The Restless Universe: Understanding X-ray Astronomy in the Age of Chandra and Newton

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OXFORD UNIVERSITY PRESS

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2002

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Oxford New York
Auckland Bangkok Buenos Aires Cape Town Chennai
Dar es Salaam Delhi Hong Kong Istanbul Karachi Kolkata
Kuala Lumpur Madrid Melbourne Mexico City Mumbai Nairobi
São Paulo Shanghai Singapore Taipei Tokyo Toronto

and an associated company in Berlin

Published by Oxford University Press, Inc.
198 Madison Avenue, New York, New York 10016

www.oup.com

Library of Congress Cataloging-in-Publication Data
is available

ISBN 0-19-514847-9

1 3 5 7 9 8 6 4 2

Printed in the United States of America
on acid-free paper

To the memory of my father, William H. Schlegel (1909–2000),
for much-needed advice at an unexpected time;
my mother, Jane S. Schlegel, for continually asking,
"When will I see your name in the paper?" to which I answer,
"Will this book do instead?"; and my wife, Lisa M. Schlegel,
for all her support and encouragement.

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Preface

Scientists exploring the field of X-ray astronomy are in the midst of a time that will not come again; we enjoy the excitement of what is often called an age of discovery.[1] Dr. Carl Sagan said that there is only one generation that gets to see things for the first time (in his case, the surfaces of the planets). This is a unique time because prior generations knew little about X rays, and subsequent generations will view today's amazing discoveries as history and as stepping-stones for yet greater discoveries.

Science advances in phases, starting from pure discovery, or "un-covery," and ending with a mature field in which most of the questions have been answered and little additional progress is possible. These advances do not parade steadily forward in time. Consider, instead, the approach fans of jigsaw puzzles follow. Assemblers first locate straight-edged pieces to build the frame. With the frame in place, they see the range of colors and note potentially easy areas on which to focus attention. They sift through the box, searching for those pieces first. When the easy areas are done, the task shifts to filling in details, all the blue sky pieces, for example.

In 1960, a relatively slim astronomy book contained essentially all of our knowledge of the planets in our solar system. By 1990, however, the discovery phase of planetary astronomy described by Sagan had essentially ended. We peered at the surface of Mars from three landers (Vikings 1 and 2 and Pathfinder), gazed upon the unique surfaces of the Galilean satellites (Io, Europa, Ganymede, and Callisto) of Jupiter, imaged the rings of Saturn and the outer planets Uranus and Neptune with their moons, rings, and atmospheric spots, discovered a moon of Pluto, and flew a satellite through the tail of a comet. Images of all the planets save one (Pluto) existed and could be bought in poster shops. Complete books for each planet had been written, summarizing the missions of the 1970s and 1980s. Arguably, those who paid attention to the planetary missions from the late 1960s to the late 1980s or early 1990s form the generation to which Sagan referred.

In X-ray astronomy, the period of our "first look" started with the Einstein Observatory (1979-81) and will end sometime in the next 10 to 20 years. Einstein provided the very first images and spectra of the X-ray universe, but for a small number of objects. By the time the Chandra and Newton missions end, we will have a robust inventory. Future generations of X-ray observatories will likely be designed for specific experiments or observational goals instead of functioning as generic observatories.

This book sends the reader on a journey, one that encompasses the entire universe. Instead of a path that leads from Earth outward, this book explores a different route by describing our view of the universe if we study the X rays that arrive from astrophysical objects.

Several approaches exist for a book such as this one. I could present the results of the discoveries of the past 30 to 40 years. I could take readers through the history of X-ray astronomy or focus on how the increasingly sophisticated instruments have allowed detailed explorations of the X-ray universe. I chose to present threads from each of these approaches; I hope I have woven a decent cloth. I do not present everything that has occurred in X-ray astronomy during the past three decades, because the resulting book would be used only as a doorstop. I also do not present each and every "gee whiz" discovery, because many would be obsolete by the time this book appears in print. Instead, I aim to provide a foundation for further learning. The threads include the history of X-ray astronomy; the hardware used to detect X rays; the satellites, past, present, and future, that have been flown to collect the data; how we interpret the data; and most particularly, the science we have learned, as well as speculations about what we will learn. I have also not attempted to place every up-to-the-minute result here, particularly since some of the most interesting science will be a complete surprise.[2]

