Observational techniques in Astrophysics: X-rays

1. General Introduction

Astrophysicists use X-ray observatories to gain insights into a plethora of cosmic objects and to study radiative properties of thermal and non-thermal emission. In practice this is possible through the study of spectral information, temporal variability and morphology.

First, let's start with a few examples of intriguing objects[1]:

X-ray Binaries

X-ray binaries contain a collapsed, compact star at the end of its evolution (a neutron star or black hole), accreting material from a more normal star as the two orbit around their common center of mass. Often, this material forms a disk around the compact object. We see a wide range of dramatic phenomena from such systems, including: pulsations from rapidly-spinning neutron stars, intense bursts from thermonuclear burning, eclipses, and dips due to occulting material on the disk edge. X-ray spectroscopy and fast timing studies reveal a wealth of information about the physical processes taking place in these complex systems.

Accreting White Dwarf Binaries

Accreting white dwarfs can be found in two broad categories of interacting binaries, cataclysmic variables (or CVs) and symbiotic stars.

CVs are compact binaries with orbital periods typically in the 1 to 10 hour range, and their mass donors are Roche-lobe filling, late type stars on or near the main sequence. In CVs, it is usual for accretion to provide most of the luminosity rather than the stellar components. A minority of white dwarfs in CVs are sufficiently magnetic to truncate, or prevent the formation of, accretion disks. In such systems (known as magnetic CVs), magnetically controlled accretion results in prominent X-ray emission. In non-magnetic CVs, the accretion disks emit in the infrared, optical, and ultraviolet, but not in X-rays. The boundary layer between the disk and the white dwarf surface is the origin of X-rays in non-magnetic CVs.

Symbiotic stars are wide binaries with orbital periods in the range from a hundred days to perhaps over a century. The mass donors are late type giants, which tend to dominate the luminosity in the optical and the infrared. Until recently, symbiotic stars had not been as well studied in X-rays as CVs. This is gradually changing, with the discovery that some symbiotic stars emit X-rays that are luminous enough and hard enough to make them detectable in the INTEGRAL and Swift BAT (Burst Alert Telescope) hard X-ray surveys. A BAT hard X-ray source

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[1] All text of the following paragraphs (type of sources) is borrowed from NASA X-ray Astrophysics Laboratory: LINK

was identified with a red giant (SU Lyn), which led to the discovery that it was indeed a symbiotic star.

Nova eruptions are the result of thermonuclear runaway on the surface of the white dwarfs in CVs or in symbiotic stars. Novae are panchromatic transients, emitting from radio through gamma-rays, with durations of days to years.

Supernova Remnants

Supernova remnants are the aftermath of the violent deaths of stars, known as supernovae. The explosion of an entire star is a tremendous release of energy; a single supernova can outshine an entire galaxy for days or weeks. The supernova explosion propels the debris of the star at high velocities and initiates a shock wave propagating into the surroundings, while a second shock heats the ejecta.

Supernovae come in two basic types. The first type, a core collapse supernova, is caused by the explosion of a massive star that runs out of fuel to burn. The core collapses in on itself, setting off a chain reaction that blows the star apart. A core-collapse supernova generally leaves behind a compact stellar remnant, such as a neutron star or a black hole. The second type, a thermonuclear supernova, is caused by the explosion of a white dwarf star, triggered by either the accretion of matter from a companion star or a collision or merger with another white dwarf.

Supernova remnants are fruitful laboratories for the study of the physics of heating and particle acceleration at shocks, the mechanism of supernova explosions, the chemical enrichment of the interstellar medium, the interaction of shocks and clouds, and the interaction of the remnant gas with compact stellar remnants. X-ray observations are relevant to all of these by providing access to the rich emission line spectra of supernova remnant gas and the nonthermal emission characteristic of particle acceleration. The fast shock waves that interact with both the interstellar medium and the stellar ejecta heat the gas there to tens of millions of degrees, hot enough to emit strongly in X-rays.

AGN

Active Galactic Nuclei (AGN) - An active galaxy contains a compact core, or nucleus, of emission that is embedded in an otherwise typical-looking galaxy. This galaxy nucleus shines at all wavelengths of the electromagnetic spectrum and is seen to be bright compared to the rest of the galaxy. Its light may also be highly variable and some AGN even change their major visual characteristics with time. In galaxies with very dense cores, the X-rays from the center can penetrate material outward from the nucleus and this provides scientists with unique insights into the physical processes occurring there. Our science team performs X-ray observations and modeling of processes in these AGN systems. At the very center of an AGN lies a supermassive black hole. Dense material from the surrounding regions can accrete onto the black hole releasing large amounts of gravitational energy. X-rays from these accreting black-hole systems can tell us about the extreme conditions in the vicinity of the black hole as well as out to the parsec-scale circumnuclear environment. X-rays coming from very close to the black hole are also gravitationally redshifted, introducing a characteristic distortion in spectral features, such as the iron K fluorescence line that is broadened by relativistic effects. Some objects are also opaque to most light, including soft X-rays, but these can be explored with multi-wavelength observations that pair the hard X-rays with the infrared.

Galaxies

Stars in the universe are organized into galaxies that often include many billions of stars. Galaxies have many additional components, including hot, warm, and cool diffuse gas, cold gas clouds, extended halos of dark matter and, sometimes, central supermassive black holes. X-rays may be emitted from interstellar gas that is hotter than a million degrees Kelvin, by individual supernova remnants and X-ray binaries that are part of the stellar population, and by gas falling into the central black hole. The detailed characteristics of these X-ray emitting components are used to study the star formation history, and the evolution and structure of galaxies - including our own Milky Way.

