Dear Harvard Students,

The Center for Astrophysics | Harvard and Smithsonian (CfA, http://www.cfa.harvard.edu/), located at 60 Garden Street opposite the Quadrangle, is one of the world's great centers for research in astrophysics, with over 300 scientists and access to powerful astronomical observatories worldwide and in space. The following is a partial list of CfA research opportunities for undergraduates. I encourage students to contact these scientists directly to inquire about these opportunities. In addition, you should feel free to reach out to any SAO scientist and faculty (some of which are listed here: https://astronomy.fas.harvard.edu/book/astrophysics-advisors) and inquire if they or someone in their group are interested in advising you — not all prospective undergraduate research advisors put down a project in this document.

In addition to a project description, some of the research advisors have indicated within which framework (e.g. senior thesis, paid semester work, summer research internship) that their research project can be carried out, as well as recommended prerequisites. I want to make two comments on this. First, if you identify a research project that you would like to pursue as a paid position during the semester, but the advisor does not have resources to support this financially, please reach out to me. We have some limited departmental resources set apart for students eligible for work-study as well as those with commensurate financial need (regardless of citizenship) who want to do astronomy research. For the summer there are many opportunities to apply for your own funding to carry out a research project (https://astronomy.fas.harvard.edu/research-opportunities-undergraduates). Second, remember that the recommended prerequisites are *recommended,* i.e. if you do not have them I would still encourage you to reach out to the advisor if you find a project you are really excited about.

Finally, Harvard has several programs to provide support for student research, described at: http://uraf.harvard.edu/ We also provide a list of useful links for internal and external undergraduate research programs here: https://astronomy.fas.harvard.edu/research-opportunities-undergraduates

If you have questions about getting involved in research at the CfA, please do not hesitate to contact me.

Charles Alcock, Director of Undergraduate Studies, Department of Astronomy

Villar Time Domain Group

Advisor: Prof. Ashley Villar (ashleyvillar@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY 91R), Paid semester work for work-study eligible students

The Villar Time Domain Group works at the intersection of high-energy observational astrophysics and machine learning. We are excited to work with undergraduates on projects which broadly focus on supernova science in the era of Big Data. Currently, the following projects are available to students:

1. Observational studies of core-collapse supernovae with the Young Supernova Experiment. Recently, our team has released a large sample of ~2,000 new supernova light curves. A variety of projects are available to explore this dataset, depending on student interests.
2. Development of specialized machine learning-based filters for transient follow-up. With thousands of cosmic explosions discovered annually, our group aims to rapidly tag exciting events for follow-up. A number of projects are available to aid in the discovery of rare events, focusing on the development of neural network-based, rapid classification algorithms.

Experience in Python is required for these projects.

Mapping the Milky Way and its Youngest Stars

Advisor: Dr. Catherine Zucker (catherine.zucker@cfa.harvard.edu)

Open for Ay98, Ay99, or summer work

My research focuses on generating new models of the Milky Way's young stars, gas, and dust, with the goal of generating physically motivated connections between star formation and the broader galactic environment. To do this, I probe the 3D structural and dynamical state of the interstellar medium by combining data visualization and data science with observational space- and ground-based datasets taken across the electromagnetic spectrum. Some of the key questions I am interested in are how molecular clouds (the sites of star formation in galaxies) form and evolve, how feedback from supernovae shapes the structure of the interstellar medium and its newly forming stars, and how young stars leave their birth places in molecular clouds and dissolve into the galactic field. To answer these questions, I often utilize synthetic observations of numerical simulations (of both individual molecular clouds and Milky Way-like galaxies at large) to understand how various physical processes (feedback, galactic dynamics, etc.) shape what we see in our own home Galaxy.

I have a broad range of projects that students could work on related to these topics, which can be tailored to a student's interests and background. See tinyurl.com/local-bubble-stars or tinyurl.com/radwave for some examples of the type of science that I do. I'd be happy to chat further with any interested student about potential projects!

