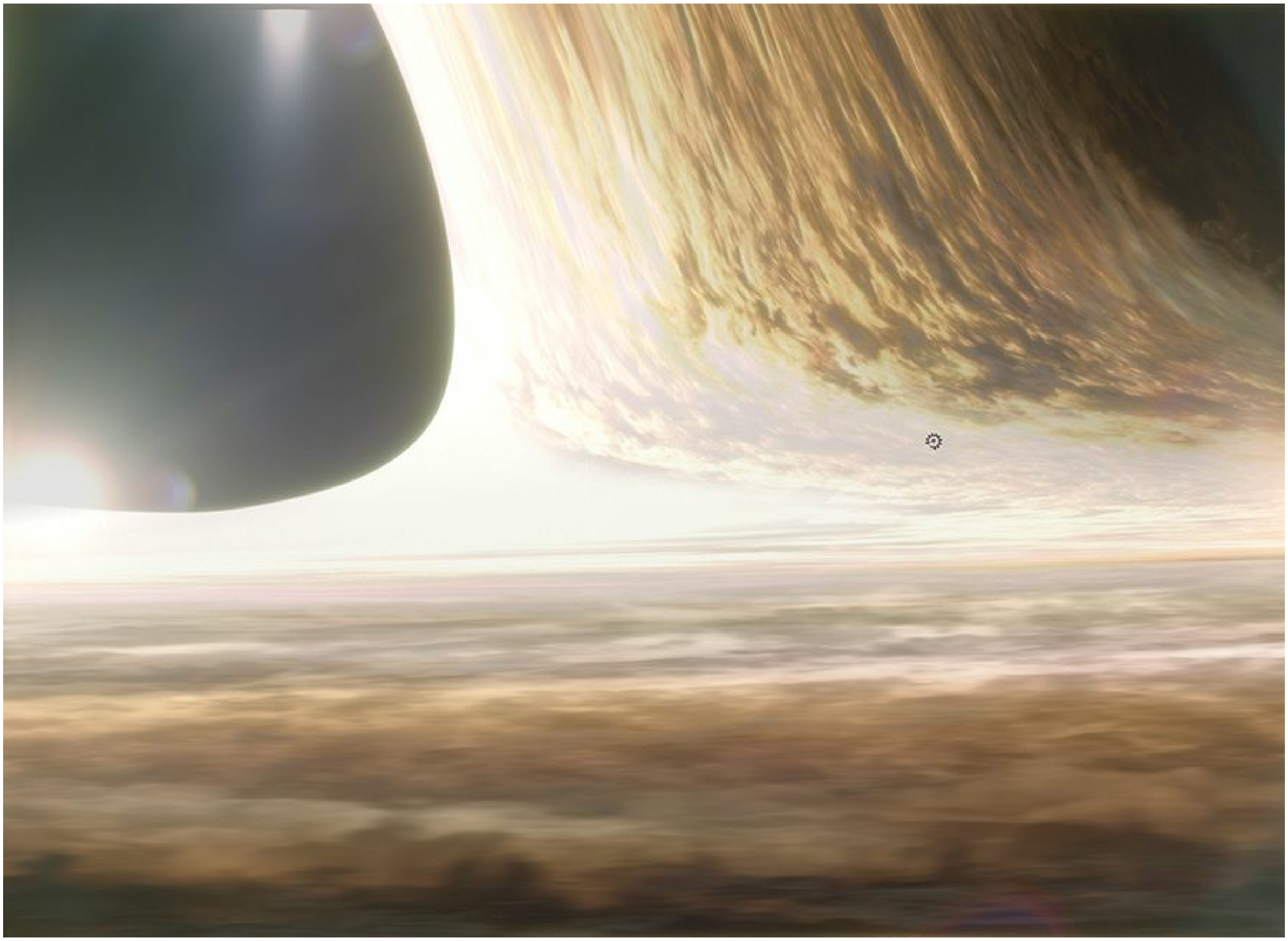

Fig. 9.11 A segment of Gargantua's disk seen up close, with the *Endurance* passing over it. The black region is Gargantua, framed by the disk and with some white scattered light in the foreground. *[From* Interstellar*, used courtesy of Warner Bros. Entertainment Inc.]*

Eugénie and her team also, of course, made the disk's gas orbit Gargantua, as it must to avoid falling in. When combined with gravitational lensing, the gas's orbital motion produced the impressive streaming effects in the movie—streaming effects that are hinted at by the gas's streamlines in Figure 9.11.

What a joy it was when I first saw these images! For the first time ever, in a Hollywood movie, a black hole and its disk depicted as we humans will really see them when we've mastered interstellar travel. And for the first time for me as a physicist, a realistic disk, gravitationally lensed, so it wraps over the top and bottom of the hole instead of being hidden behind the hole's shadow.

With Gargantua's disk anemic, though gorgeously beautiful, and with no jet, is Gargantua's environment truly benign? Amelia Brand thinks so . . .

21 The friction arises through a complex process where moving gas winds the field up, strengthening it and thereby converting energy of motion into magnetic energy; and then the magnetic field, pointing in opposite directions in neighboring regions of space, reconnects and in the process converts magnetic energy into heat. That's the nature of friction: a conversion of motion into heat.

22 I changed the size of the hole to that of Gargantua and the size of the star to that of a red giant, and changed the time markers in Figure 9.5 accordingly.

10

Accident Is the First Building Block of Evolution

In *Interstellar*, upon finding Miller's planet sterile, Amelia Brand argues for going next to a planet very far from Gargantua, Edmunds' planet, instead of the closer Mann's planet: "Accident is the first building block of evolution," she tells Cooper. "But when you're orbiting a black hole, not enough can happen—it sucks in asteroids and comets, other events that would otherwise reach you. We need to go further afield."

This is one of the few spots in *Interstellar* where the characters get the science wrong. Christopher Nolan knew that Brand's argument was wrong, but he chose to retain these lines from Jonah's draft of the screenplay. No scientist has perfect judgment.

Although Gargantua tries to suck asteroids and comets into itself, and planets and stars and small black holes too, it rarely succeeds. Why?

When far from Gargantua, any object has a large angular momentum,[23] unless its orbit is headed almost directly toward the black hole. That large angular momentum produces centrifugal forces that easily overwhelm Gargantua's gravitational pull whenever the object's orbit carries it near the black hole.

A typical orbit has a form like that in Figure 10.1. The object travels inward, pulled by Gargantua's strong gravity. But before it reaches the horizon, centrifugal forces grow strong enough to fling the object back outward. This happens over and over again, almost endlessly.

