Introduction

X-ray astronomy reveals an invisible universe. Having evolved beneath an atmosphere that absorbs incoming X-rays, human beings are blind to the cosmic phenomena that produce the emanations. But in 1962, Geiger counters launched above the atmosphere caught the first glimpse of an X-ray star. Spewing forth X-rays 100 million times faster than the Sun, the extraordinary object intrigued scientists. To explain the huge emissions, investigators discarded classical theories of stellar energy production and resorted to esoteric concepts that encompassed rotating neutron stars and black holes. Though now common in the professional and popular press, these ideas bordered on science fiction 20 years ago. As it appears today, the invisible X-ray universe is very different from the one observed through unaided eyes: it is a cosmos of explosive high temperatures, intense gravitational fields, and rapid time variations.

This book deals with the evolution of X-ray astronomy during the field's initial phase of development. The period of interest begins in the late 1950s when scientists first considered studying high-energy radiations emitted by celestial objects other than the Sun. After the discovery of an unexpectedly bright X-ray source in 1962, theorists and experimentalists quickly entered the field and strove to answer the central question: what physical processes cause celestial X-ray emissions? In 1972 scientists demarcated the field's development as their thinking coalesced around a conceptual framework for resolving the major part of this problem. Armed with some paradigmatic principles, X-ray investigators in the next stage began exploring questions of interest to the broader discipline of astronomy.

In examining only the early period of the field's history, when scientists acquired fundamental data and basic theoretical principles, the book does more than simply document the accomplishments of investigators working to answer a well-defined question. Such a discussion would be inadequate.

It would not explain why the field emerged when it did, nor how scientists gained support for making and interpreting their observations. To understand these historical dimensions, one must realize that the investigations were intricately related to concomitant advances in research technology and to a political program designed to bolster the declining prestige of the United States. The book, therefore, also explores how technological innovation and broad public policies played important roles in the emergence of X-ray astronomy.

Beyond describing the emergence of a specific scientific field, this history of X-ray astronomy highlights three interrelated transformations that characterize the entire astronomy discipline in the United States since World War II. First, it demonstrates that the classical task of studying the cosmos in optical wavelengths has been augmented by observations in other spectral bands. As seen in Figure 1, the atmosphere provides only a few windows in the electromagnetic spectrum for terrestrial observers. Other than optical wavelengths (between about 4000 Å and 7000 Å), ground-based astronomers can only examine portions of the radio and infrared spectra. The X-ray region, for example, lying between 0.1 Å and 100 Å, is totally obscured. Taking advantage of new electronic technologies developed during World War II, radio astronomers were the first to broaden the perspective of astronomy by observing a highly energetic universe that was invisible to classically trained optical astronomers.[1] Soon thereafter, adventurous physicists installed radiation detectors on rockets that flew above the absorbing atmosphere and viewed the Sun and stars through the ultraviolet window of the spectrum. As the space race of the late 1950s and 1960s intensified, astronomical studies from high-altitude vehicles diversified into the gamma ray, infrared, and X-ray regions, making astronomy an all-wavelength activity. Of these areas of spectral research, X-ray astronomy gained the largest following in the shortest time span.

The second major change in modern astronomy consisted of the government's preemption of private institutions as the predominant funding source. In 1972, for example, federal support for astronomy amounted to $125 million, putting it in the league of nuclear physics and other 'big' sciences. Though this amounted to about one-third of funding for physics research, government spending for astronomy nevertheless eclipsed private sector allocations of $94 million for *both* astronomy and physics.[2] Beginning soon after World War II, this support initially came from military services, which supplied grants for basic investigations and new research technologies.[3] Later, by creating the National Science Foundation in 1950 and the National Aeronautics and Space Administra-