These projects have no prerequisites and are open to all undergraduates.

Observing Exoplanets

Advisor: Prof. Dave Charbonneau (dcharbonneau@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY 91R), Paid semester work for work-study eligible students, Paid semester work for non-work-study eligible students, Summer research paid by advisor, Summer Research with external stipend

I would welcome working with undergraduate students on a variety of observational or instrumentation projects related to exoplanets. My primary activities are as follows:
(1) The Tierras Observatory is a recently commissioned ultra-precise automated photometer located atop Mt. Hopkins Arizona. Tierras is designed for follow-up of nearby, small stars that host transiting exoplanets, to search for rings, moons, and the presence of additional planets.
(2) The HARPS-N Project is an ultra-stable, high-resolution spectrograph located on the Italian National Galileo Telescope in the Canary Islands. Our international team is gathering data to measure the masses and hence learn something about the composition of small planets.
(3) NASA TESS Mission is scouring the sky to find the nearest transiting exoplanets, which are optimal for characterization. I participate in efforts to confirm and characterize these newly found worlds.
(4) My team is conducting a census of nearby M-dwarfs to deduce their fundamental properties and develop methods to facilitate their characterization. M-dwarfs outnumber Sun-like stars 12:1, and so if they too host habitable planets, then likely the closest and most observationally accessible Earth-like planets orbit M-dwarfs in our census.

Please reach out if any of these projects interest you!

These projects have no prerequisites and are open to all undergraduate students.

Observing Exoplanets: follow-up of TESS objects of interest

Advisors: Dr. Dave Latham (dlatham@cfa.harvard.edu) and group members

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY 91R), Paid semester work for work-study eligible students, Paid semester work for non-work-study eligible students, Summer research paid by advisor, Summer Research with external stipend

My group is actively involved in the confirmation and characterization of exoplanets discovered by photometric surveys for transiting planets. Our main focus now is on follow-up observations of candidate transiting planets identified by NASA's Transiting Exoplanet Survey Satellite (TESS), although we are also still working on interesting candidates from NASA's Kepler and K2 missions.

We use KeplerCam on the 1.2-m telescope at SAO's Whipple Observatory, for high-quality light curves of transit events, and the Tillinghast Reflector Echelle Spectrograph on the 1.5-m telescope, also on Mount Hopkins, both for spectroscopic determinations of host star parameters and for orbital solutions and mass determinations for giant planets. This is an opportunity to learn about astronomical photometry and/or spectroscopy while working to follow up recently discovered TESS Objects of Interest.

We also have guaranteed access to HARPS-N on the 3.6-m Telescopio Nazionale Galileo located on La Palma in the Canary Islands. This is a state-of-the-art facility for precise radial-velocity observations suitable for measuring masses of small planets.

We are happy to talk to any interested students about possible projects.

This project has no prerequisites and is open to all undergraduate students.

Searching for Planets and Flares at X-ray Wavelengths

Open for Ay98, Ay99, or summer paid work

Advisor: Dr. Rosanne Di Stefano (rdistefano@cfa.harvard.edu)

During the past several years, my group has been studying the short-time-scale behaviour of X-ray sources across the sky. These explorations represent the first systematic mining of scientifically rich data sets, and has led to the first discovery of a candidate planet in an external galaxy. Ongoing research is finding more candidates as well as high-energy flares due to a range of physical phenomena, possibly including gravitational lensing.

Students who join these efforts will be able to participate in the analysis of a range of data sets and discover and study diverse phenomena. Theoretically-minded students can model binary, triple, and planetary systems with the aim of understanding the discovered phenomena and potentially making new predictions. Whatever their choice of specific project, students will start with a foundation built largely by student efforts during the past year, and will also have a chance to work with others.