The only thing that can intervene is an accidental near encounter with some other massive body (a small black hole or star or planet). The object swings around the other body on a slingshot trajectory (Chapter 7), and thereby is thrown into a new orbit around Gargantua with a changed angular momentum. The new orbit almost always has a large angular momentum, like the old one did, with centrifugal forces that save the object from Gargantua. Very rarely the new orbit carries the object almost directly toward Gargantua, with a small enough angular momentum that centrifugal forces can't win, so the object plunges through Gargantua's horizon.

Astrophysicists have carried out simulations of the simultaneous orbital motions of millions of stars around a gigantic black hole like Gargantua. Slingshots gradually change all the orbits and thereby change the density of stars (how many stars there are in some chosen volume). The star density near Gargantua does not go down; it grows. And the density of asteroids and comets will also grow. Random bombardment by asteroids and comets will become more frequent, not less frequent. The environment near Gargantua will become more dangerous for individual life forms, including humans, promoting faster evolution if enough individuals survive.

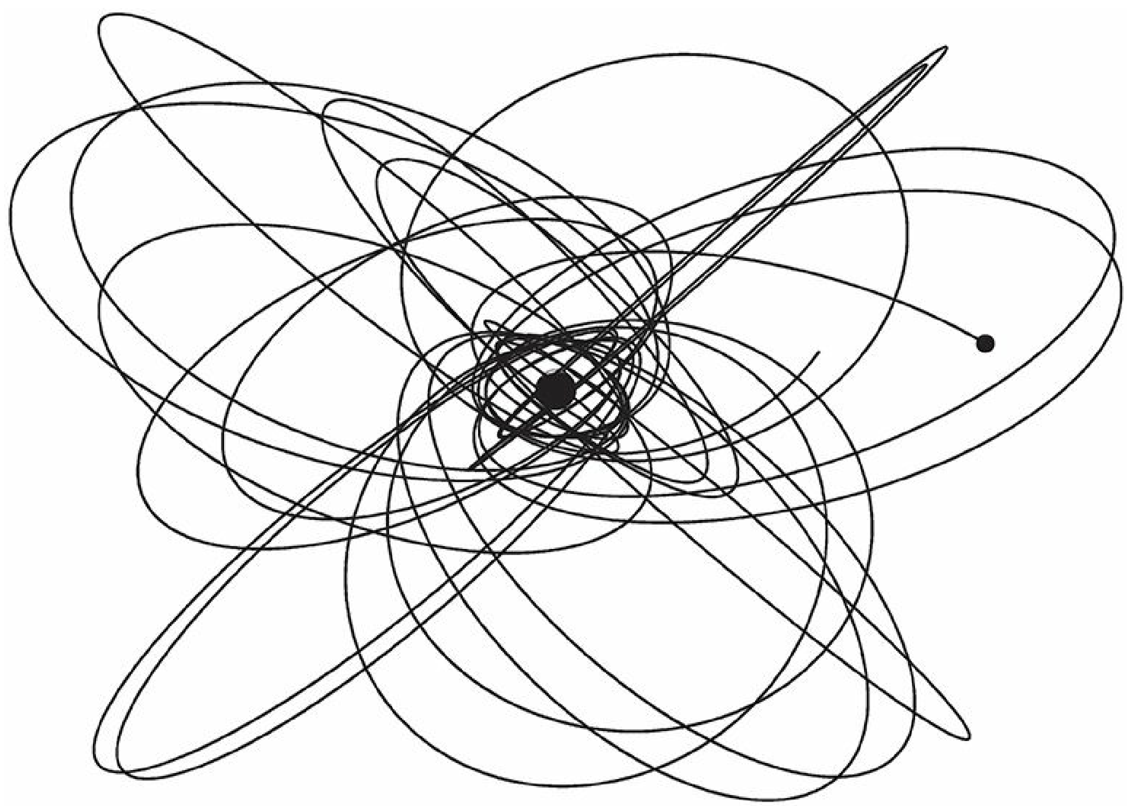

Fig. 10.1. Typical orbit of an object around a fast-spinning black hole like Gargantua. *[From a simulation by Steve Drasco.]*

With Gargantua and its dangerous environment under our belts, let's make a brief change of direction: to Earth and our solar system; to disaster on Earth and the extreme challenge of escaping disaster via interstellar travel.

23 The angular momentum is the object's circumferential speed multiplied by its distance from Gargantua; and this angular momentum is important because it is constant along the object's orbit, even if the orbit is complicated.

III

DISASTER ON EARTH

11

Blight

In 2007, when Jonathan (Jonah) Nolan joined *Interstellar* as screenwriter, he set the movie in an era when human civilization is a pale remnant of today's and is being dealt a final blow by blight. Later, when Jonah's brother Christopher Nolan took over as director, he embraced this idea.

But Lynda Obst, Jonah, and I worried a bit about the scientific plausibility of Cooper's world, as envisioned by Jonah: How could human civilization decline so far, yet seem so normal in many respects? And is it scientifically possible that a blight could wipe out all edible crops?

I don't know much about blight, so we turned to experts for advice. I organized a dinner at the Caltech faculty club, the Athenaeum, on July 8, 2008. Great food. Superb wine. Jonah, Lynda, me, and four Caltech biologists with the right mixture of expertise: Elliot Meyerowitz, an expert on plants; Jared Leadbetter, an expert on the diverse microbes that degrade plants; Mel Simon, an expert on the cells that make up plants and how they are affected by microbes; and David Baltimore, a Nobel laureate with a broad perspective on all of biology. (Caltech is a wonderful place. Named the top university in the world by the *Times* of London in each of the last three years, it is small enough—just 300 professors, 1000 undergrads, and 1200 graduate students—that I know Caltech experts in all branches of science. It was easy to find and recruit the experts we needed for our Blight Dinner.)

As dinner began I placed a microphone at the center of our round table and recorded our two-and-a-half-hour, free-wheeling conversation. This chapter is based on that recording, but I've paraphrased what people said—and they checked and approved my paraphrasing.

Our final consensus, easily reached, is that Cooper's world is scientifically possible, *but not very likely*. It is very unlikely to happen, but it could. That's why I labeled this chapter for speculative.

Cooper's World

Over wine and hors d'oevres, Jonah described his vision for Cooper's world (Figure 11.1): Some combination of catastrophes has reduced the population of North America tenfold or more, and similarly on all other continents. We have become a largely agrarian society, struggling to feed and shelter ourselves. But ours is not a dystopia. Life is still tolerable and in some ways pleasant, with little amenities such as baseball continuing. However, we no longer think big. We no longer aspire to great things. We aspire to little more than just keeping life going.