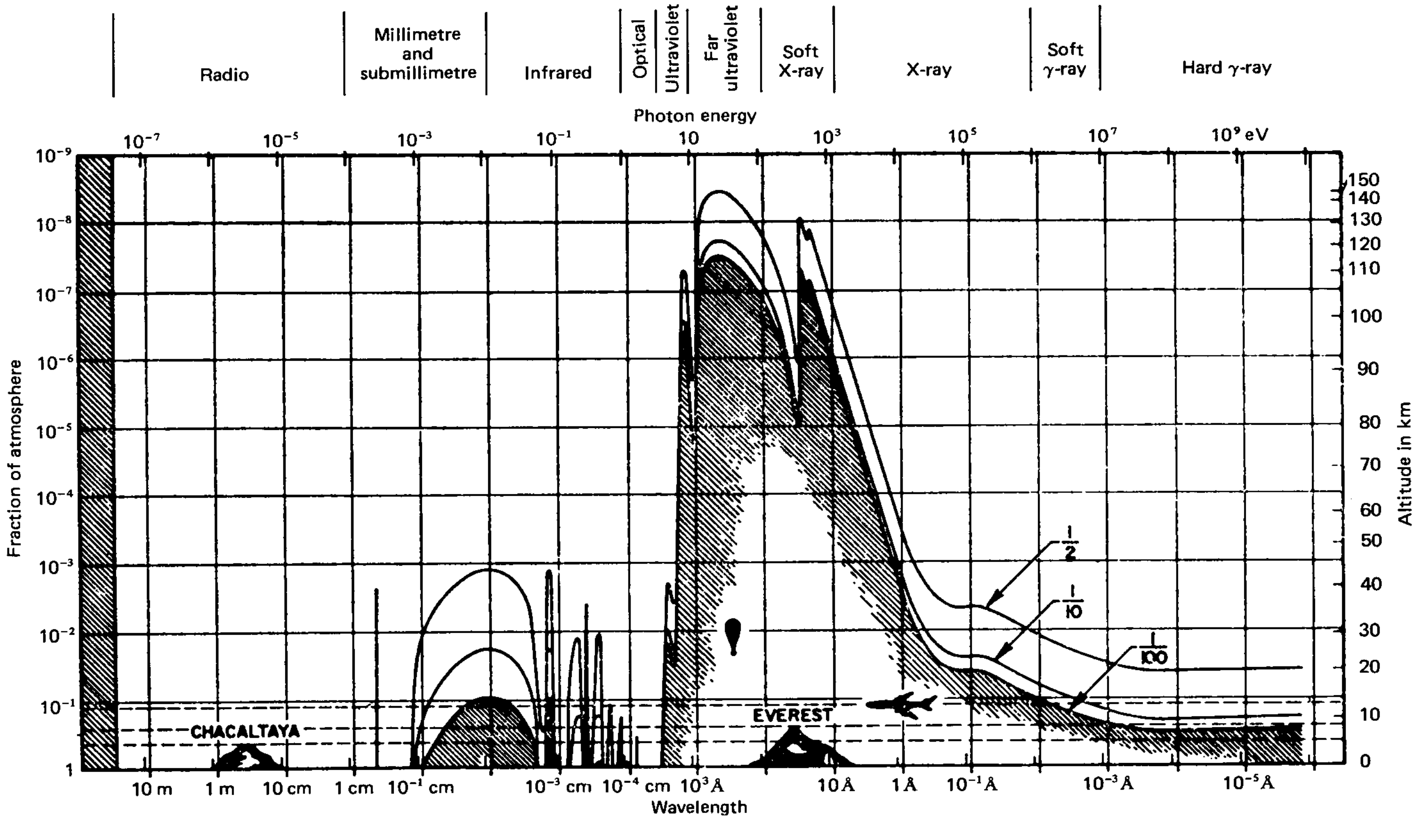

Figure 1. Attenuation of electromagnetic radiation in the atmosphere. Solid curves indicate the altitude (and corresponding pressure as a fraction of one atmosphere) at which the indicated fractional attenuation occurs for radiation of a given wavelength. Along the top of the diagram are the conventional designations of the different wavebands. X-rays are bracketed by far ultraviolet and soft gamma radiation. From M. S. Longair, *High Energy Astrophysics* (Cambridge University Press, 1981), p. 90.

tion (NASA) in 1958, the government provided still more benefactors for astronomers. This enhanced support reflected a new public policy aimed at producing a store of fundamental scientific knowledge and technically trained people for use in national emergencies. Americans perceived such an emergency when the Russians launched the Sputnik satellite in 1957. While the government initiated no public policy specifically for X-ray astronomy, the specialty benefited in the 1960s as an unintended consequence of the massive support for space exploration following the Russians' space spectacular.

Transformations in the scope and funding of astronomical investigations contributed to the third significant change in the discipline: the greatly altered size and social structure of the research community. The old guard optical astronomers, trained to work in seclusion with existing instruments, were joined by a growing number of technologically oriented radio engineers and physicists collaborating in large teams. Only slowly did classically educated astronomers become accustomed to working with the 'migrants' in a synergistic manner. X-ray astronomers were typical of the new breed of star gazers. Trained in experimental fields of physics, they 'invaded' the new specialty and immediately constituted a large fraction of publishing scientists.