Cosmological large-scale structure and galaxy formation

Advisor: Daniel Eisenstein (deisenstein@cfa.harvard.edu)

Open for Ay98, Ay99, or summer work

My group focuses on the study of large-scale structure in the Universe, combining observation, theoretical, and computational methods. The large-scale clustering of galaxies results from tiny imperfections in the early moments of the Big Bang, which then grow in contrast due to gravity. The clustering reflects the role of dark matter and dark energy. Modern surveys make beautiful maps of multi-Gpc volumes of the Universe and then generate statistical measurements of the clustering to compare to the results of analytic perturbation theories and cosmological simulations.

Observationally, my focus is on the Dark Energy Spectroscopic Instrument, a major new facility now operating at Kitt Peak National Observatory in Arizona. DESI has already collected over 15 million spectroscopic redshifts in its first year of operation. The coming year will be a key period for the analyses of the initial maps.

Theoretically, I consider new ways to use the data, for example using cross-correlations and improved statistical methodologies, including applications of machine learning to cosmology.

Numerically, my group has produced a vast set of cosmological N-body simulations, named AbacusSummit, with nearly 60 trillion particles, 97 separate cosmologies, and 2 PB of data products. This provides a testing ground for new methods and generation of mock catalogs for DESI. Students interested in high-performance computing and data processing could get involved with this massive data set.

Separately, my group is active in the James Webb Space Telescope (JWST) Advanced Deep Extragalactic Survey (JADES), which will be observing this fall to produce super-deep imaging and spectroscopy of faint galaxies, particularly at $z>3$. In the coming academic year, we will be working on the initial reductions and analyses of this data set!

I would be happy to discuss student projects on any of these topics.

Generating Images of the Interstellar Medium with Non-Gaussianity

Advisor: Prof. Doug Finkbeiner (dfinkbeiner@cfa.harvard.edu), Andrew Saydjari (andrew.saydjari@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99)

Project Description: The complex interplay of magnetohydrodynamics, gravity, and turbulence in the interstellar medium (ISM) introduces "non-Gaussian" structure that is beautiful and diverse, but difficult to describe with concise statistics. Recent work in our group has enabled synthetic image generation with some degree of non-Gaussianity using a form of conditional Gaussian Process Regression (https://arxiv.org/abs/2201.07246). This project would aim to quantitatively measure and describe the non-Gaussianity in these synthetic images using summary statistics such as the Wavelet Scattering Transform (https://arxiv.org/abs/2010.11963).

Students can expect to gain exposure to high performance computing, "classical" machine learning, and statistical image analysis. Project focus and extensions will cater to student interest in astronomy, math/statistics, and/or computer science. Please reach out if you are interested and want to discuss/learn more!

Recommended prerequisites: This project was constructed with (rising) junior and senior students in mind. Some basic coding experience (python or otherwise) is required.

Advisor: Edo Berger (eberger@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), and all other semester or summer research opportunities

My group carries out observational work in time-domain and gravitational-wave astrophysics, including work on supernovae, gamma-ray bursts, and mergers of compact object binaries (black holes and neutron stars). We additionally develop and utilize machine learning based approaches in these studies, including the development of target selection for the upcoming Vera C. Rubin Observatory/LSST, as well as the development of deep learning based algorithms for gravitational wave data analysis. Projects include the use of optical, radio, millimeter, and X-ray data.

Mapping the Connection Between Supernovae and Molecular Clouds

Advisors: Michael Foley (michael.foley@cfa.harvard.edu), Eric Koch, Sarah Jeffreson

Open for Summer research paid by advisor, Summer Research with external stipend

The stars in our Galaxy and beyond are formed within the cold, dense gas of giant molecular clouds (GMCs). As such, the drivers of GMC evolution play a key role in setting the global star formation rates of galaxies, and in dictating the course of galaxy evolution.