Galaxy Clusters

Galaxy clusters are the most massive gravitationally bound objects in the Universe, with masses of up to a thousand trillion times that of our sun (10^15 Msun) and extending millions of light years. Though called clusters of galaxies (and indeed containing tens of thousands of galaxies), most of their mass is actually dark matter. We learned of that in the 1930s, when Zwicky realized that galaxies in clusters move so fast that they must be held together by a much stronger gravity field than their own. Today, we can also observe X-ray emission from the tenuous, hot (10-100 million degrees) intergalactic plasma that is trapped in the potential well of the cluster. It confirms the dominance of dark matter in clusters and in the Universe as a whole, since the matter content in clusters is representative of the whole Universe.

The intracluster plasma consists mostly of primordial hydrogen and helium, but it also has traces of heavier elements, such as oxygen and iron, produced by stars inside the galaxies. Those elements are driven out from the galaxies into the intracluster medium by supernovae winds and ram pressure exerted as the galaxies move through the intracluster medium. When we observe an energy spectrum of the X-ray emission from clusters, we see emission lines produced by those elements. Those lines contain a wealth of information about the physics of galaxies and the intracluster plasma. For example, the Doppler shifts and broadening of those lines reveal the flows and turbulence in the plasma. The figure shows an X-ray spectrum of the Perseus Cluster observed with Hitomi, the first instrument capable of obtaining high-resolution spectra for extended objects such as clusters; multiple narrow lines of Iron and Nickel are seen.

2. About this Lab course

The main goal of this lab is to motivate all students to pursue research in astrophysics and provide insight into how one can analyze X-ray data and interpret the results based on physical models. To keep things interesting we will look into different objects and methods. We will also present methods and techniques for analysis and fitting that are based on standard minimization statistics and Bayessian inference. For a few topics we will perhaps just scratch the surface, but the goal is to motivate students to follow up on any particular topic on their own (i.e. via research projects). Also given the available time we will be open in shifting some of the focus of the course to areas that students find interesting.

Many of you are here not knowing what will be asked from you (reports, exams, grades) so lets put this out of the way.

- Part 1: For the first 2 courses we will ask you to prepare very short reports, i.e. produce plots or tables with minimal commenting, the goal of this is to be sure that you complete tasks in time and do not leave everything in the end, in principle all the requirements would already be completed within the lab. Together with your overall participation and performance in the lab this will count part of your grade
- Part 2: You will have to complete a short (3 pages max) research paper, with introduction to the topic (about one page), methods and analysis (one page) and commentary on results. You will be evaluated on clarity of text, presentation of results (tables, plots, treatment of uncertainties) and comments on the results. The assignment will cover the second part of the course, i.e. weeks 3-4
- Part 3: For the final part of the course we will ask you to prepare a proposal (3 pages max) requesting observing time from a space observatory and/or ground facilities.

For grading we will weigh your general performance, giving 20% weight to part 1, while parts 2 & 3 you will be graded according to individual performance with 30% and 50% weights. Meaning if one student gets a better score in part 3, this will count as 50% of the final grade, while if another student gets better score in part 2, then part 2 will count as 50% and part 3 with 30%.

Tools and Software:

We will start with a first introduction of X-ray data analysis and how we can use spectra to characterize properties of accreting objects like Neutron Stars, White Dwarfs and Black holes. Given the diversity of X-ray telescopes, observatories and detectors we will not be able to cover all of them, but present the basic principles of X-ray astronomy and focus on analysis of data from CCD detectors. For convenience we will also use data from selected telescopes that are supported by tools developed by NASA and the **High Energy Astrophysics Science Archive Research Center (HEASARC)** and supported software **HEASoft**.

https://heasarc.gsfc.nasa.gov/
https://heasarc.gsfc.nasa.gov/docs/software/heasoft/

Within the lab we will work with **python (Conda, Jupyter)** and **HEASoft** that should be installed in every lab computer. We will also offer a virtual environment in **SciSoft** server that you can use to operate notebooks from home.

A tentative schedule and tasks per lab course is the following:

- DAY 1: X-ray analysis and my first spectrum
    - Intro to X-ray telescopes, data and data analysis: SciServer & Heasoft/Heasarc
    - Source detection in X-ray images (Homework: literature search for sources in image)
    - Extract a spectrum from the brightest sources
    - Fit a spectrum with a basic one component model
- Day 2: Spectral analysis
    - Goodness of fit
    - Model comparison
    - Fit a spectrum with multiple components
    - Bayessian analysis (if we have time)
- Day 3: A study of a black-hole binary during outburst
    - Analyze the daily spectra of an X-ray binary during an outburst (last weeks)
    - Identify spectral states and evolution
    - Compare with other monitoring X-ray telescopes
- Day 4: Simulations of X-ray spectra
    - How do we prepare an observational experiment?
    - Students will be split into teams. Each student will simulate spectra of a particular model.
    - Simulated spectra will be distributed among students (semi-randomly) and each student will analyze the simulated spectra in order to reproduce model parameters.
- Day 5: Proposal day 1 (X-ray observatories)
    - Open discussion about sources that we might like to observe
    - Set up observing plans and simulations.
    - Calculating visibility & observing times
    - Start writing a proposal
- Day 6: Proposal day 2 (Ground based telescopes)
    - Sky Coordinates
    - Visibility from the ground
    - Coordinated observations (from Space, Earth)

3. Literature

- Book: Exploring the X-ray Universe; Frederick D. Seward and Philip A. Charles; CAMBRIDGE UNIVERSITY PRESS (LINK)
- Swift XRT Analysis: https://www.swift.ac.uk/analysis/xrt/