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Session R Abstracts

Precision light control and tracking for high-resolution infrared spectroscopy at the diffraction limit with Keck-HISPEC
Yann C. Terrien
Mentors: Dimitri P. Mawet, Ashley Baker, and Nemanja Jovanovic

The High-resolution Infrared SPectrograph for Exoplanet Characterization (HISPEC) is a future instrument for the Keck II telescope, designed to perform precise observations of exoplanets by capturing infrared light at extremely high spectral resolution. A critical subsystem of this instrument is the front-end instrument, which prepares and stabilizes the incoming starlight before it reaches the spectrographs. The front-end system combines real-time beam alignment, image stabilization, and atmospheric dispersion correction to ensure efficient light transmission. It splits the light into two paths optimized for different infrared bands and actively maintains the alignment using a dedicated tracking camera and fast correction optics. To limit thermal noise and improve sensitivity, the tracking detector and associated optics are cryogenically cooled. Recent work has concentrated on optimizing alignment and validating optical performance.

The design was finalized in 2024, and the instrument is now undergoing full-scale development, with initial operations anticipated in 2026.

Implementation of a control algorithm for a tip-tilt mirror for beam jitter correction
Ariana M. Pearson
Mentors: Dimitri P. Mawet and Susan Redmond

The High Contrast High-Resolution Spectroscopy for Segmented Telescopes Testbed (HCST) tests and develops hardware and technology for exoplanet detection using direct imaging techniques. The testbed can currently reach a dark hole contrast of 1E-8, but beam jitter caused by room vibrations degrades the coronagraph's performance and can diminish the contrast attained. By taking the reflection of the beam off the focal plane mask and redirecting it to a designated camera, a control algorithm loop will be developed for a tip-tilt mirror to correct for beam jitter. The algorithm, written in Python, is service-based and will use a PID controller. This implementation is expected to increase the testbed's run efficiency and will allow for continued technology development.

Refined characterization of brown dwarf binary Gliese 229B with sika
Sage J. Santomenna
Mentors: Dimitri P. Mawet and Jerry Xuan

Recent research has demonstrated that the brown dwarf system Gliese 229B is an extremely close binary orbiting at a separation of just 0.042 AU, a discovery that gives us an opportunity to study the dynamics of a class of stellar systems that are just beginning to be detectable with high-resolution spectroscopy. In this work we first detail the development of sika, a flexible modeling framework that allows us to efficiently and reproducibly fit complex models to astronomical data. We then use sika to refine our characterization of the Gliese 229B system using new high-resolution spectroscopic observations.

Enhancing binary black hole simulations through adaptive mesh refinement
Hannah Röttgen
Mentors: Saul A. Teukolsky, Mark A. Scheel, and Nils Vu

Accurate simulations of binary black hole mergers are crucial for understanding gravitational waves. As detectors become more sensitive, the need for higher-precision numerical relativity simulations grows. My project contributes to the development of such simulations within the SpECTRE code, which uses discontinuous Galerkin methods to achieve high resolution and scalability. A key feature of this method is adaptive mesh refinement (AMR), which adjusts the simulation's resolution based on local accuracy needs. My work focuses on improving the refinement criteria that guide this process and integrate them into binary black hole simulations using the SpECTRE code. I began by analyzing diagnostic tools such as truncation errors and convergence rates in both scalar wave and binary black hole simulations. After identifying limitations in the current refinement approach, I implemented and tested new strategies, starting with simpler scalar wave cases. I will apply these strategies to binary black hole simulations, aiming to improve accuracy and efficiency while maintaining reasonable computational cost. The results will inform future refinement techniques used in high-precision gravitational wave modeling.

Modeling core-collapse supernovae beyond shock breakout
Maria F. Gonzalez
Mentors: David Vartanyan, James W. Fuller, and Daichi Tsuna

Core-collapse supernovae (CCSNe) shape galactic evolution, form neutron stars and black holes, and disperse alpha-capture elements up to, and beyond, the iron peak. Current observations reveal strong asymmetries in supernova morphology whose origins remain unclear. Further investigation requires three-dimensional simulations, which are critical for modeling the chemical and dynamic properties of CCSNe. We conduct a case study using three-dimensional hydrodynamic simulations to examine how parametrically evolved profiles of circumstellar material (CSM)— the host environment of a star— affect late-time observed properties of CCSNe. We model CSM with constant, power-law, and hybrid density profiles and varying masses for a 17-$M_{\odot}$ progenitor. Our simulations begin ~1 day post-explosion and follow shock evolution through the CSM over timescales of days to weeks. Increasing the CSM mass by a factor of 10 delays the shock's outward progression by ~3-4 days. While differences in morphology are dependent on constant and power-law density profiles, they are not as prominent. This study underscores the impact that the CSM of progenitors may have on CCSNe and their observed asymmetries. Future work may synthesize light curves as the explosion propagates through the CSM.