Fig. 11.1. Aspects of life in Cooper's world. *Top*: A baseball game with a dust storm on the horizon. *Bottom*: Cooper's home and truck after the storm. *[From* Interstellar*, used courtesy of Warner Bros. Entertainment Inc.]*

Most of us think the catastrophes are finished, that we humans are securing ourselves in this new world and things may start improving. But in reality the blight is so lethal, and leaps so quickly from crop to crop, that the human race is doomed within the lifetime of Cooper's grandchildren.

What Catastrophes?

What kind of catastrophes could have produced Cooper's world? Our biologist experts offered a number of possible, but improbable, answers. Here are several:

Leadbetter: Today (2008) most people aren't growing their own food. We're dependent on a global system for growing and distributing food, and for distributing water. You could imagine that system breaking down due to some biological or geophysical catastrophe. As an example on a small scale, if there was no snow in the Sierra Nevada Mountains for a few consecutive years, there would be little drinking water in Los Angeles. Ten million people would be forced to migrate, and agricultural output in California would plummet. You can easily imagine much larger scale catastrophes. In Cooper's world, with a vastly reduced population and a return to agrarian society, the production and distribution problems are lessened.

Simon: Another possible catastrophe: Over human history there has been a continual battle between us and *pathogens* (microbes that attack the human body or attack plants or other animals). We humans have developed a sophisticated immune system to deal with the pathogens that attack us directly. But the pathogens keep evolving and we're always half a step behind them. At some point there could be a catastrophe where the pathogens change so fast that our immune systems can't keep up.

Baltimore: For example, the AIDS virus could quickly evolve into a far more contagious form, one transmitted by coughing or breathing instead of sex.

Simon: The Earth's ice caps, melting due to global warming, could release a long-dormant lethal pathogen from before the last ice age.

Leadbetter: Yet another scenario: People could panic about global warming. The warming is largely caused by increasing carbon dioxide in the atmosphere. To save us, they might fertilize the Earth's oceans to produce algae that will eat much of the atmosphere's carbon dioxide via photosynthesis. A lot of iron, thrown into the oceans, could do the job. But there might be catastrophic unintended side effects. You might get some new kinds of algae that produce *toxins* (poison chemicals, not deadly life-forms) that poison the oceans. There would be a massive kill off of fish and plant life. Human civilization depends heavily on the oceans. This could be catastrophic for humans. Is it impossible? Not at all. Experiments have been done where iron was thrown locally into the ocean to produce algae—so much algae that it could be seen from space as green spots (Figure 11.2). Some of the algae that bloomed were of types never before known to science! We were lucky: the new algae were not noxious, but they might have been.

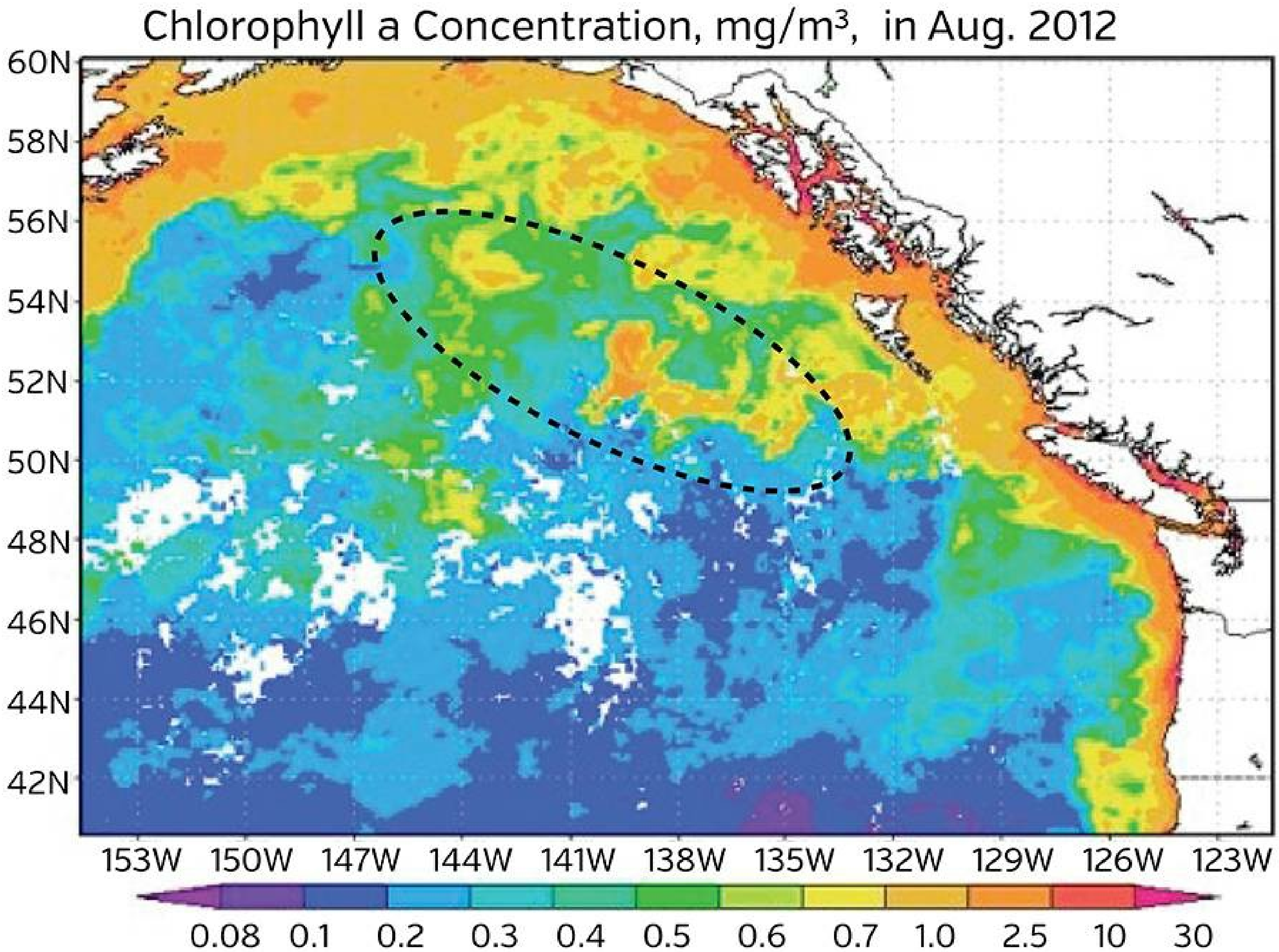

Fig. 11.2. Map of chlorophyll concentration (algae) after dumping 100 tons of iron sulphate into the ocean off the coast of British Columbia. Iron-stimulated algae growth produced the high algae concentration inside the dashed ellipse. *[From Giovanni/Goddard Earth Sciences Data and Information Services Center/NASA.]*

Meyerowitz: Ultraviolet light, streaming through our atmosphere's ozone hole, could mutate your enormous bloom of algae so it creates new pathogens. These pathogens could wipe out plants in the ocean, and then jump to land and start wiping out crops.

