Caltech Student-Faculty Programs

Session V Abstracts

Transient ULX case study: M31 ULX-3 (LSXPS J004321.0+411833)
Ferdinand
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Ultraluminous X-ray sources (ULXs) are off-nuclear X-ray sources with luminosities exceeding the Eddington limit of typical stellar-mass compact objects. While most known ULXs are relatively persistent sources, transient ULXs emerge as a distinct population that offers unique insight into studying extreme super-Eddington accretion. We report the discovery and X-ray characterization of a newly identified transient ULX in M31. First detected serendipitously on 2021 June 9, the source reached a peak X-ray luminosity of $\sim 1-2\times10^{39}\,\mathrm{erg\,s^{-1}}$. Its spectral evolution suggests increasing advection at later epochs, opposite to the expected transition from a super-Eddington slim disk toward a standard thin disk during the decay of the outburst. The observed X-ray light curve can be reproduced using the disk-instability model of Hameury & Lasota, with characteristic timescales of $\sim 60-85$ days. The inferred mass-accretion rate is super-Eddington for a $1.4\,M_\odot$ neutron star but sub-Eddington for a $10\,M_\odot$ stellar-mass black hole. Nearby optical sources from the *Hubble Source Catalog*, suggest a possible giant donor with an age of $\log_{10}(\mathrm{age/yr})\sim 8.5$ and a mass of $3.2\,M_\odot$, when compared with stellar isochrones with an assumed $A_V=1.58$. We estimate a transient ULX occurrence rate in M31 of $0.15\pm0.09\,\mathrm{yr^{-1}}$.This rate is lower than those reported for other galaxies in previous studies. M31 ULX-3 expands the small population of known transient ULXs in M31 and highlights the importance of continued, uniform X-ray monitoring of nearby galaxies.

Mapping the inner geometry of active galactic nuclei using Wiener Deconvolution of X-ray reverberation
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Observations of X-ray reverberation time-lags provide a powerful probe of the geometry of space surrounding supermassive black holes in the center of active galactic nuclei (AGN). Current techniques for measuring these lags primarily rely on Fourier-domain cross-correlation analyses. While effective, these methods recover only aggregate time-lag properties of the system rather than directly resolving the impulse response function that encodes its underlying geometry.

The novel astronomical Wiener Deconvolution (WD) technique not only improves the accuracy and precision of time-lag measurements by suppressing instrumental noise, but also directly estimates the response function, which holds physical information about the system's geometry and light-travel delay processes. In this work, we apply the WD method to AGN with previously detected X-ray reverberation lags. By reconstructing the response function and searching for lags, we investigate whether Wiener deconvolution can place tighter constraints on the geometry of the innermost regions surrounding the central black holes.

Accretion flow and jet evolution during the 2021 outburst of GX 339-4
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Mentors: Fiona A. Harrison and Shina Adegoke

GX 339−4 is a stellar-mass black hole system that brightens in recurrent outbursts as gas from the companion star changes the structure of the surrounding accretion flow. This project investigates how the disk, the coronal high-energy emission, and the radio jet evolved during its 2021 outburst. To do this, we used data from the Neutron Star Interior Composition Explorer mission, covering the 0.3—12 keV energy range, together with contemporaneous radio measurements from MeerKAT between

January and November 2021. Preliminary results show that while in the disk-dominated soft state, the disk-luminosity versus temperature relation in the GX 339-4 system agrees with theoretical prediction, suggesting that the disk likely remained stable at the innermost stable circular orbit of the black hole throughout the soft state evolution.

Disk-wind diagnostics from the 2025 outburst of black hole transient IGR J17091-3624
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Mentors: Fiona A. Harrison and Shina Adegoke

Black hole X-ray binaries (BHXBs) undergo outbursts when the mass accretion rate onto the black hole increases dramatically, producing a rapid increase in X-ray luminosity. BHXBs frequently exhibit signs of emitted disk-winds during the soft-state of an outburst. The BHXB candidate IGR J17091-3624 underwent a failed outburst in 2025 that showed evidence of highly ionized iron XXV or iron XXVI lines, indicative of disk-winds, despite the outburst never reaching the soft-state. This outburst was monitored by several X-ray missions, including NuSTAR and XRISM. While absorption lines were detected by NuSTAR, these lines appear to be missing from concurrent observations with XRISM, despite its higher spectral resolution. We aim to identify and characterize iron XXV or iron XXVI lines in NuSTAR and XRISM data. Then, we use Monte Carlo simulations to determine the statistical significance of these lines and compare the detections of the two telescopes. This comparison will help clarify the relative sensitivity of NuSTAR, with its larger effective area, and XRISM, with its higher spectral resolution but smaller effective area. Our results will also provide insight into the underlying mechanisms driving disk-winds in outburst.