The analysis of X-ray astronomy's evolution is organized into four sections comprising 11 chapters. The first section of three chapters describes the scientific, technological, and political environments in which X-ray astronomy emerged. In retrospect, one can see that several areas of high-altitude research, such as ionospheric physics and solar X-ray astronomy, were forerunners of the new field. They provided the research technologies, in the forms of rockets and detectors, that would be adopted wholesale in X-ray astronomy. They also instituted a scientific tradition of investigations in and above the atmosphere that would be continued by later practitioners. By examining X-ray emissions from the Sun, for example, scientists obtained their initial – albeit limited – look at the high-energy universe. In view of knowledge gathered in the 1960s, the solar observations appear ironic, because they implied that X-rays from nonsolar sources would be feeble and undetectable. But the political situation created by Sputnik prompted people to explore original fields of space investigation, including X-ray astronomy. Despite predictions that augured poorly for the specialty, Riccardo Giacconi, a young and ambitious scientist at a small research company, developed an exploratory program that led to the detection of the first intense X-ray emitter in 1962.

In the second section of three chapters, the book discusses the social structure of the X-ray astronomy community. It begins with a description

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of how Giacconi's team encountered competition from other groups even before the first discovery. Herbert Friedman, a long-time rocket scientist bouyed by vast resources at a government research laboratory, led one competing team. A classic scientific rivalry immediately developed, spurring both groups to pursue imaginative research throughout the 1960s. Meanwhile, still more scientists entered the field because they saw the immediate and potential implications it had for resolving cosmological problems and for altering views of the universe. Migrating from physics specialties and with the support from NASA and some untraditional sources, these investigators made X-ray astronomy the fourth largest astronomy specialty by 1972.

The four chapters in the penultimate section examine attempts made during the 1960s and early 1970s to resolve the field's major problem concerning the physics of X-ray sources. They discuss the research strategies of the leading groups and how the programs and advanced technologies led to discoveries of unusual features of X-ray emitters. The chapters further outline how concurrent events in theoretical astrophysics and radio astronomy provided new avenues for research on such esoteric objects as neutron stars. Despite these efforts, the nature of most celestial X-ray phenomena remained a mystery in 1970. By the end of 1971, however, the conceptual deadlock in the field began to weaken. Giacconi and his colleagues provided the critical advance with a satellite named 'Uhuru,' which effectively ended the 'glimpsing' phase in the field's history and ushered in one characterized by long-term observations. Acquiring crucial data that could not be garnered by rocket-borne instruments, investigators resolved the central problem by suggesting a model that considered most galactic X-ray sources as binary systems consisting of a compact star and a large companion. As the small body – either a neutron star or a black hole – attracted matter from its partner, X-rays would be produced. Assimilating most observational facts gathered in the first 10 years of experimental research, this framework also served as the basis for understanding newly detected X-ray phenomena during the next phase of its evolution.

The final section, an epilogue, reviews trends in technology and public policy that affected the first phase of X-ray astronomy's evolution. It describes the importance of public policy in supporting advances in research technology, which in turn stimulated dramatic progress in conceptual understanding. It also documents the impact on the specialty of a nebulous public policy in the 1970s – a policy that no longer promised the consistently high level of funding enjoyed in the previous decade. Instead of being a favored group of investigators, X-ray astronomers constituted one of many political interest groups vying for a slice of the federal budget pie. Consequently, the scientists learned that their dependent relationship on the government acted like a double-edged sword: the governmental support incubated their field and established it as a major force in the discipline. But once built up, the relationship led to disappointments when political sentiments changed. Of course, vacillating public policies have affected several scientific specialties besides X-ray astronomy. For this reason alone, the history of the field reveals much about the way science evolves – or stumbles along – in the modern United States.

SECTION I

THE SCIENTIFIC, TECHNOLOGICAL, AND POLITICAL ENVIRONMENTS

1

The heritage of X-ray astronomy

X-ray astronomy is a gift of technology. Without the rocket technology developed in the first half of the twentieth century, instruments could not have been lifted above the attenuating atmosphere. And without specialized detectors used previously for observing cosmic radiation, scientists would have had difficulty studying nonsolar X-rays. But beyond this technological heritage, X-ray astronomy belongs historically to a class of specialties in physics and astronomy that was concerned with the upper atmosphere. At high altitudes, where the air is thin, physical phenomena occurred that held practical significance for terrestrial observers. The upper atmosphere was also the site from which cosmic phenomena could be studied most effectively. X-ray astronomy is, therefore, one of the more recent descendants of work done by scientists – mostly physicists – who lofted instruments into the upper atmosphere and beyond.