Baltimore: When faced with catastrophes like these, our only hope for dealing with them is advanced science and technology. If, politically, we don't invest in science and technology, or we hobble them by anti-intellectual ideologies such as denial of evolution, the very source of these catastrophes, we may find ourselves without the solutions we need.

And then there is *blight*—the consequence of many of these scenarios.

Blight

Blight is a general term for most any disease in a plant that is caused by a pathogen.

Baltimore: If you want something to wipe out humanity, there might be no better way than a blight that attacks plants. We are dependent on plants to eat. Yes, we can eat animals or fish instead, but they ate plants.

Meyerowitz: It might be sufficient for the blight just to kill off the grasses and nothing else. Grasses are the basis of most of our agriculture: rice, corn, barley, sorghum, wheat. And most animals that we eat feed on grasses.

Meyerowitz: We already live in a world where 50 percent of the food grown is destroyed by pathogens, and it's much higher than that in Africa. Fungi, bacteria, viruses, . . . they all can be pathogens. The East Coast used to be covered with chestnut trees. They are no more. They were killed by a blight. The species of banana preferred by most people in the eighteenth century was wiped out by a blight. The replacement species, the Cavendish banana, today is being threatened by blight.

Kip: I thought that blights are *specialists* that attack only one narrow group of plants and don't jump to others.

Leadbetter: There are also *generalist* blights. There seems to be a tradeoff between being a generalist that attacks many species and a specialist that attacks only a few. For the specialist blight, the lethality can be turned up really high; it can knock out, say, 99 percent of a very specific group of plants. For the generalist, the range of plants attacked is much broader, but its lethality for any one plant in that range might be much smaller. That's a pattern we see again and again in Nature.

Lynda: Could you have a generalist blight that becomes much more lethal?

Meyerowitz: Something like that has happened before. Early in the Earth's history, when cyanobacteria started making oxygen, thereby changing radically the composition of the Earth's atmosphere, they managed to kill most everything else on Earth.

Leadbetter: But the oxygen was a lethal byproduct, a poison, produced by the cyanobacteria; not a generalist pathogen.

Baltimore: We may not have seen it, but I can imagine a very lethal specialist pathogen becoming a lethal generalist. It could spread the range of plants it attacks with the help of an insect that carries it to many species. A Japanese beetle, for example, which eats something like two hundred different plant species, could infect many species with the pathogen it carries, and the pathogen might adapt to attack those species, lethally.

Meyerowitz: I can conceive of a totally lethal generalist: a pathogen that attacks chloroplasts. Chloroplasts are something that all plants have in common. They are crucial to photosynthesis (the process where a plant combines sunlight with carbon dioxide from the air, and water from its roots, to produce carbohydrates that it needs for growth). Without chloroplasts, a plant will die. Now suppose that some new pathogen evolves, for example in the oceans, that attacks chloroplasts. It could wipe out all algae and plant life in the oceans, and jump to the land where it wipes out all land plants. So everything becomes a desert. This is possible; I see nothing to prevent it. But it's not very plausible. It is unlikely ever to happen, but it could be a basis for Cooper's world.

These speculations give us a sense of the kinds of nightmare scenarios that could keep a biologist awake at night. In *Interstellar*, the focus is a lethal generalist blight running rampant over the Earth. But Professor Brand has a secondary worry: humankind's running out of oxygen to breathe.

12

Gasping for Oxygen

Early in *Interstellar* Professor Brand says to Cooper: "Earth's atmosphere is 80 percent nitrogen. We don't even breathe nitrogen. Blight does. And as it thrives, our air gets less and less oxygen. The last people to starve will be the first to suffocate. And your daughter's generation will be the last to survive on Earth."

Is there any basis in science for the Professor's prediction?

This question lies at the interface of two branches of science: biology and geophysics. So I asked the biologists at our Blight Dinner, particularly Elliot Meyerowitz, and I asked two geophysicists, Caltech professors Gerald Wasserburg (an expert on the origin and history of the Earth, Moon, and solar system) and Yuk Yung (an expert on the physics and chemistry of our Earth's atmosphere, and the atmospheres of other planets). From them, and from technical articles they pointed me to, I learned the following.

Creating and Destroying Breathable Oxygen

The oxygen we breathe is O_2: a molecule made of two oxygen atoms, bound together by electrons. There is lots of oxygen on Earth in other forms: carbon dioxide, water, minerals in the Earth's crust, to name a few. But our bodies can't use that oxygen until some organism liberates it and converts it to O_2.

The atmosphere's O_2 is *destroyed* by breathing, burning, and decay. When we breathe in O_2 our bodies combine it with carbon to form carbon dioxide, CO_2, releasing lots of energy that our bodies use. When wood is burned, the flames rapidly combine the atmosphere's O_2 with the wood's carbon to form CO_2, which generates the heat that keeps the burning going. When dead plants decay on the forest floor, their carbon is slowly combined with the atmosphere's O_2 to form CO_2 and heat.

The atmosphere's O_2 is *created* primarily by photosynthesis: chloroplasts in plants[24] (Chapter 11) use energy from sunlight to split CO_2 into C and O_2. The O_2 is liberated into the Earth's atmosphere, while the plants combine the carbon with hydrogen and oxygen from water to form the carbohydrates that they need for growth.

O_2 Destruction and CO_2 Poisoning

Suppose evolution creates a pathogen that destroys chloroplasts, as speculated by Elliot Meyerowitz at the end of the last chapter. Photosynthesis ends, not all at once, but gradually as plants die out. O_2 is no longer being created, but it is still being destroyed by breathing, burning, and decay—primarily decay, it turns out. Fortunately for the remaining humans, there is not enough decaying plant life on the Earth's surface to swallow up all the O_2.

