Handbook of X-ray Astronomy

Edited by

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Introduction

X-ray astronomy was born in the aftermath of World War II as military rockets were repurposed to lift radiation detectors above the atmosphere for a few minutes at a time. These early flights detected and studied X-ray emission from the Solar corona. The first sources beyond the Solar System were detected during a rocket flight in 1962 by a team headed by Riccardo Giacconi at American Science and Engineering, a company founded by physicists from MIT. The rocket used Geiger counters with a system designed to reduce non-X-ray backgrounds and collimators limiting the region of sky seen by the counters. As the rocket spun, the field of view (FOV) happened to pass over what was later found to be the brightest non-Solar X-ray source; later designated Sco X-1. It also detected a uniform background glow which could not be resolved into individual sources. A follow-up campaign using X-ray detectors with better spatial resolution and optical telescopes identified Sco X-1 as an interacting binary with a compact (neutron star) primary.

This success led to further suborbital rocket flights by a number of groups. More X-ray binaries were discovered, as well as X-ray emission from supernova remnants, the radio galaxies M87 and Cygnus-A, and the Coma cluster. Detectors were improved and Geiger counters were replaced by proportional counters, which provided information about energy spectra of the sources. A constant challenge was determining precise positions of sources as only collimators were available.

The first X-ray astronomy satellite, Uhuru, was developed by Giacconi's team and launched by NASA in 1970. In its first day it exceeded the combined observation time of all previous X-ray astronomy experiments. Uhuru performed an all-sky survey using collimated proportional counters and detected over 300 individual sources. Among the discoveries from Uhuru were pulsations from X-ray binaries and extended X-ray emission from clusters of galaxies. The 1970s saw a succession of increasingly sophisticated satellites with X-ray detectors. Among them were Copernicus, Ariel-V (from the UK), ANS (from the Netherlands), OSO-8, and HEAO-1. These missions established further classes of astronomical objects as X-ray sources, observed more types of time variability from X-ray binaries, and detected iron emission lines.

The next revolution in X-ray astronomy was wrought by the Einstein Observatory, launched in 1979 and named in honour of the centenary of his birth. X-ray focusing optics had been flown on Copernicus and as part of the Solar astronomy experiment on Skylab but the Einstein Observatory provided the first X-ray images of many classes of astronomical objects. The combination of an X-ray telescope and an imaging proportional counter provided the sensitivity to observe large samples of stars, binaries, galaxies, clusters of galaxies, and active galactic nuclei (AGN). In addition, the focusing optics allowed the use of physically small detectors such as solid state and crystal spectrometers as well as a grating that dispersed the spectrum onto a microchannel plate detector. The Einstein Observatory was one of the first astronomy satellites to have a guest observer program. Another innovation was an automated data reduction pipeline and a public archive. Although this predated the internet, and thus required actual travel to the archive, it was an important first step.

The 1980s were a lean period for X-ray astronomy in the US but progress continued in Europe and Japan. Exosat was launched by ESA in 1983 into a deep 90-hour period orbit which allowed long, continuous observations of sources. The Japanese scientific space agency, ISAS, pursued a program of placing mainly large area proportional and scintillation counters on a series of satellites: Hakucho, Tenma and Ginga. Among the discoveries in this decade were quasi-periodic oscillations (QPOs) in X-ray binaries, iron emission and absorption lines from AGN and iron emission lines from the Galactic center. The successor to the Einstein Observatory was ROSAT, a German-US-UK collaboration with X-ray and EUV telescopes, which was launched in 1990. The first six months were spent performing an all-sky survey, generating a catalogue of more than 150,000 objects, followed by another eight years of targeted observations as part of a guest observer program, accumulating another catalogue of 100,000 serendipitous sources. ROSAT was able to image over a two degree FOV providing good observations of large supernova remnants, clusters of galaxies, structure in the interstellar medium, and comets.