In recent years, high-resolution three-dimensional observations of nearby gas and dust have revealed that the GMCs and young stars closest to our Sun are arranged on the surfaces of hot, ionized supernova-driven bubbles in the surrounding interstellar gas. These results imply that the expansion of such "superbubble" may trigger GMC formation (and thus star formation) via the compression of gas at their edges. But as yet, there has been no study of the global impact of superbubbles on GMC evolution across varied galactic environments. In other words, we are not yet sure how important superbubbles are for driving star formation on galactic scales.

In this project, the student will address this gap in our understanding of star formation by analyzing a large sample of observed superbubbles and GMCs at high resolution from galaxies within our Local Group, and matching these with a set of three-dimensional, time-evolving simulated superbubbles. As such, the student will address the key open questions of (1) how does the fraction of GMC mass formed via positive feedback vary with the galactic environment? And (2) How does this process influence the galactic star formation rate?

Prerequisites: We emphasize that there are no prerequisites or experience requirements for this project. We are looking for students who are keen to get started with astronomy research by answering these open questions (1) and (2). This project is very likely to produce a result that is of substantial interest to the astronomical community, as any constraint on the impact of superbubbles is both novel and informative.

Cosmic Microwave Background Instrumentation

Advisors: Prof. John Kovac (jmkovac@cfa.harvard.edu), for some projects in combination with Dr. Clara Verges (clara.verges@cfa.harvard.edu) or other senior group members.

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY91R), Paid semester work for work-study eligible students, Paid semester work for non-work-study eligible students, Summer research paid by advisor, Summer Research with external stipend

The Kovac Group's Cosmic Microwave Background (CMB) Lab at the CfA works to design, build, operate, and analyze data from some of the most sensitive microwave telescopes ever built, currently including BICEP3, the BICEP Array, the 10m South Pole Telescope, and instruments of the large CMB-Stage 4 project currently under delopment. Our telescopes observe the CMB from the South Pole, searching for signatures of Inflation that may be imprinted as a specific pattern of polarization in the CMB, while also using the maps we make to study gravitational lensing, dark matter, and our own galaxy. This year, we are gearing up for another season at the South Pole, while running a full testing programs of new microwave optics technologies and cryogenic telescope systems here at Harvard.

We have current projects potentially suited to committed undergraduates ranging from design, development, construction, and testing of optics and calibration instrumentation for CMB telescopes operating at the South Pole to analysis of data returned by these telescopes to constrain inflationary observables and simulation of CMB lensing observations. Our group is also focused on analysis of calibration data from these telescopes, and exploring new analysis techniques to mitigate systematic effects that can be applied to current and future datasets. Projects in these areas offer opportunities to directly improve the design and performance of some of the world's leading current and planned cosmology experiments. Visit the group website (https://www.google.com/url?q=http://www.cfa.harvard.edu/CMB/&source=gmail-imap&ust=1659137672000000&usg=AOvVaw1mBVuFGJkZB3wC9vfQkEYk) to see a little more about what we do or contact us to come by and check out what is going on in the lab.

Grindlay Research Group Projects

Advisor: Josh Grindlay (jgrindlay@cfa.harvard.edu) and group members

Projects for Ay98 or Ay99

1. GRB-ML Research Project:

Advisor: Jonathan (Josh) Grindlay (Robert Treat Paine Professor of Astronomy), Dr. Branden Allen and Dr. Jae Sub Hong

