2023 Institute of Astronomy Summer Research Opportunity

Project Booklet

Contents

1) Title: Astronomy in the Era of Big Data–Study the origin of the emission from the one and only Galactic ultra-luminous X-ray pulsar with the Neil Gehrels Swift Observatory

Supervisor: Dr Jiachen Jiang

Description:

Ultraluminous X-ray sources (ULXs) are non-nuclear objects that appear very luminous under the assumption of isotropic emission. Most ULXs are X-ray binaries powered by the accretion processes onto a compact object. Their luminosities are around or above the Eddington luminosity of typical stellar-mass black holes of 5-20 solar masses. ULXs were believed to host intermediate-mass black holes due to their high luminosities. Surprisingly, NuSTAR found coherent X-ray pulsations from a ULX with a peak luminosity above 10^40 erg s/1 (Bachetti et al., 2014). Since then, we have found a few more ULX pulsars. Such coherent pulsation signals provide evidence of a rotating neutron star accreting at a rate significantly above the Eddington limit.

Optical and UV luminosities are often found to be strongly correlated with X-rays during the outburst of X-ray binaries. The origin of their optical and UV emission is, however, more complicated: whether an optically thin synchrotron spectrum from the jet may exist, optically thick, self-absorbed synchrotron jet emission may be an alternative, the contribution from the companion star or blackbody emission from the outer accretion disk may dominate. Several methods have been applied to study the origin of the optical and UV emission in X-ray binaries and their correlation with X-rays, e.g., SED modelling, fast variability studies and multi-wavelength correlation studies (e.g., Saikia et al. 2022).

Most ULXs are discovered in external galaxies. Swift J0243.6+6124 (Swift J0243) is a unique system being the first and only known ULX in our Galaxy (see Sugizaki et al. 2022 for an X-ray overview of the outburst of Swift J0243). The significant correlated optical and X-ray luminosity changes suggest a common origin in Swift J0243 (Reig et al., 2020). However, how much contribution may be from the jet? How about the emission of the donor star at these wavelengths considering its high mass nature? Does the optical and UV emission of Swift J0243 originate in the outer region of the accretion disk? How does the only Galactic high-mass Be ULX pulsar Swift J0243 compare to other Galactic low-mass and high-mass X-ray binaries?

Neil Gehrels Swift Observatory (Swift) is a NASA-led multi-wavelength space mission consisting of three main instruments, UVOT, XRT and BAT. They provide a large number of simultaneous monitoring observations in the optical/UV, soft and hard X-ray bands. Swift will be the perfect mission for us to study the multi-wavelength correlation of Swift J0243. This project will be a good opportunity for the student to have a taste of astronomy in the era of big data.

Useful references:

1. Russel, D., et al., "Global optical/infrared–X-ray correlations in X-ray binaries: quantifying disc and jet contributions", MNRAS, 371, 1334-1350.
2. Kaaret, P., et al., "Ultraluminous X-Ray Sources", Annual Review of Astronomy and Astrophysics, 55, 303-341.
3. Bachetti, M., et al., 2014, Nature, 514, 202
4. Reig, P., et al., 2020, A&A 640, A35
5. Saikia, P., et al., 2022, ApJ, 932, 38

2) Title: Wrong Model, Right Answer: Recovering Traces of Dynamical Binary Black Hole Formation from Gravitational-Wave Data

Supervisors: Dr Isobel Romero-Shaw, Dr Suhail Dhawan

Description:

Binary black holes, inspiralling around each other until they collide and merge, have been detected via their influence on gravity: their cataclysmic collision produces ripples in space-time known as gravitational waves. Since the first detection in 2015, about 100 of these signals have been detected. Yet despite their abundance, it is not yet known how binary black holes form.

There are two main possibilities. One: merging binary black holes may be the remnants of isolated binary stars, which can only merge within the age of the Universe in specific scenarios. Two: binary black holes assemble during dynamical interactions in densely-populated environments, like the cores of star clusters. Dynamical formation, which can cause significant orbital eccentricity and/or spin-induced precession of the orbital plane, should leave its mark on the gravitational-wave signal. However, conventional signal models do not include the effects of dynamical formation.