Meteorology and cosmic ray physics

The prehistory of X-ray astronomy can be traced back over 200 years to the first high-altitude research on the weather. As early as 1749, the Scotsman Alexander Wilson rigged a kite, a 2500-year-old Chinese invention, to obtain atmospheric temperatures at different altitudes. Systematized meteorological research began in the 1880s and 1890s, when effective box kites first carried self-recording instruments. Soaring up to a height of 7000 meters, the kites flew regularly for the US Weather Bureau. By the 1930s, however, they had become a hazard to the increasing number of aircraft flying the skies, and the Bureau discontinued their use.[1]

Developed in the 1780s, hot air and hydrogen balloons proved more successful than kites for meteorological studies. Their value was demonstrated on 1 December 1783, when the French physicist J. A. C. Charles, author of the gas law bearing his name, rose in a balloon to an altitude of about 3000 meters, where he measured a temperature that was 12 degrees Celsius lower than on the ground.[2] This first ascent for scientific purposes impressed other investigators, including the chemist Antoine-Laurent Lavoisier, who wrote that it showed how researchers 'can rise up to the clouds to study the cause of meteors [i.e., the cause of the weather].'[3] By the 1870s scientists realized they did not need weighty human operators to measure the temperature, pressure, and other atmospheric features at high altitudes. Using vehicles known as 'sounding balloons,' a term derived from seamen who used sounding lines to measure the unknown depths of waters, scientists could send instruments to oxygen-poor altitudes of about 30 km. In 1898, Leon Teisserenc de Bort of France and Richard Assman of Germany exploited balloon techniques and independently discovered the stratospheric region of the atmosphere, where the temperature remained constant – instead of falling – at altitudes above 10 km.[4] This observation constituted 'the most surprising discovery in the whole of meteorology' in the words of the prominent early twentieth century meteorologist, Sir Napier Shaw.[5] Since the discovery, sounding balloon measurements of the stratosphere became routine.

In contrast to meteorologists interested in occurrences *in* the atmosphere, another group of scientists used the atmosphere as a location for studying phenomena *beyond* it. These investigators examined high-energy extra-terrestrial radiations, and their 'cosmic ray' research became a major activity within the experimental physics community. Following 1912, when the Austrian Victor F. Hess determined that nonsolar radiations struck the Earth from beyond the atmosphere,[6] the major question in the field concerned their nature. Were they, as Robert A. Millikan of the California Institute of Technology argued, high-energy photons like the penetrating gamma radiation emitted by radioactive substances, or were they charged particles of matter? In theory, a test for determining the answer was simple. If charged (and hence, material), the radiations would be deflected by the Earth's magnetic field. Near the north magnetic pole where the field lines converge, the deflection would be greatest, and near the equator, it would be minimal. In the late 1920s, Millikan and others attempted to discover this 'latitude effect' by measuring cosmic ray intensities at different locations on the Earth's surface. The results of several experiments, however, were equivocal.[7]

Another way to determine the charged nature of cosmic rays consisted of detecting the 'east–west effect.' If positively charged, cosmic ray particles would be deflected by the Earth's magnetic field and arrive in greater quantities from the west. Negatively charged particles would have higher intensities coming from the east. The effect would not only tell whether cosmic rays were charged; it would also indicate which particles predominated by noting a difference in their directional preference.

To search for the effect, Bruno B. Rossi, a physicist at the University of Bologna in Italy, invented a cosmic ray 'telescope' in 1931. The major component of this instrument was a gas-filled tube that had a thin wire stretched along its axis. As demonstrated by the device's inventors, the German physicists Hans Geiger and Walther Muller, the gas would remain barely stable when a negative potential of greater than 2000 volts was maintained on the tube's walls. If a penetrating photon or particle entered the tube, it would ionize a gas molecule and trigger a cascade of electrons, producing a pulse of current that could be amplified and recorded by a mechanical register. To make his telescope, Rossi placed two of these 'Geiger' (or 'Geiger–Muller') counters in a line and connected them in a single circuit so that when a cosmic ray traversed both the tubes, an almost simultaneous discharge, or 'coincidence,' would be produced. By increasing the distance between the tubes, he decreased the telescope's field of view, because only rays coming in a narrow cone could produce the telling coincidences.[8]

While theoretically sound, the experiment for detecting the effect was difficult to perform. Only in 1933 did Rossi and other investigators succeed by finding an excess of radiation in the west direction – an indication that cosmic rays reaching the Earth's surface consisted largely of positively charged particles. High-altitude observations conducted from mountain tops and balloons in the same year demonstrated conclusively the existence of the latitude effect. Along with Rossi's observations, these classical experiments by Millikan and Arthur H. Compton of the University of Chicago indicated the material nature of most cosmic radiation.[9] Cosmic ray research attracted physicists because the radiation constituted a natural source of extremely high-energy particles (up to 10^{14} eV) in the days before powerful accelerators. It quickly became clear, however, that many rays observed on the Earth's surface were not the same as those entering the atmosphere. The incident 'primary' cosmic rays, it appeared, interacted with atmospheric matter to create showers of 'secondary' particles. Only a small fraction of the primary rays made it to the surface unscathed. To study the primary radiation, then, scientists needed to raise instruments high into the atmosphere, an activity that became routine with balloons. Data were obtained by converting measurements into electric signals, broadcasting them from the vehicle and receiving them at ground. From this 'telemetered' information, balloon-borne experiments revealed that