Investigating the nature of a serendipitous hard X-ray source in the Kepler field
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Mentors: Fiona A. Harrison and Hannah Earnshaw

During observations of the Kepler Supernova Remnant, the Nuclear Spectroscopic Telescope Array (NuSTAR) serendipitously detected an unidentified hard X-ray source, Source S2. Classifying these detections is important since it helps reduce target selection bias to provide us with a true catalogue of the high-energy universe. We aim to characterize and classify Source S2 by investigating the source's spectral and temporal X-ray properties. We analysed archival NuSTAR observations of Source S2 spanning multiple epochs, performing spectral analysis to characterize its X-ray emission and timing analysis to investigate variability and periodic behaviour. Using Chandra and Swift observations, we refined the source's position and extended the analysis to lower X-ray energies. We determined that Source S2 is a faint astrophysical source detected at high X-ray energies, regularly up to 20–30 keV, showing no significant periodic behaviour. Additionally, the source's spectrum is well described by an absorbed power-law model, consistent with non-thermal emission. The observed flux provides evidence for moderate long-term variability. The nature of Source S2 remains uncertain, with an active galactic nucleus, X-ray binary, or magnetic cataclysmic variable being the leading possibilities. Further analysis of lower-energy observations and identification of an optical counterpart will help distinguish between the possibilities.

Infrared variability studies of Active Galactic Nuclei with SPHEREx
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Mentors: Fiona A. Harrison and Elias Kammoun

The recent release of Spectro-Photometer for the History of the universe, Epoch of Reionization, and Ices Explorer (SPHEREx) data has ushered in an exciting time for the study of variability in Active Galactic Nuclei (AGN). These are the supermassive black holes that lie at the centers of galaxies and consume tremendous amounts of surrounding matter. SPHEREx presents a unique way of studying these objects, as it is the first all-sky survey in the near infrared (spanning λ = 0.75-5 μm and 102 wavelength channels), and it surveys the North and South Ecliptic Poles daily, amassing tens of thousands of observations of the same patch of sky. SPHEREx also makes use of a Linear Variable Filter (LVF) in order to capture the same sources in different wavelengths, providing thorough spectra. In this paper, we present a comprehensive data reduction process of SPHEREx data on a sample of AGN with the use of the SPExPI pipeline. The results consist of background-subtracted and errorhandled spectra and light curves that span 102 wavelength channels and 10 months of daily observations. These products provide the foundation for future studies of near-infrared AGN variability with SPHEREx.

Reflection from the plunging region of accreting black holes: A systematic study of spin measurements
Mercan Demiroglu
Mentors: Fiona A. Harrison and Elias Kammoun

The spin angular momentum of black holes is a fundamental property which encodes information about their origins, evolution, and cosmological impact. X-ray reflection spectroscopy, i.e. modeling of the reprocessed high energy X-ray emission from the ionized accretion disks of accreting black holes, is a powerful tool for constraining spin, and over the past few decades it has become a commonly adopted method of estimating the spins of black holes in X-ray binaries. However, standard models typically assume that the reflecting medium, the spiraling accretion disk, is truncated at the innermost stable circular orbit (ISCO), thus neglecting contributions from the plunging region. We will present results from a new model that extends the emitting/reflecting region down to the event horizon considering the contribution of the plunging region. We investigate how the inclusion of this region affects the BH spin measurements. We show that neglecting the aforementioned plunging region contribution introduces systematic biases in parameter estimation, consistently leading to an overestimation of measured spin values, especially in systems with lower intrinsic spins. We investigate these biases in detail, identifying the regions of parameter space where the deviations are most significant and explore their physical origins. This has major consequences for the current best estimates of black hole spin distributions across the entire mass scale.