I have benefited from countless conversations, about X-ray astronomy and its discoveries, with colleagues at science meetings and at the two places I've worked during the past ten years (the NASA-Goddard Space Flight Center and the Smithsonian Astrophysical Observatory). These colleagues are too numerous for me to identify individually; I thank all for lively discussions, whether they remember them or not. I also gained knowledge from many people connected with the Chandra project. A project the size of Chandra requires many hundreds of people, from administrative assistants to scientists, engineers, and project managers. Space constraints preclude listing even a small fraction of these people. The list of institutions significantly involved in Chandra's design and construction is itself long: NASA's Marshall Space Flight Center (Huntsville, Alabama); the Office of Space Science at NASA headquarters (Washington, D.C.); the TRW Space and Electronic Group (Redondo Beach, California); Raytheon Optical Systems, Inc. (Danbury, Connecticut), now a division of Goodrich Corporation; Optical Coating Laboratory, Inc. (Santa Rosa, California); Eastman Kodak Company (Rochester, New York); Pennsylvania State University (University Park, Pennsylvania); Space Research Organization Netherlands (Utrecht, Netherlands); Max Planck Institute (Garching, Germany); Massachusetts Institute of Technology and Smithsonian

Astrophysical Observatory (Cambridge, Massachusetts), and Ball Aerospace and Technologies Corporation (Boulder, Colorado).

I thank my agent, Jeanne Hanson, and my editor, Kirk Jensen, for seeing the potential in an early draft of this book. Thanks to the copyeditor, Jane Taylor, for catching several recurrently missed mistakes, and to the production editor, Joellyn Ausanka and the overall compositor, Anne Holmes, for turning a stack of manuscript and illustration pages into a sharp-looking book. I hope the words live up to their efforts; any errors that remain are mine.

I especially thank my wife, Lisa, for her love and encouragement on those days when the universe seemed too amazing to be described by mere words.

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Overview

Brevis esse laboro, obscurus fio.
(When I labor to be brief, I become obscure.)
—Horace

X rays are light, light that is fundamentally no different from the optical light that enters our eyes or the radio light that carries the signal from our favorite radio stations to our cars.[1] All of these—X rays, visible light, radio light, and more—may be described as waves, specifically electromagnetic waves,[2] first described by the Scottish physicist James Clerk Maxwell (1831–79) in the 1860s. At that time, X rays were unknown, not to be discovered for another 30 years. As we shall see, X rays give us a picture of the universe very different from the one available to our eyes and our optical telescopes.

Anyone who has been to a dentist or to a doctor to repair a broken arm knows what an X ray is. Unfortunately, the term *X ray*, so applied, refers to the piece of film illuminated by X rays. Mention "X-ray astronomy" to people and too often they think we send beams of X rays *into* space to obtain an "X ray" of an object. Many of us who carry out research on X-ray energies quickly learn to indicate that the X rays we study come *from* somewhere in the universe. That comment is usually accompanied by a motion of the arm that starts with it fully extended and ends with it close to the body.

So what are X rays? That we cannot see them with our eyes is irrelevant. Each of the major areas of scientific knowledge is hip-deep in examples of insight gained by looking at things we cannot see. X rays bathe Earth each second, arriving from everywhere in the universe. Long before anyone discovered them, X rays carried their energetic message, and they will do so long after Earth has ceased to exist. What we have learned in the past 30 years about the X-ray universe is astounding. The space missions that have been and gone, and those that still collect data, have largely defined the straight-edged pieces of the puzzle. The view of the universe given to us by X rays may turn out to be absolutely critical to our understanding.

Not only can our eyes not detect X rays, but the atmosphere of Earth blocks X rays from even reaching the ground. If our atmosphere did not do so, life would likely never have started on this planet. The atmosphere protects us from the cellular damage that the absorption of X rays produces. We need telescopes and detectors, sensitive to X-ray light and launched on satellites above Earth's atmosphere, to study the X-ray universe. The Chandra X-ray Observatory,[3] Newton, and Astro-E, the three satellites discussed in chapter 1, are the latest in a series of observatories to explore the X-ray universe, continuing the endeavor of the past 35 years.