In this project, we will produce and study mock gravitational-wave data. We will create data using the Python-based Bayesian inference software library Bilby, and will assume instrument noise consistent with current sensitivity of the LIGO detectors. We will inject signals containing the influences of dynamical formation, and analyse the data with signal models that ignore these effects. By subtracting the wrong model from the data and studying the residuals, we will establish how strong the effects of dynamical formation must be to leave characteristic traces in the residuals. We will look for patterns and correlations between the strength of the effect and the characteristics of the residuals. This project requires some experience with Python and UNIX shells.

Related reading

When models fail: An introduction to posterior predictive checks and model misspecification in gravitational-wave astronomy - I. M. Romero-Shaw, E. Thrane, P. D. Lasky [https://ui.adsabs.harvard.edu/abs/2022PASA...39...25R/abstract]

Binary black hole mergers: formation and populations - M. Mapelli [https://ui.adsabs.harvard.edu/abs/2020FrASS...7...38M/abstract]

Eccentricity, spin, and the origins of colliding black holes - S. Kohler [https://aasnova.org/2020/11/06/eccentricity-spin-and-the-origins-of-colliding-black-holes/]

3) Title: Novel method for time-delay cosmography: Harnessing the power of lensed supernova spectra

Supervisor: Dr. Suhail Dhawan

The Hubble tension is arguably one of the biggest problems in modern cosmology. Strongly lensed supernovae (LSNe) are an excellent probe of the Hubble constant (H0) and hence, an important route to resolve this tension. Measuring H0 from LSNe requires two main ingredients, a model for the deflector galaxy and a robust time-delay.

Conventionally, SN time delays are measured using a time evolution of the flux, i.e. from their lightcurves. A new channel to measure time delays is from the spectra of the SNe. Since SN SEDs and their evolution are well-understood, the spectra are a powerful measure of the phase of the SN and hence, the time delay. This has the additional benefit of requiring only a single epoch of observations to get a robust time delay. It has been demonstrated as a viability technique with observations of iPTF16geu and a suite of models for core collapse (CC) SNe.

In this project, the student will analyse high-quality spectroscopic data for SNe discovered in wide-field surveys like the Zwicky Transient Facility. ZTF has assemble a large, homogeneously characterised sample of both thermonuclear and CC SNe. The aim of the project will be to quantify how well can spectroscopic phases be measured using both template fitting techniques, e.g. SNID and the velocity evolution of the individual spectral features. Refining this technique will be a very important component in reducing the final error budget in H0 inference.

Skills required: Prior experience with python will be useful. Some prior experience with time series data while desirable is not mandatory.

References:

1. Johansson et al. 2021, MNRAS, 502, 510
2. Bayer et al. 2021, A&A, 653, 29
3. Blondin & Tonry, 2007, ApJ, 666, 1024
4. Piro & Nakar, 2014, A&A, 784, 85

4) Title: Constraining Cosmic Chronology with HERA

Supervisor: Thomas Gessey-Jones & Anastasia Fialkov

The Hydrogen Epoch of Reionization Array (HERA) [1] is a radio interferometer designed to probe the universe between the formation of the first stars and reionization (about 100 million to 1 billion years after the big bang). It aims to do this by detecting the emission or absorption from the neutral hydrogen gas that filled the universe at hydrogen's 21-cm spectral line. The detection of this signal has not yet been achieved by HERA, but it has put the best current upper limits on the power spectrum of the 21-cm signal [2], with further improvements expected in the coming years. Already these upper limits from HERA are sufficient for us to start to learn about the properties of the first stars and galaxies in the universe [3].

In this project, you will take the existing parameter constraints from HERA describing the properties of the first stars, and transform them into constraints on when key events happened in the early universe. These events include, when the first stars formed, when the metal-free (Pop III) to metal-containing (Pop II) star transition occurred, and when the universe became fully ionized. This will allow us to reinterpret the HERA results in terms of the chronology of these key events, and hence provide further insight into the enigmatic first billion years of the universe's life. Should time allow the project could be further extended to forecast the constraints that could be achieved from upcoming HERA surveys, and the near-future Square Kilometer Array.

Through this project, you will gain experience working with start-of-the-art cosmological datasets, neural network emulators, and using high-performance computing facilities. Some experience with Python3 is required, a basic knowledge of neural networks would be helpful but is not essential.