Most of the decay will be finished after thirty years, and only about 1 percent of the O_2 will be used up. There is still plenty for Cooper's children and grandchildren to breathe, if they can find anything to eat.

But that 1 percent of the atmospheric O_2 will have been converted into carbon dioxide, which means 0.2 percent of the atmosphere will then be CO_2 (since most of the atmosphere is nitrogen). That's enough CO_2 to make breathing unpleasant for highly sensitive people and perhaps drive the Earth's temperature up (via the greenhouse effect) by 10 degrees Celsius (18 degrees Fahrenheit)—unpleasant for everyone, to put it mildly!

To make everyone's breathing uncomfortable and induce drowsiness, ten times more atmospheric O_2 would have to be converted into CO_2; and to kill most everyone by CO_2 poisoning, an additional five times more would have to be converted, a factor of fifty in all. I have not found a plausible mechanism for this.

So is Professor Brand wrong? (Even theoretical physicists can make mistakes. Especially theoretical physicists. I know; I am one.) Probably yes, he is wrong, but conceivably no. The Professor *could* be right, but it would require geophysicists' understanding of ocean bottoms to be severely flawed.

There is undecayed organic material on the ocean bottoms as well as on land. Geophysicists estimate that the amount on ocean bottoms is about one-twentieth that on land. *If* they are wrong and there is fifty times more on the ocean bottoms than on land, and *if* there is a mechanism to quickly dredge it up, then its decay to produce CO_2 could leave everyone gasping for oxygen and dying of CO_2 poisoning.

Now, once every many thousand years, an instability triggers the ocean to turn over. Water from the surface sinks to the bottom and drives bottom water to the surface. It is conceivable that in Cooper's era there is such an overturn so vigorous that the upwelling bottom water brings with itself most of the ocean bottoms' organic material. Suddenly exposed to the atmosphere, this material could decay, converting atmospheric O_2 into lethal amounts of CO_2.

Conceivable, yes. But highly improbable on two counts: highly unlikely that there is 1000 times more undecayed ocean-bottom organic material than geophysicists think, and highly unlikely that a sufficiently vigorous oceanic overturn will occur.[25]

Nevertheless, in *Interstellar* the Earth is surely dying and humanity must find a new home. The solar system, aside from Earth, is inhospitable, so the search is on, beyond our solar system.

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24 Chloroplasts and photosynthesis also occur in algae, and in cyanobacteria in the ocean, both of which I treat as plant life in my simplified description. (In some sense, cyanobacteria are a form of chloroplast.)

25 For some quantitative details and explanations of the huge uncertainties in the geophysical estimates, see *Some Technical Notes* at the end of the book.

13

Interstellar Travel

Professor Brand tells Cooper, in their first meeting, that the Lazarus missions have been sent out to search for new homes for humanity. Cooper responds, “There’s no planet in our solar system that can support life, and it’d take a thousand years to reach the nearest star. That doesn’t even qualify as futile. Where did you send them, Professor?”

The worse-than-futile challenge, if you don’t have a wormhole, is obvious when you realize just how far it is to the nearest stars (Figure 13.1).

Distances to Nearest Stars

The nearest star (other than our Sun) thought to have a habitable planet is Tau Ceti, 11.9 light-years from Earth, so traveling at light speed you would need 11.9 years to reach it. If there are any habitable planets closer than that, they can’t be much closer.

To get some sense of just how far Tau Ceti *is* compared to more familiar things, let’s scale its distance down enormously. Imagine it as the distance from New York City to Perth, Australia, about halfway around the world.