Chandra is the third of NASA's "Great Observatories." The first is the Hubble Space Telescope,[4] the second is the Compton Gamma-ray Observatory.[5] The fourth and final Great Observatory will be the Space Infrared Telescope Facility (SIRTF), currently scheduled for launch in late 2002. Each of these observatories has made, or will make, fundamental contributions to our understanding of our universe. The Compton Observatory for the first time made the discovery and observation of sources emitting gamma rays relatively easy. Data returned from the Hubble Space Telescope clearly excite everyone who sees them. Few can look at the images of the Eagle Nebula, for example, with its tall pillars of dark matter surrounded by glowing, ionized gas, without wonder.

Chandra, as an observatory, is to X rays as the Hubble Space Telescope is to visible light. The results from Chandra will continue to transform our understanding of our universe, if our experiences with Hubble are a guide.

The Restless Universe

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"By three methods we may learn wisdom . . ."

—Confucius

Chandra, Newton, and Astro-E: three satellites, all dedicated to the study of X rays. Two and a half billion dollars spent. What is so important about X rays from space? Why were three satellites built by three different space agencies representing different countries? Astronomers designed and built only one satellite to study the visible universe (the Hubble Space Telescope). What makes the X-ray universe different? What are the differences among the three satellites? What have we learned from previous X-ray missions? Why do X-ray images look so different from those returned by the Hubble Space Telescope? Why was the loss of Astro-E so devastating to X-ray astrophysics?[1] Will Chandra, Newton, or Astro-E answer all of our questions about the X-ray universe?[2] What are X rays?

Launch: The Chandra X-ray Observatory

On 20 July 1999,[3] at 12:30 A.M. eastern daylight time (EDT), the first launch attempt of the space shuttle Columbia, carrying the Chandra X-ray Observatory, halted at T–7[4] seconds. A hydrogen sensor in the hazardous-gas-detection system surged to 640 parts per million (ppm) from a normal level of about 110 ppm. Engineers had designed the sensor to sample the air in the aft engine compartment every eight seconds. At T–16 seconds, the sensor had reported its first high reading. An engineer on the launch team waited for the next sample at T–8 seconds. When it reported the second high reading, he manually executed a launch abort, stopping the countdown about three seconds before main-engine ignition. Subsequent examination of the data revealed a faulty sensor. The backup sensor, although less sensitive than the primary one, never showed any increase in the gas level.

Forty-eight hours later, on July 22, after the investigation of the gas detection sensors, after the replacement of the ignitors,[5] and after the refilling of the propellants, the shuttle again stood bathed in spotlights. The second launch countdown proceeded smoothly to the planned hold at T–20 minutes. All launches have built-in holds, usually lasting 10 minutes, that provide the team sufficient time to review all the sensors and checklists to be certain that the shuttle, rockets, and crew are ready to go. Toward the end of each hold, the launch director polls the team leaders for a final "go" recommendation to lift the hold.

On July 22, the weather team reported the existence of a thunderstorm eight miles from the launch site. The lightning protocol allows no lightning within 20 miles of the launch complex, or no lightning within 10 miles plus at least 15 minutes of elapsed time since the last detected stroke.

Flight controllers restarted the countdown clock at the end of the planned hold with the understanding that another hold would occur at T–5 minutes until the weather cleared. When the launch window opened at 12:26 A.M., the thunderstorm cell was still present. At 1:11 A.M., the launch director announced that an extra six minutes had been added to the launch window, extending it to 1:24 A.M. Just as the launch team readied to resume the count after the T–5 hold, a lightning strike occurred eight miles from the shuttle. The launch director immediately announced the second launch abort.

On July 23, 1999, at 12:31 A.M. EDT, Columbia lifted off into clear skies (Fig. 1.1). Five seconds after liftoff, one of the electrical buses short-circuited, causing a loss of two of the engine controllers. Each shuttle engine has two separate controllers, so the liftoff proceeded. Had the short occurred before engine ignition, the launch director would have aborted the launch. In addition, had one more engine controller short-circuited during takeoff, shuttle commander Eileen Collins and pilot Jeffrey Ashby would have been the first crew to attempt to abort a takeoff and land the shuttle at the backup landing site in Banjul, Gambia, on the west coast of Africa.

Fig. 1.1. July 23, 1999, 12:31 A.M. eastern daylight time: the launch of the space shuttle Columbia carrying the Chandra X-ray Observatory. Eileen Collins commanded the shuttle and the crew of four astronauts. (Image courtesy of the public image launch archives at the NASA-Kennedy Space Center.)