References:

1. DeBoer, D., et al. Hydrogen Epoch of Reionization Array (HERA), Publications of the Astronomical Society of the Pacific, Volume 129, Issue 974, pp. 045001 (2017).
2. HERA Collaboration, Improved Constraints on the 21 cm EoR Power Spectrum and the X-Ray Heating of the IGM with HERA Phase I Observations, arXiv:2210.04912.
3. HERA Collaboration, HERA Phase I Limits on the Cosmic 21 cm Signal: Constraints on Astrophysics and Cosmology during the Epoch of Reionization, The Astrophysical Journal, Volume 924, Issue 2, id.51, 30 pp.

5) Title: What can we learn from the JWST not seeing the largest supernovae in the universe?

Supervisor: Thomas Gessey-Jones & Anastasia Fialkov

The JWST has already provided us with a treasure trove of new information about some of the earliest galaxies in the universe [1]. Along with seeing these distant galaxies, the JWST should be able to observe the massive supernovae produced by the larger of the first generation of stars. These metal-free stars form from the primordial gas that is left behind after recombination and are expected to be unusually large and have very different fates from their modern counterparts. Current predictions are that metal-free stars of around 150 solar masses, should end their lives in an incredibly energetic pair-instability supernova (PISNe), in which the star annihilates itself leaving behind no remnant. The resulting explosion is so luminous in the UV range that it has been predicted that JWST should be able to see a few of these explosions, should they occur [3].

So far, to our knowledge, JWST has not detected any PISNe or PISNe candidates. This suggests a few possibilities: Pop III stars are rarer than expected at the epochs JWST can see, Pop III stars are smaller than expected and so do not undergo PISNe, or our understanding of how Pop III stars end their lives is wrong and PISNe do not occur at all. Assuming one of the first two options, we can possibly constrain the abundance of the first generation of stars or their mass distribution from this JWST null detection. In this project, you will start by calculating expected PISNe detection rates from JWST for different star formation histories and mass distributions. Then you will convert these to constraints on the star formation rates and mass distribution given the current null detection. Should these constraints prove substantial this project could be extended to include joint constraints with 21-cm signal measurements.

This project will largely consist of data analysis and so familiarity with statistics and a programming language, ideally, Python3 or MATLAB, will be required for this project.

References:

1. Robertson, B. E., et al. Discovery and properties of the earliest galaxies with confirmed distances. arXiv:2212.04480
2. Lazar, A., and Bromm, V. Probing the initial mass function of the first stars with transients. Monthly Notices of the Royal Astronomical Society, Volume 511, Issue 2, pp.2505-2514.

6) Title: Understanding the properties of host galaxies and haloes of first gravitational wave sources

Supervisors: Dr Anastasia Fialkov (afialkov@ast.cam.ac.uk) and Dr Boyuan Liu (bl527@cam.ac.uk)

Given their unique, massive nature the first generation of stars, the so-called Population III (Pop III) stars, are promising progenitors of binary back hole mergers which are loud gravitational wave sources. Ideally, the 3rd generation gravitational wave detectors (e.g., Einstein Telescope), reaching redshift 10, will be able to detect and identify a few hundred Pop III mergers per year. Understanding the properties of the host systems (galaxies and dark matter haloes) of these mergers is important to guide follow-up observations (in the electromagnetic window), which can also shed light on the properties of Pop III binary stars, high-redshift star clusters and binary black hole evolution at Cosmic Dawn.

In this project, you will analyze the outputs from a state-of-the-art semi-analytical model for early structure/galaxy/star formation, A-SLOTH, to characterize the host galaxies/haloes of Pop III gravitational wave sources as a function of redshift and explore their dependence on underlying physics. We may also evaluate the signatures and detectability of these systems as seen by current and planned telescopes such as the James Webb Space Telescope.

7) Title: Identifying planetary material accreting onto white dwarfs

Supervisors: Dr Laura Rogers and Dr Amy Bonsor

We have now discovered over 5000 exoplanets, but how can we determine their interior composition? Observations of polluted white dwarfs are unique laboratories which can be used to find their bulk composition. White dwarfs are the leftover cores of low to medium mass stars which have ended their life on the main sequence. As white dwarfs are so dense, heavy elements should not be observable in their atmospheres as they quickly sink towards the core. However, ~30% of white dwarfs are observed with heavy elements in their atmosphere, these features have been identified as planetary material. Planetary material which approaches the white dwarf is torn apart, and subsequently falls onto the atmosphere of the white dwarf. From spectroscopic observations of white dwarfs' atmospheres we can discover the composition of the planetary material accreted.