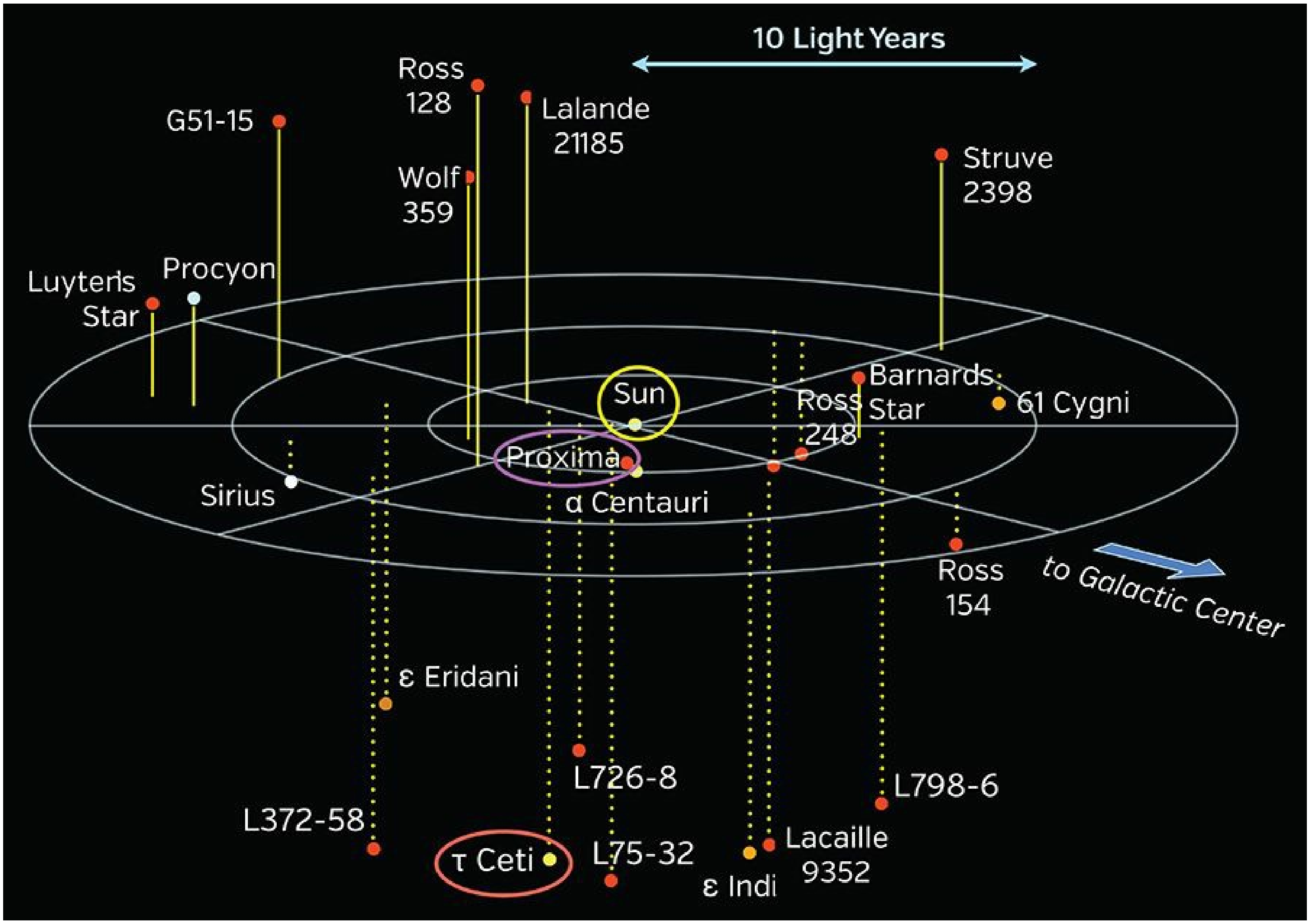

Fig. 13.1. All the stars within 12 light-years of Earth. The Sun, Proxima Centauri, and Tau Ceti are circled in yellow, purple, and red. *[I adapted this map from Richard Powell's www.atlasoftheuniverse.com.]*

The very nearest star other than the Sun is Proxima Centauri, 4.24 light-years from Earth, but there is no evidence it has habitable planets. With Tau Ceti's distance imagined as New York to Perth, then Proxima Centauri's is like New York to Berlin. It's not a lot closer than Tau Ceti!

For comparison, the most distant unmanned spacecraft that humans have sent into interstellar space is *Voyager 1*, now about 18 light-hours from Earth. It has been traveling for thirty-seven years to get there. With Tau Ceti's distance imagined as New York to Perth, then Earth to *Voyager 1* is about 3 kilometers (2 miles): the distance from the Empire State Building to the southern end of Greenwich Village. That's hugely less than New York to Perth.

The Earth to Saturn is even smaller: 200 meters, two east-west blocks in New York City, from the Empire State Building to Park Avenue. The Earth to Mars is just 20 meters; and the Earth to the Moon (the greatest distance humans have ever yet traveled) is just 7 centimeters—about two and a half inches!

Compare what we have achieved in going to the Moon, *two and a half inches*, with the challenge of going *halfway around the world*. That's the leap of technology required to take humans to habitable planets outside our solar system!

Travel Times with Twenty-First-Century Technology

Voyager 1 is traveling out of the solar system at 17 kilometers per second, having been boosted by gravitational slingshots around Jupiter and Saturn. In *Interstellar*, the *Endurance* travels from Earth to Saturn in two years, at an average speed of about 20 kilometers per second. The fastest speed I think rocket technology plus solar system slingshots are likely to achieve in this, the twenty-first century, is about 300 kilometers per second.

At that 300 kilometers per second, we would need 5000 years to reach Proxima Centauri and 13,000 years to reach Tau Ceti. Not a pleasant prospect!

To get there far faster in the tweny-first century, you need something like a wormhole (Chapter 14).

Far-Future Technology

Technically savvy scientists and engineers have put much effort into conceiving far-future technologies that might make possible near-light-speed travel. You can learn a lot about their ideas by browsing the web. It will take many centuries for humans to make any of those ideas real, I think. But they do convince me that ultra-advanced civilizations are likely to travel between the stars at a tenth the speed of light or faster.

Here are three far-out examples of near-light-speed propulsion that intrigue me.

Thermonuclear Fusion

Thermonuclear fusion is the most conventional of the three ideas. R&D to develop controlled-fusion power plants on Earth was initiated in the 1950s, and full success will not come until the 2050s. A full century of R&D! That's a realistic measure of the difficulties.

And what will fusion power plants in 2050 mean for spacecraft propulsion by fusion? The most practical designs may achieve 100 kilometers per second, and conceivably 300 kilometers per second by the end of this century. A whole new approach to harnessing fusion will be required for reaching near light speed.

A simple calculation shows fusion's possibility: When two deuterium (heavy hydrogen) atoms are fused to form a helium atom, 0.0064 (nearly 1 percent) of their rest mass gets converted into energy. If this were all transformed to kinetic energy (energy of motion) of the helium atom, the atom would move at about one-tenth the speed of light.[26] This suggests that, if we could convert all the fusion energy of deuterium fuel into ordered motion of a spacecraft, we could achieve a spacecraft speed of roughly 1/10 the speed of light—and somewhat higher if we are clever.

In 1968 Freeman Dyson, a brilliant physicist for whom I have great respect, described and analyzed a crude propulsion system that, in the hands of a sufficiently advanced civilization, could achieve this.

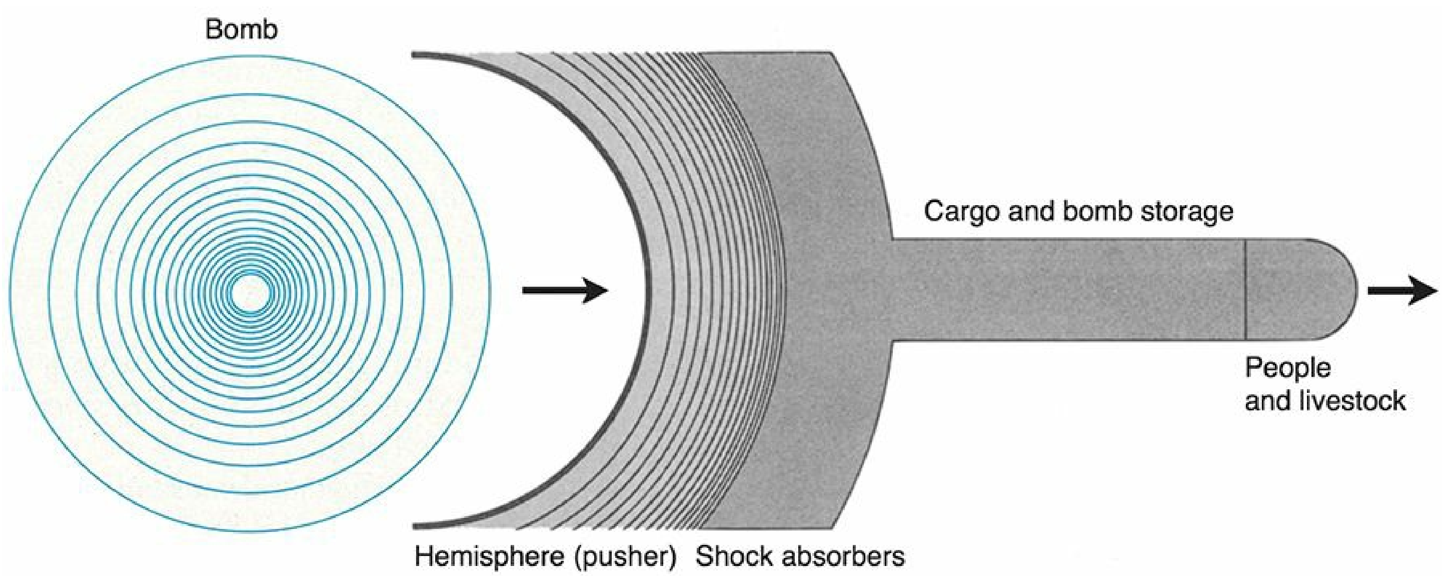

Fig. 13.2. Freeman Dyson's bomb-powered propulsion system. *[From Dyson (1968).]*