Columbia reached an orbit seven miles lower than had been calculated. The flight team later traced the likely cause of the lower orbit to a fuel leak discovered in the aft engine compartment.[6] The shuttle's crew deployed the Chandra Observatory seven hours after launch (Fig. 1.2). During the subsequent two weeks, ground controllers gradually placed the observatory into its final orbit and unfurled the solar-

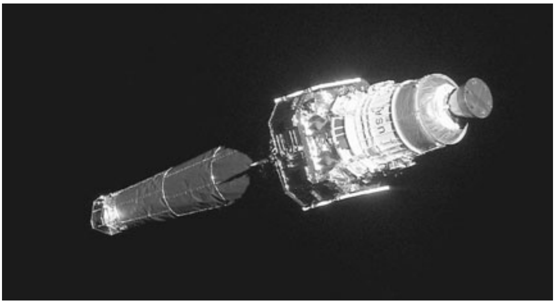


Fig. 1.2. The deployment of Chandra occurred seven hours after launch. Chandra is one of the largest payloads ever carried aloft by the shuttle. The image appears distorted because a portion of Chandra lies in shadow. (Image courtesy of the public image launch archives at the NASA-Kennedy Space Center.)

cell panels (Fig. 1.3). Prior to the observatory becoming operational, all of the parts used to construct Chandra had to first "outgas," or lose the moisture accumulated while in the atmosphere of Earth, to the vacuum of space. Outgassing is necessary before any telescope is opened in space; a failure to outgas can cause the accumulated moisture to freeze onto the telescope mirrors and detectors, considerably reducing their effectiveness. Several weeks of additional work were necessary before confirmation of Chandra's status as an observatory, but it was finally in orbit.

More than twenty years had elapsed from the time NASA received the first proposal to build a high-resolution X-ray telescope. During that time, countless design meetings, months of design reviews, years of work, and four launch slips

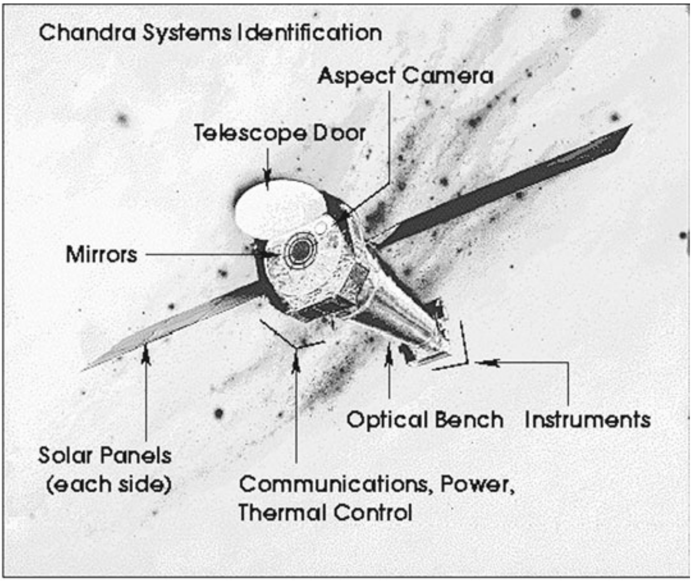


Fig. 1.3. An artist's sketch of Chandra in orbit with its solar panels deployed. The individual parts of the satellite have been labeled. (Artist's concept courtesy of TRW, Inc.)

had occurred. Thousands of people had contributed to placing the observatory into orbit: project and program managers and their administrative assistants; budget teams; mechanical, thermal, and electrical engineers; data aides and technical assistants; members of test teams; and scientists.