This summer project focuses on these spectroscopic observations of white dwarfs. These observations have the power to reveal absorption features from a plethora of elements that make up the exoplanetary material accreted onto each white dwarf. From these features we can deduce the composition of the exoplanetary material. The project starts by analysing existing low resolution spectra of polluted white dwarfs. These spectra tell us whether or not these white dwarfs have planetary material in their atmosphere, but are unlikely to reveal multiple different elements, as required to tell us the bulk composition. The project will focus on determining the priority targets for follow-up observations scheduled in July. The student will have the opportunity to join remotely for these observations, so they can obtain hands on experience with spectroscopic observations. The student will then start the process of analysing the data during the remainder of their summer project: potentially detecting elements such as Mg, Fe, Si, O, Cr, Ti in the spectra. It should be noted that this project is an observational focused project and the project would require the student to begin on 19th June, as the observations are scheduled for July.

8) Title: Cosmology with unresolved lensed transients

Supervisors: Dr Suhail Dhawan, Prof Vasily Belokurov

The Hubble tension, i.e. the discrepancy between early and late universe inferences of the Hubble constant, is one of the most important open questions in modern cosmology. Lensed transients, e.g. quasars and supernovae are excellent probes of cosmology as they measure the Hubble constant through completely independent methods compared to the conventional local distance ladder. Lensed quasars and supernovae measure distances from difference in the arrival time between the multiple images of the lensed source. Modern transient surveys like the Zwicky Transient Facility and the imminently online Rubin Observatory have found / will find hundreds to thousands of such events. The wealth of data can be exploited to obtain robust time-delays for a large sample of objects to infer cosmology with high precision. While the data from these surveys is densely sampled, the resolution is not optimised to resolve the multiple images of the lensed transient. This is the key gap to be filled by this project. The aim is to develop a software for estimating the time-delays of known lensed quasars and supernovae. Depending on the timeline, the student can also directly apply this to archival ZTF data.

The student will write code to simulate lightcurves for a wide array of lensed transients, e.g. SNe and QSOs. The project will involve analysing the simulated lightcurves to test whether the algorithms in the literature can recover input parameters, e.g. the time-delay.

Ideally, this will be done in python, with simulations either taken from a combination of the time-delay data challenge and generated from software like SNTD (Pierel et al. 2019). If time allows, the student will apply these technique to the real data stream from surveys like ZTF.

Skills required: Familiarity with or motivation to learn time series data analysis would be beneficial, some prior experience with statistics in astronomy.

Desired (though not essential): experience coding with Python and manipulating datasets

Useful references: (List of important papers/review articles relevant to the project)

1. Shu et al. 2021, MNRAS, 502, 2912
2. Bag et al., 2022, ApJ, 927, 191
3. Wong et al. 2020, MNRAS, 498, 1420
4. Denissenya & Linder, 2022, arxiv: 2202.11903

5. Bag et al. 2021, ApJ, 910, 35

9) Title: Modelling the collisional erosion and detectability of exo-Trojan asteroids

Supervisor: Mark Wyatt

Description:

Around 20% of nearby stars are known to host belts of asteroids and comets, detectable from their collisional grinding that creates dust that can be detected at infrared and millimetre wavelengths. Such belts, known as “debris disks”, are a component of the star’s planetary system, and are shaped by dynamical interactions with those planets. For example, most belts are thought to be truncated at their inner edge by interactions similar to those between Neptune and our Kuiper Belt, while warps, clumps and offsets seen in these disks can all be explained as a consequence of dynamical perturbations from planets. The dust in these disks is usually much easier to detect than the planets and these features can be used as a signature of unseen planets.

This project aims to model an as yet unexplored signature of planet-disk interactions, which is dust created between collisions amongst planetesimals trapped in the planet's Trojan swarms. Trojan planetesimals orbit at the Lagrange equilibrium points L4 and L5, resulting in concentrations of planetesimals that orbit 60 degrees in front of and behind the planet. These are a significant feature of the Solar System, with Jupiter’s Trojan points particularly populated. We have yet to identify Trojan swarms around other stars, however the inferred proximity of exoplanets to the known debris disks suggests that such planets would be likely to have their own Trojans, and an ongoing ALMA programme to image debris disks already shows tantalising evidence that this feature has been detected to one system.