Thermonuclear bombs ("hydrogen bombs") are detonated just behind a hemispherical shock absorber that is 20 kilometers in diameter (Figure 13.2). The bomb debris pushes the ship forward, achieving, in Dyson's most optimistic estimate, a speed one-thirtieth that of light. A less crude design could do somewhat better. In 1968 Dyson estimated that such a propulsion system would not be practical any sooner than the late twenty-second century, 150 years from now. I think that's overly optimistic.

Laser Beam and Light Sail

In 1962 Robert Forward, another physicist whom I respect, wrote a short article in a popular magazine about a spacecraft with a sail, pushed by a distant, focused laser beam (Forward 1962). In a 1984 technical article, he made this concept more sophisticated and precise (Figure 13.3.)

An array of solar-powered lasers in space or on the Moon generates a laser beam with 7.2 terawatts of power (about twice the total power consumption of the United States in 2014!). This beam is focused, by a Fresnel lens 1000 kilometers in diameter. It is focused onto a distant sail, 100 kilometers in diameter and weighing about 1000 metric tons, that is attached to a less massive spacecraft. (The beam direction must be accurate to about a millionth of an arcsecond.) The beam's light pressure pushes the sail and spacecraft up to about a fifth the speed of light halfway through a forty-year trip to Proxima Centauri. A modification of this scheme then slows the ship down during the second half of the trip, so it arrives at its destination with a speed low enough to rendezvous with a planet. (Can you figure out how the slow down is achieved?)

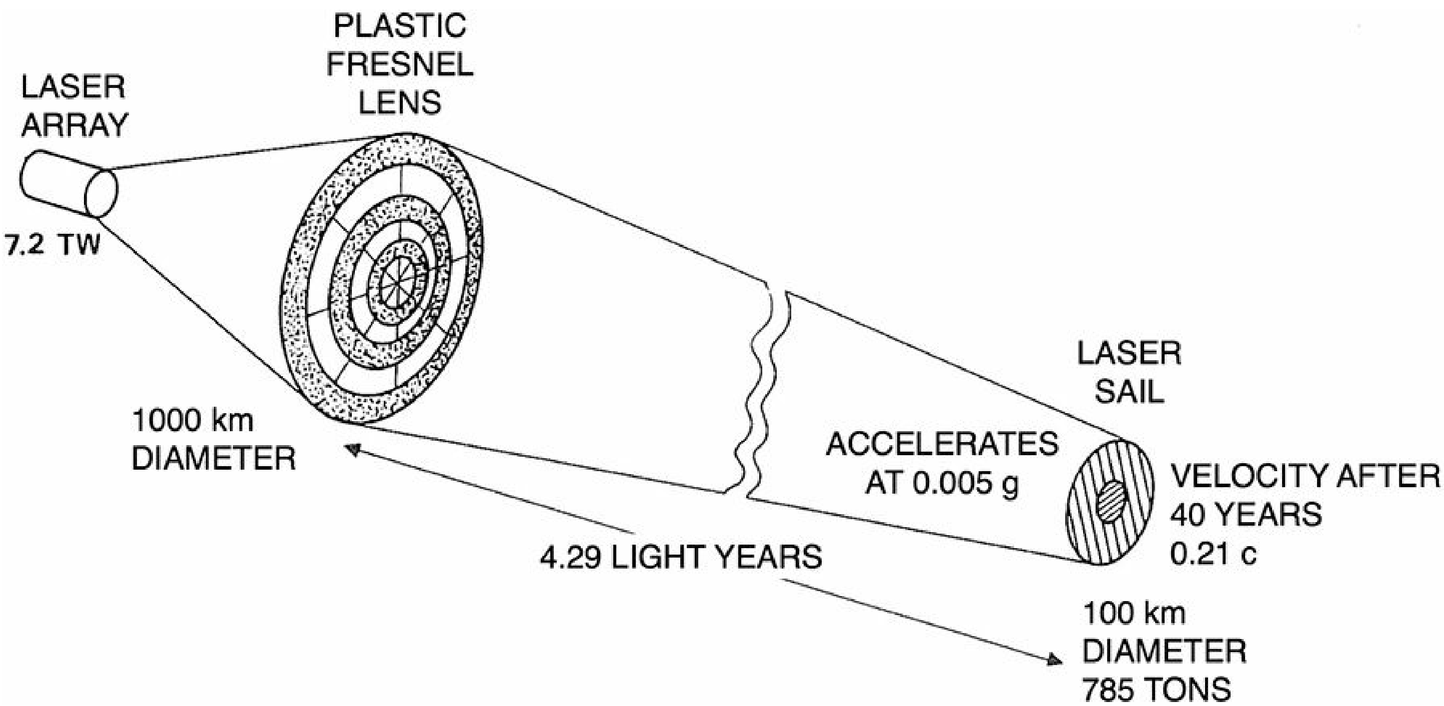

Fig. 13.3. Robert Forward's laser beam and light sail propulsion system. *[From Forward (1984).]*

Forward, like Dyson, imagined his scheme practical in the twenty-second century. When I look at the technical challenges, I think longer.

Gravitational Slingshots in a Black-Hole Binary

My third example is my own wild—very wild!—variant of an idea due to Dyson (1963).

Suppose you want to fly across much of the universe (not just interstellar travel, but intergalactic travel) at near light speed in a few years of your own life. You can do so with the aid of two black holes that are orbiting each other, a *black-hole binary*. They must be in a highly elliptical orbit and must be large enough that their tidal forces do not destroy your ship.