Chandra's first observation occurred just after the outer sunshade door, built to protect the sensitive instruments from the overpowering light of the Sun, opened on command on August 12, 1999. The official "First Light" would take place after a check that the mirrors and detectors were working correctly. The prime instrument, ACIS (Advanced Charge-Coupled Device Imaging Spectrometer), imaged a

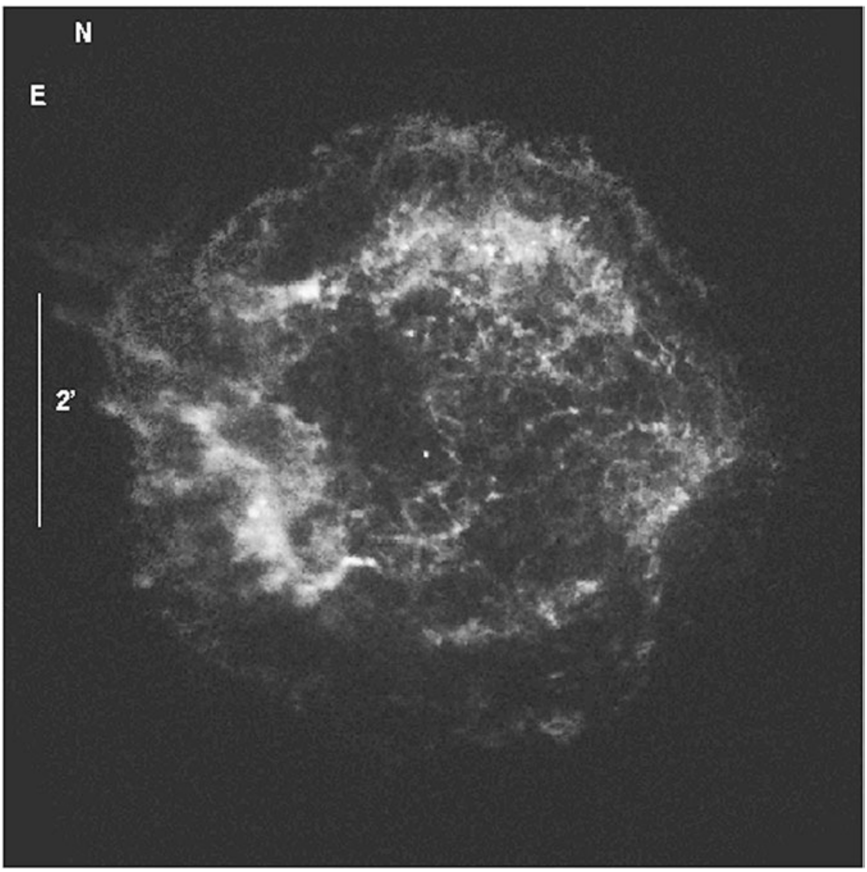
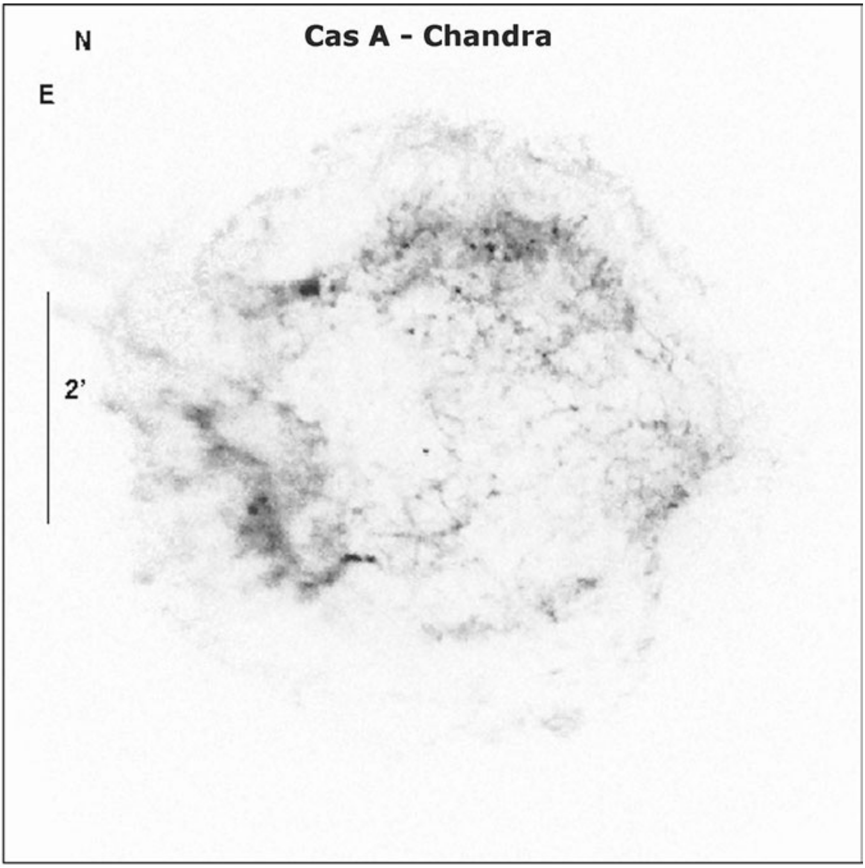