Deriving a large "Training Set" of the 2 types of Gamma-Ray Burst (GRB) with measured redshift for ~500 Long Gamma-Ray Bursts (LGRBs), produced by core collapse to a black hole (BH) of a spinning massive star that produces a relativistic Jet) and ~200 Short GRBs (SGRBs, produced by mergers of a binary neutron star (NS-NS) or a NS-BH binary) to enable Machine Learning (ML) to test if they can be correctly classified by 2 new parameters and not just the simple GRB duration for 90% of flux (T90), with SGRBs defined as T90 <;=2 sec used since 1992. The 2 new parameters are the peak energy (**Ep**) of the GRB and the isotropic total energy (**E**iso) and "**H**ardness" ratio (spectral ratio of high energy gamma-rays/soft gamma-rays in the burst) combined as **EH** (Eq. 2). This can be derived from the spectra of GRBs (with measured z for each burst) by using reported spectral fits, usually a simple power law, but we shall fit with a "Band function" (originally derived by a former grad student of mine, David Band) that is more sensitive. You will start this project by reading 2 papers arXiv:2008.12752 and arXiv:1912.09810 . The first paper presents a new GRB classification scheme to properly define SGRBs (Type I) from LGRBs (Type II) using the EH (Eq. 2) and intrinsic T90 (both in rest frame), T90i, parameters for 275 Type II's and 45 Type I's. This is a promising new approach that would allow GRB redshifts to be estimated by the burst spectrum and duration. If this can be "proven" by using an independent and much LARGER sample of GRBs than the 45 SGRBs and 275 LGRBs, used by the 2 authors, this will be a major result. A much larger "Training Set" is required to demonstrate the validity of this new approach. Work with us this Fall and next year!

If this can be confirmed and strengthened, it will be a major part of a NASA proposal we plan to submit in July 2025 for the next Small Explorer, SMEX, mission: the High-resolution SmallSat Extremes Explorer (***HSEE***) with novel GRB X-ray/Gamma-ray telescopes on 2 Small Satellites (SmallSats) in the same Low Earth Orbit but on opposite sides of Earth for continuous full-sky imaging to measure ALL GRBs and ALL high-energy transients (TDAMM). The broad energy band (3 keV – 10 MeV) of this mission could clearly distinguish LGRBs from SGRBs (proper classification) and estimate Type II GRB z values that if >7 could trigger JWST for prompt (~3-5 days) followup for mid-IR spectra of the GRB afterglow to identify the redshift of the first Pop III stars at z >12–15 for the first time.

Requirements: Python coding experience (moderate to advanced); C coding would be very useful but not required

2. Grindlay HSEE Detector Module (HDM) - Lab Testing/Coding Research Project:
Advisor: Josh Grindlay (Robert Treat Paine Professor of Astronomy),
Dr. Branden Allen and Dr. Jae Sub Hong

Over the coming 1.5 year (Sept. 2023 - June 2024) there will be significant testing and development of the large area (1024 cm^2) *HSEE* imaging X-ray detector (3 - 300 keV) that is comprised of 4 x 4 HDM detector arrays, each firmly mounted on the optical bench, for readout and commanding from the Detector Mother Board (DMB) below. The HDM is the 2 x 2 array of Detector Crystal Array (DCA) boards that comprise the basic unit of the 2 x 2 CdZnTe (CZT) detectors, each readout and commanded by the NuSTAR ASIC bonded to each CZT crystal.

This multi-layered detector packaging allows for precision alignment optical bench and the data and power connections to be simplified. Testing of the DCA boards (each with 2 x 2 CZT/ASICs) will begin by Oct. 2023 and HDM testing by Dec. Testing is done first on a lab bench and then with the same module (DCA or HDM) testing in our lab Thermal Vacuum Chamber (TVAC) in our PG08 lab.

HSEE has 2 detector systems. The first is the High Resolution Energetic X-ray Imaging (**HREXI**) detector is the 4 x 4 HDM CZT array that records the X, Y position of the 0.6mm pixel that the photon is incident on for each photon incident on the detector. The X-ray photons (3 – 300 keV) from a cosmic source (GRB, or X-ray persistent but variable X-ray binary, or quasar are imaged for precise source position on sky by the photons having to pass through a Tungsten coded aperture mask. The mask is a random pattern of square holes, for Imaging a continuous (or a short burst). This is done by measuring the distribution of X,Y positions that are detected in the CZT and readout by the NuSTAR ASIC on each CZT detector by cross-correlating the detector X,Y positions of a stream of photons with fixed X, Y positions of the open holes in the mask. Think of this as measuring how the shadow of the closed mask pixels is shifted in X, Y coordinates if the X-ray source is shifted in X, Y position on the sky. It works!