A multi-wavelength archival search for counterparts and hosts of NuSTAR fast X-ray transients
Tooba Ansar
Mentors: Fiona A. Harrison and Guillem Megias Homar

Fast X-ray transients (FXTs) are a recently expanding class of short-lived X-ray bursts whose origins remain poorly understood. While recent advancements in soft X-ray surveys have enabled the detection of and rapid follow-up on several FXTs in the soft X-ray range, leading to the identification of various multi-wavelength counterparts, the nature of FXTs found in archival hard X-ray observations remains largely unexplored. In this work, we conduct a systematic multi-wavelength search for the counterparts to seven FXTs found in archival data taken by NuSTAR, a mission that observes the hard X-ray sky in the 3-79 keV range. Due to the limited localization accuracy of NuSTAR and the absence of contemporaneous follow-up, identifying genuine counterparts remains challenging. We search for associated emissions in the optical, radio, and ultraviolet using archival survey data and aim to provide constraints on the presence of counterparts to hard X-ray FXTs in these regimes.

PySimSat: An open-source Python package for simulating satellite X-ray spectra
Michael Burch
Mentors: Fiona A. Harrison and Gaurav Waratkar

We present PySimSat, an open-source Python package designed to simulate X-ray spectra and evaluate instrument performance for concept satellite missions. Existing mission performance simulations combine mission specific software with ray tracing toolkits such as GEANT4 to model detector response and observed spectra. However, these simulations are often computationally expensive, complex, and time-intensive, with some simulations taking weeks or even months to complete. Additionally, these simulations are generally developed for a specific mission and are not easily adapted to new mission concepts. We developed PySimSat to provide fast, simple performance simulations of concept missions. Given the characteristics of the concept mission, including satellite geometry, detector properties, optics, and orbital configuration, PySimSat generates satellite response files and simulates the observed background and source spectra. We use the Burst Alert Telescope

(BAT) and AstroSat as case studies to validate PySimSat by comparing PySimSat simulated spectra with actual observations. We then apply PySimSat to optimize a CubeSat mission designed to constrain the corona temperature of active galactic nuclei (AGN) and investigate the processes responsible for X-ray emission in the corona.

Systematic study of the long-term behavior of hot electrons surrounding the supermassive black hole
Wenda Chen
Mentors: Fiona A. Harrison and Xiurui Zhao

Most of the X-ray photons in the extragalactic universe are emitted by accreting supermassive black holes (SMBHs), known as active galactic nuclei (AGN). The intrinsic X-ray emission from AGN is primarily produced in a region surrounding the SMBH, known as the corona. Understanding the physical properties of this cosmic X-ray emitter is therefore essential for revealing how SMBHs release their accretion energy. However, the physical properties of AGN coronae remain poorly understood. Current coronal models predict that the coronal temperature should evolve with luminosity. In this work, we perform the first systematic study of the evolution of coronal temperature with luminosity. We carefully select a sample of 10 AGN whose coronal temperatures can be well constrained with current X-ray telescopes and that have multiple epochs of high-quality X-ray observations with the NuSTAR space telescope. This project enables us to systematically probe the evolution of coronal temperature for the first time. Our results provide important new insights into the physical mechanisms governing AGN coronae and have significant implications for current theoretical models of the corona.

Advancing the image simulator for the Ultraviolet Explorer (UVEX): Vignetting and red leak
Kenji P. Farrell
Mentor: Fiona A. Harrison

UVEX is an upcoming NASA space mission that will observe the universe at ultraviolet (UV) wavelengths. With the capability to detect sources 50 times fainter than previous missions, it will conduct the deepest UV survey of the sky. Equipped with Near-UV (NUV) and Far-UV (FUV) imaging units and a low-resolution spectrograph, UVEX will address a broad range of astrophysical questions, including the evolution of low-mass galaxies, early UV emission from cosmic explosions, and stellar astrophysics. UVEX is currently in its instrument design phase, during which the optics and detector configurations are being finalized, making realistic image simulators critical to this process. This summer, I have been working with the UVEX team to develop a new simulator for the NUV and FUV imagers using ScopeSim, an open-source instrument simulation framework. Building on a vignetting model developed during my previous SURF project, we refined the model by applying Gaussian smoothing and piecewise polynomial fits to convert noisy ray-tracing output into a continuous transmission map, which was then integrated into the simulator. We are now investigating red leak, in which out-of-band red photons pass through the UV filters and are detected as UV signal. By separating simulated stellar spectra into in-band and out-of-band components, we quantify how much of the recovered flux originates from genuine UV emission. The completed simulator will be integral to evaluating UVEX's expected performance and informing its final instrument design.