Fig. 1.4. The First Light image of the supernova remnant Cassiopeia A. On the left is the normal view; on the right is a view with black and white inverted. The image is displayed inverted because black on white offers higher contrast of the details; in addition, an excess of black ink sometimes bleeds into the smaller, whiter areas during image production, particularly if image features are thin and narrow. For both reasons, most astronomical images are displayed in the inverted manner, and this book follows that convention. All figures include a scale bar somewhere in the figure, usually on

source lying just off the optical axis of the telescope. Chandra's value lies in its image quality, known as the point-spread function.[7] The size of the point-spread function, when measured after the data were received in the Operations Center, proved that Chandra focused X rays more sharply than had any previous X-ray telescope. This measurement occurred even before attempts were made to sharpen the focus or correct for any drift of the pointing direction.

The official First Light image, obtained on August 19, 1999, is stunning (Fig. 1.4). Cassiopeia A (Cas A) is a supernova remnant, the grave marker of an exploded star.[8] The light from the explosion reached Earth in the year 1670. The



the left, to indicate the size of the object. The scale is usually in minutes of arc (one minute of arc equals 1/60th of a degree) but occasionally is much smaller. In the upper left corner of all figures are the direction designations: the top of the figure is the north edge; east lies to the left. This orients the object as an observer would see it in the sky. The small dot at the center of Cas A is the proposed corpse of the star that blew up to form the remnant. (Image produced from data obtained from the Chandra public data archive at the Smithsonian Astrophysical Observatory.)

distance to Cas A is estimated to be 10,000 light-years, so the star actually exploded about 8000 B.C.; the light traveled for 10,000 years before reaching Earth. The X-ray image shows filaments of hot gas from the exploded star as well as a dot of light at the center of the remnant. That dot is likely the actual carcass of the star, and it had not been detected by any other telescope at any wavelength. So far as we know, essentially two paths exist for a star that is about to explode. The path taken depends on the mass of the star—the quantity of material contained in it. Astrophysicists believe that lower-mass stars explode completely, leaving no stellar corpse behind. For the higher-mass stars, however, the inner layers collapse to form a neutron star or black hole; the collapse blows off the outer layers. Some of the hot filaments in Cas A show evidence of oxygen, silicon, and iron. Combined with the presence of a pointlike source as a candidate for the stellar corpse, Cas A is the gravestone of a high-mass star. Investigations into the point source commenced as soon as the First Light image appeared.

There's more to learn from the First Light image. Examine the figure closely and you will see a faint plateau of light that lies just outside the filaments. This is the expanding shock wave. The explosion of a star not only disrupts the star itself, but also creates a shock wave that expands outward. The expanding shock stirs the gas that lies between the stars. Under the correct conditions, some of that stirred gas will collapse and form new stars. By measuring the speed with which the shock moves—for example, by obtaining a second image several years later and measuring the increased diameter of the shock—we can obtain a better estimate of the age of the remnant. For Cas A, the remnant's age happens to be relatively well known. For other remnants, however, that information could allow us to narrow our search in the historical records for notes indicating the first appearance of the supernova in our sky.[9]

Launch: XMM-Newton

In contrast to the launch of Chandra, that of the European X-ray satellite, the X-ray Multi-Mirror Mission (XMM), from Kourou in French Guiana, South America, on December 10, 1999, proceeded without a hitch (Fig. 1.5). The rocket carrying the satellite aloft was the Ariane 5, a new rocket for the European Space Agency with heavy-lift capability. The launch, while flawless, was not without tension: the test launch of the Ariane 5 had exploded shortly after ignition of the main engines. For the European Space Agency, the XMM launch was a triumph because XMM, although a pure science satellite, represented its first commercial payload.

Controllers on the ground gradually raised XMM's orbit so that, at its closest approach to Earth, it was about 7,000 kilometers high; at the farthest point, it was about 114,000 kilometers from the surface. By December 15, the solar panels were deployed and several of its instruments had been powered up (Fig. 1.6). Mission