The second detector system on ***HSEE*** is an array of scintillators along each of the 4 sides of the coded mask, which is 80 cm above the CZT detector array. You may have learned about scintillators in a physics lab? If not, we will introduce you. The scintillator is a crystal (10 x 10 x 2cm) of a high-Z (atomic number) element (e.g. CsI = Cesium Iodide, or GAAG) These 4 scintillators are tilted downward from the plane of the Tungsten mask by an amount that allows them to see the high energy X-ray source that the HREXI detector/telescope is pointing at but also to see sources on all 4 sides of the pointing. direction This is designed to be able to detect (from one HSEE telescope on one side of Earth, that telescope can “see” All the sky facing away from Earth. So with 2 HSEE telescopes the ENTIRE sky is continuously monitored for GRBs (or any other transient source). Thus the scintillator arrays are Transient Event Detectors, but since they cover the full sky, they are All SKy Transient Event Detectors or ASKTED, which can then in real-time provide a crude position for HSEE to point (within ~5min) to precisely locate the GRB or transient to within 40 arcsec.

This research project is appropriate for students that want to learn about, and work on detector instrumentation for operation in Space. The boards on which the detectors are mounted are all designed by Dr. Allen and the TVAC chamber (to simulate space vacuum conditions with the thermal systems to keep the CZT temperature constant is largely designed by Dr. Hong. The data handling and processing is a Key part of this project. Readout and commanding of BOTH the HREXI and ASKTED detectors must be continuous and coordinated.

3. Grindlay DASCH software development for improved photometry of fading transients BH-LMXBs and AGN/Blazars vs. bright targets (e.g. SNe)

Advisor: Josh Grindlay (Robert Treat Paine Professor of Astronomy),
Dr. Peter Williams (Chief Software Engineer for DASCH), Dr. Thom Burns (Acting Curator of the Harvard Plates)

The Digital Access to the Sky Century @ Harvard (*DASCH*) project, initiated by our first proposal to NSF for the world's fastest, most accurate, glass plate scanner for ~500,000 glass plate images at the HCO of the entire sky (both northern and southern), is expected to complete scanning and data processing by December 2023. Intensive analysis of the data has revealed two small defects in the photometry that can be improved for both the analysis of the full (or any part of) the entire database. First, "non-detections" of objects near the Limiting magnitude (plotted for each detected image) are not being properly registered as clear visual indications of image detection are not being recognized. And on the opposite end of the brightness scale, photometry saturated stellar images can be still measured by an image diameter vs. magnitude calibration (which is what the famed Women Astronomers at Harvard did to derive ALL stellar magnitudes) can and should be done, which should be straight forward. The challenge is when to make the transition from digitized "blackness" of the stellar image negative to a saturated image diameter measurement of a bright star. I (JG) found these defects in our processing by examining many new detections of both faint fading transients and bright enormous flares (SN1987A).

When scanning and data processing is complete for DASCH, there are other new science projects that can be started for DASCH and the priceless data:
1) observe calibration stars (bright, B = 8-14 used for calibration standards and thus NON-variables, for their measured magnitude vs. elevation above the horizon to measure long term (decades to century) variations due to increased dust/smoke or Climate Change effects for the 106-year span of the Harvard Plates. A Colleague in the EPS Department strongly encouraged that this should be done when I described it. This could be done over a 1 - 2 year period to include seasonal variations (apart from distant forest fires).
2) Develop image subtraction techniques to greatly improve DASCH for crowded fields. This is not a simple as with CCD detectors which are linear in response to increasing flux. Astronomical plate images have logarithmic response and can likely be improved with "background" stars and diffuse emission in a DASCH digitized image can be measured in a higher resolution digital image (e.g. digitized Palomar plates, which will be scanned by DASCH after HCO plates are finished).