This project aims to develop a model for Trojan swarms of asteroids and their collisional destruction that will be used to predict the brightness of these swarms, and to simulate how they would appear in images. The project will start with N-body simulations to follow the dynamical evolution of the Trojan planetesimals. This will then be post-processed to determine the rate at which collisions occur at different points within the swarm. This information will then be coupled to an analytical consideration of the dust produced from which to determine the brightness. Consideration will also be needed for the dynamical evolution of the dust. This will then be used to make simulated images of the dust distribution to consider how the detectability depends on parameters such as planet mass and orbital location.

10) Title: Testing the effective methods to study the dynamics of stars in the Milky Way with missing information

Supervisor: GyuChul Myeong (gyuchul.myeong@cfa.harvard.edu)

Description:

The recent data releases from the Gaia mission has opened a new era for Galactic Archaeology. Gaia's precise astrometry has made it possible for us to study the motions of individual stars in the Milky Way with the scale and details unmatchable to the pre-Gaia time. For millions of stars across the Galaxy, we can now analyse the orbit of individual stars and study the dynamical structure of the Galaxy.

To derive a star's obit in the Galactic frame, we rely on 6-dimensional phase space information which consists of 3-dimensional position and 3-dimensional velocity. We can rely on the observables such as sky coordinates, heliocentric distance, proper motions, and line-of-sight velocity.

Among approximately 1.6 billion Gaia observed sources, Gaia provides complete 6D information for its subset of relatively bright stars as Radial Velocity Spectrograph (RVS) sample. Although this is, by far, the largest catalogue of complete phase space information that has ever became available for us, the majority of Gaia observed stars are still left with incomplete phase space information which limits understanding of the true motion of these larger number of stars. The RVS sample is also biased towards giant stars because they are brighter and easier to observe than main-sequence stars. This means the RVS sample is dominated by a certain type of stars, which can affect the results of stellar population studies that rely on the RVS data.

In this project, we will build effective methods to overcome this limitation and derive the stellar orbit for stars with missing phase space information, which will allow us to utilise the Gaia data beyond its RVS subset.

With good progress made on the project, we will additionally study the dynamical structure of the Milky Way based on the new dataset we constructed from the above method.

11) Title: Galactic Archaeology with ancient chemically peculiar stars

Supervisors: Dr. Anke Arentsen & Dr. Stephanie Monty

Description:

The Milky Way galaxy contains stars of different ages, and the oldest stars still alive today are unique windows into the early Universe. Ancient stars are expected to be metal-poor — they formed from gas that had not yet been enriched by many previous generations. Many very metal-poor stars share a peculiar characteristic: they are strongly enhanced in carbon. Based on their detailed chemical compositions, we can separate carbon-enhanced metal-poor (CEMP) stars into two main categories: those that were born out of carbon-enhanced gas enriched by the First Stars, and those that became carbon-rich later in life due to interaction with a binary companion.

Most searches for metal-poor stars have been focussed on the Galactic halo, but recently the search has been extended to the very heart of our Galaxy: the Galactic bulge. This is the part of the Milky Way that assembled first and we expect to find the most ancient stars here, but it is challenging to study due to dust extinction and a high density of metal-rich stars. The efficient Pristine Inner Galaxy Survey (PIGS) is the largest survey of metal-poor stars in the Milky Way bulge region, and produced the first large sample of CEMP stars in the inner Galaxy (Arentsen et al. 2021). To better understand the nature of these CEMP stars, we performed dedicated spectroscopic follow-up with the X-shooter instrument on the VLT.

The project consists of analysing the X-shooter spectra for CEMP stars in PIGS and interpreting the results in the context of the different CEMP formation scenarios. These spectra have not yet been analysed by anyone else. The student would work on determining their stellar parameters (effective temperature, surface gravity, metallicity) and would derive chemical compositions by measuring the absorption lines in the spectra. If there is more time in the project, it could also include a dynamical analysis of these stars in the Milky Way.

This is a data analysis project. Some prior knowledge about stars would be useful. Experience with spectroscopy is an advantage but not a must.

Useful references:

- Arentsen et al. — The Pristine Inner Galaxy Survey (PIGS) III: carbon-enhanced metal-poor stars in the bulge, 2021, MNRAS, 505, 1239
- Frebel & Norris — Near-Field Cosmology with Extremely Metal-Poor Stars, 2015, ARA&A, 53, 631 (review paper)