Realistic baryon-ejection from the recoil of magnetar giant flares
Ruimian Zheng
Mentors: Elias R. Most and Yuan Feng

Giant Flares (GFs) are the most energetic transient outbursts from Magnetars. Recent models predict baryon-ejection from the "recoil force" of the GFs to explain the GF radio rebrightening and identify the potential for r-process. We performed GRMHD simulations using AthenaK to localize the shock and observe the ablation of the crust at various initial conditions. By varying the equation of state, we probe different regimes of the neutron star crust. We systematically quantify the mass ejection and its nuclear composition.

Spectral-motivated grid refinement criterion for GRMHD simulations
Sam W. Solod
Mentors: Elias R. Most, Nils Vu, and Yoonsoo Kim

Numerical simulations of astrophysical flows around compact objects such as black holes demand high accuracy in regions of sharp gradients, turbulence, and discontinuities, while also requiring computational efficiency over large domains. Adaptive mesh refinement (AMR) offers a powerful tool to achieve this balance, but the success of AMR hinges on the quality of refinement and de-refinement criteria. In this work, we explore a grid refinement strategy inspired by spectral methods, applying a criterion based on modal coefficients, originally developed for discontinuous Galerkin codes, to a finite volume framework. We implement this method in the GPU-parallelized code AthenaK and evaluate its effectiveness on a number of problems that test the numerical accuracy and efficiency of the method. We find that the criterion can effectively track discontinuities without over refining smooth regions while nicely coarsening grid structure over smooth regions. This approach has promising applications to general relativistic magneto-hydrodynamic (GRMHD) simulations of accretion flows and jet launching, where capturing small scale physics as well as computational efficiency is crucial. This work takes a step towards a physically informed refinement strategy that could enable faster and more accurate simulations of extreme astrophysical phenomena.

A reaction network for probing strangeness equilibration in neutron star mergers
Melvin Storbacka
Mentors: Elias R. Most and Jiaxi Wu

One of the main goals of gravitational astrophysics is to constrain the equation of state (EoS) of neutron stars. For EoSs including strange matter, the high densities and temperatures during a neutron-star merger are associated with the emergence of large amounts of strange matter. However, depending on the equilibration timescale of strange matter, the merger could drive the system out of equilibrium, which in turn could affect the dynamics of the merger. Therefore, quantifying equilibration timescales is important for determining whether future merger simulations should include strangeness out-of-equilibrium effects.

To this end, we develop a reaction network for solving the time evolution of the number densities of an arbitrary number of included particle species and reactions. The network couples to a chiral mean field EoS and can be used with time-dependent trajectories from astrophysical simulations. This network will enable post-processing of neutron-star merger simulations for analysis of strange equilibration.

Investigating the optical variability in BAL and non-BAL quasars as a parametrizing factor for BAL classification
Josie C. Carrillo
Mentor: Matthew J. Graham

Broad Absorption Line (BAL) Quasars or Quasi-Stellar Objects (QSOs) are a subclass of active galactic nuclei (AGN) distinguished by high-velocity outflows observable through blueshifted absorption features in their spectra. While these objects are spectroscopically well-studied, their optical variability characteristics remain mostly unexplored. There have been individual examples of BAL Quasars showing extreme variability (\cite{Stern_2017}). This project presents an initial investigation into the variability of BAL quasars compared to a matched sample of non-BAL quasars. We plan to apply a range of statistical variability metrics to quantify and compare across both populations. We also explore the potential of using machine learning models to classify BAL quasars based on their variability. This work aims to assess whether BAL quasars exhibit unique variability signatures that could create a new identification method in future large-scale surveys. These results will contribute valuable insight into the behavior of AGNs and inform the development of a variability-based classification system.

Investigating Changing-Look AGN subpopulations with unsupervised machine learning techniques
Sufia Birmingham
Mentor: Matthew J. Graham

Changing-Look Active Galactic Nuclei (CLAGN) are a rare subset of AGN that exhibit dramatic changes in the flux of their broad Balmer emission lines, accompanied by strong photometric variability. There are about 1500 confirmed CLAGN to date; this population is almost certainly heterogeneous. We investigate whether differences among CLAGN arise from natural internal variations within a population, or are indicative of distinct CLAGN subgroups that have different underlying physical mechanisms. We construct recurrence plots (RP) from the Zwicky Transient Facility light curves of the CLAGN population to capture the dynamical structure of these nonlinear and irregularly-sampled optical time series. We devise a new technique to construct RPs that utilizes the Wasserstein distance. To investigate possible subpopulations of CLAGN, we feed these Wasserstein RPs (WRP) into the t-SNE and UMAP algorithms to perform a high-to-low dimensional projection. We apply DBSCAN to the projected space to identify WRP clusters. Additionally, we train an unsupervised Siamese neural network on augmented images of our WRPs, and apply DBSCAN to the learned embeddings to identify clusters of CLAGN. We identify clusters of CLAGN which display distinct dynamical behavior, suggesting the existence of subpopulations of CLAGN driven by different underlying physical mechanisms.