The next big technological advance was the use of X-ray sensitive CCDs, which provide better imaging and spectroscopic properties than imaging proportional counters or scintillators. ASCA, launched in 1993 and a collaboration between ISAS and NASA, was the first X-ray astronomy satellite carrying CCDs. ASCA's other innovation was light-weight optics which provided a much larger area than those used for ROSAT although with poorer spatial resolution. The light-weight optics were placed in an extendable structure giving a long enough focal length to take the ASCA bandpass up to 10 keV, thus including the important 6–7 keV iron line region. This improvement enabled the detection and study of relativistically-broadened iron lines in the accretion disks around black holes. Another major discovery made possible by the broad energy bandpass was that of non-thermal X-ray emission in supernova remnants.

While most X-ray satellites now use focusing optics, there is still a place for large area proportional counters. RXTE, launched by NASA in 1996, was designed to collect many events from bright sources and to examine their variability down to microsecond timescales. An all-sky monitor tracked the brightest sources on day to year timescales. Among RXTE's discoveries were spin periods in low-mass X-ray binaries and kilohertz QPOs. RXTE's all-sky monitoring duties have now been taken over by the Japanese MAXI detector on the International Space Station.

In recent years, X-ray observations of gamma-ray bursts have become important. The Italian-Dutch satellite BeppoSAX, launched in 1996, had two sets of detectors. Proportional counters behind coded aperture masks were used to detect gamma-ray bursts and determine their approximate positions. These positions were used by ground controllers to point a set of narrow-field detectors at the source to observe the X-ray afterglow. This strategy was improved upon by the NASA satellite Swift, launched in 2004, which autonomously points its X-ray and UV/optical telescopes at bursts detected by its wide-field coded aperture mask camera.

We are now in the era of great observatories with Chandra from NASA, XMM-Newton from ESA, and Suzaku from JAXA, all operational. Chandra's strength is its sub-arcsecond resolution telescope giving high-resolution images and, using gratings, spectra. XMM-Newton has the largest area of any focusing X-ray telescope while Suzaku covers a wider energy bandpass and has the lowest background. In the next few years, a number of other X-ray astronomy missions are planned. From NASA, NuSTAR will use focusing optics at energies above 10 keV for the first time and GEMS will measure X-ray polarization. A collaboration between Russia and Germany, Spectrum-Roentgen-Gamma, will perform a new, more sensitive, all-sky survey. Astro-H, the next JAXA mission, done in collaboration with NASA, will feature a microcalorimeter providing sensitive, non-dispersive, high-resolution spectroscopy. The international basis of X-ray astronomy is expanding as India, China, and Brazil all prepare their own satellites.

After its first half century, observations in the X-ray waveband have become important in many topics in astronomy. Despite this, its techniques remain unfamiliar to many astronomers. One reason is that X-rays are almost always detected event by event instead of as a bolometric flux over a specific bandpass, as is common in other wavebands. However, the differences are not just in detection methods. While optical spectroscopy is concerned principly with line emission and absorption and radio spectroscopy with continuum emission, the processes that generate X-rays create significant continuum as well as line emission and both must be modelled correctly. Complicating this further, until recently X-ray detectors did not have the spectral resolution needed to separate the lines from the continuum cleanly.

These and other issues have continued to make X-ray data analysis challenging. Following the launch of Chandra and XMM-Newton the need for more systematic training of graduate students interested in X-ray astronomy became clear, leading to a series of X-ray "schools." These schools have been organised in the US by the Chandra X-ray Center (CXC) and NASA Goddard Space Flight Center (GSFC), in Europe by the XMM-Newton Science Operation Centre (SOC), and in the developing world by the COSPAR Capacity-Building Workshop program. All of the authors of this handbook have lectured at these schools, in most cases multiple times, and the material collected here was developed through interactions with the students at the schools.

We have attempted to steer a middle course between pure theoretical exposition and explicitly detailing commands, albeit with excursions to both sides. We hope that this handbook proves to be a useful guide to beginning X-ray astronomers as well as experienced scientists who need to remember a conversion factor. To that end, we have arranged the text in three sections. The first three chapters cover the optics and detectors used on X-ray satellites. The next five chapters describe analysis issues, including data preparation, calibration, and modelling. Finally, the appendices contain a range of useful tables, including atomic data, conversion factors, and typical X-ray sources, amongst other information.

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