Using chemical or nuclear fuel, you navigate your ship into an orbit that comes close to one of the black holes: a so-called zoom-whirl orbit (Figure 13.4). Your ship zooms close to the hole, whirls around it a few times, and then, when the hole is traveling nearly directly toward its companion, the ship zooms out, crosses over to the companion hole, and slides into a whirl around it. If the two holes are still headed toward each other, the whirl is brief: you zoom back toward the first hole. If the holes are no longer headed toward each other, the whirl is much longer; you must park yourself in orbit around the second hole until the holes are again headed toward each other, and then launch back toward the first hole. In this way, always traveling between holes only when the holes are approaching each other, your ship gets boosted to higher and higher speeds, approaching as close as you wish to the speed of light if the binary is sufficiently elliptical.

It is a remarkable fact that you only need a small amount of rocket fuel to control how long you linger around each hole. The key is to navigate onto the hole's critical orbit, and there perform your controlled whirl. I discuss the critical orbit in Chapter 27. For now, suffice it to say that this is a highly *unstable* orbit. It is rather like riding a motorcycle around a very smooth volcano rim. If you balance delicately, you can stay on the rim as long as you want. When you wish to leave, a slight turn of the bike's front wheel will send you careening off the rim. When you want to leave the critical orbit, a slight rocket thrust will enable centrifugal forces to take over and send your ship careening toward the other black hole.

Once you are as close to the speed of light as you wish, you can launch yourself off a critical orbit toward your target galaxy in the distant universe (Figure 13.5).

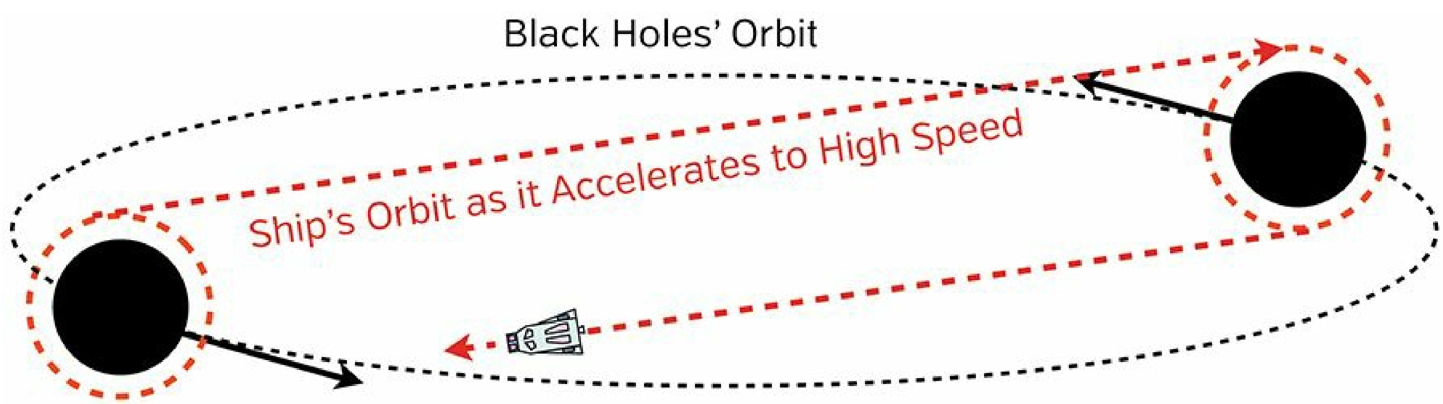

Fig. 13.4. Zoom-whirl orbit brings a spacecraft up to near light speed.

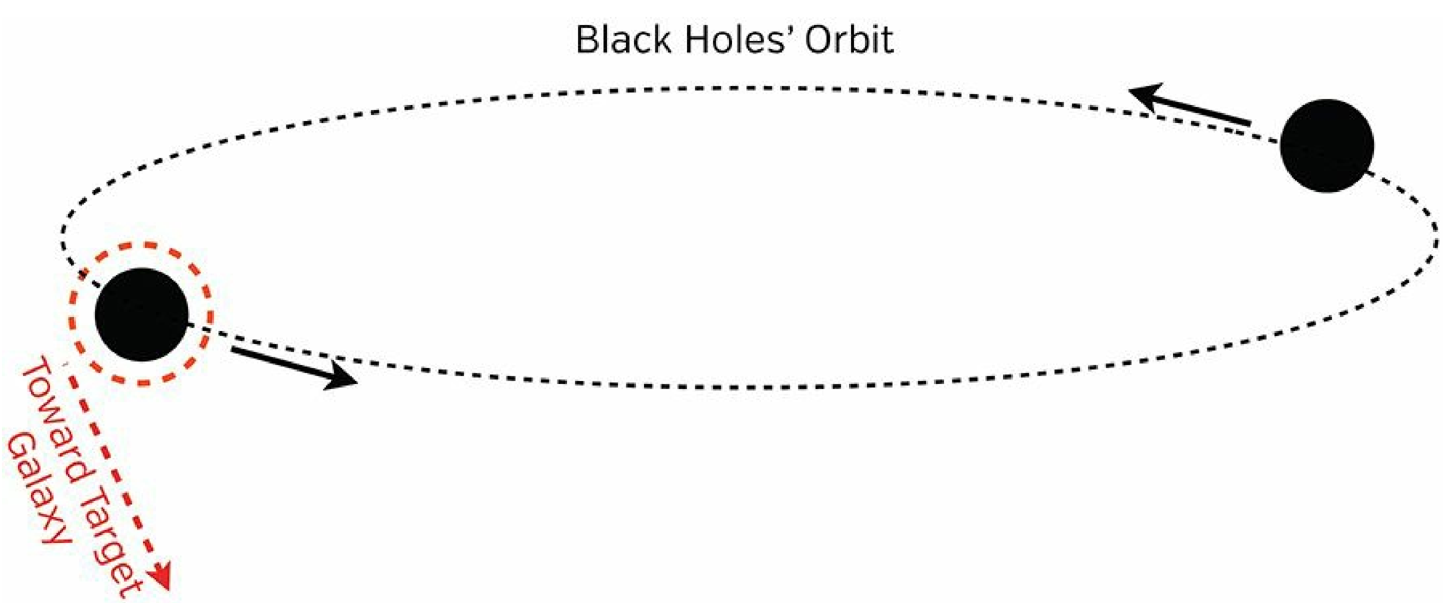

Fig. 13.5. Launching off a critical orbit toward a distant galaxy.

The trip may be long; as much as 10 billion light-years' distance. But when you move at near