Searching for Extraterrestrial Technological Objects

Advisor: Prof. Avi Loeb, Head of the Galileo Project (and research team members) (aloeb@cfa.harvard.edu)

The Galileo Project aims to bring the astronomical search for extraterrestrial technological objects near Earth from accidental or anecdotal observations to the mainstream of transparent, validated and systematic scientific research. This project is complementary to traditional SETI, in that it searches for physical objects, and not electromagnetic signals from distant sources.

Having designed and assembled a suite of instrumentation that will detect, track and characterize aerial objects, we are now entering the next phase of the project. In this phase, we intend to get new data from instrumentation, software, and AI models, refine our working observatory and start making copies.

With this new phase come new opportunities. We are therefore seeking talented individuals to join our diverse team of scientists, engineers, and support staff. There are a range of sub-projects to work on, including the analysis of satellite data for anomalies, object detection and classification, and passive radar.

Individuals at any level (including junior or senior thesis) are welcome to apply, but we are particularly interested in hearing from individuals with interests in physics and astronomy and any of the following skills:

- Programming (Python, C/C++, Java)
- Data analysis (images, video, audio, timeseries)
- Machine Learning (building, training and evaluating models)
- Instrumentation
- Computer vision

Successful applicants should have strong problem-solving skills, can work both alone and in a team environment, be good communicators and most of all: enjoy exciting challenges.

Further reading:
https://arxiv.org/pdf/2209.02479.pdf

Characterizing atmospheric turbulence above the Magellan Telescopes

Advisor: Brian McLeod (bmcleod@cfa.harvard.edu)

Open for: Senior thesis

The goal of this instrumentation project is to characterize the atmospheric turbulence at Magellan to determine what fraction of the atmospheric seeing could potentially be corrected in the future with a ground layer adaptive optics system. The student will be involved in assembling and testing the optics of a Shack-Hartmann wavefront sensor before it is installed at Las Campanas Observatory, writing and testing the software to collect and process the data, and analyzing the results. No instrumentation experience is needed, but a knowledge of Python is.

Astrochemistry and Planet Formation

Advisor: Prof. Karin Öberg (koberg@cfa.harvard.edu), Alexia Simon and other group members

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY 91R), Paid semester work for work-study eligible students, Paid semester work for non-work-study eligible students, Summer research paid by advisor, Summer Research with external stipend

Star and planet forming regions present a rich chemistry, which regulates which kind of planets are formed where, including the likelihood delivering prebiotic material to rocky planets. Molecules can also be used to trace the star and planet formation process through observations of molecular lines that are sensitive to e.g. the details of the radiation fields, temperature and density profiles. In the astrochemistry group we combine laboratory experiments and radio observations of protostars and planet-forming disks to characterize this often exotic chemistry that results in the formation of molecular probes and prebiotic molecules. Undergraduate projects are available in the areas of spatially resolved molecular line observations ('astrochemical imaging') of different astronomical objects, interpretation of radio astrochemical spectra, and in laboratory astrochemistry, exploring the physics and chemistry of interstellar ices. If this seems fascinating to you, please reach out — I am always happy to meet with interested students.

One particular project that we would be excited to pursue this fall is a laboratory investigation into the entrapment of volatiles in ices, when there are multiple volatiles that can compete for good entrapment spots. This is directly relevant for predicting the composition of ices in protoplanetary disks at different distances from the star, and therefore to the composition of planets and planetesimals that assemble in the disk.

These projects are open to undergraduate students at all levels.

Laboratory Characterization of Benzene and Benzene Derivatives Ices

Advisor: Dr. Elettra Piacentino (elettra.piacentino@cfa.harvard.edu) and Prof. Karin Öberg

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester Research for Credit (AY 91R), Paid semester work for work-study eligible students, Paid semester work for non-work-study eligible students, Summer research paid by advisor, Summer Research with external stipend

Small aromatic molecules have been found in meteorites samples and benzene and toluene have recently been detected on comet 67P. In the ISM, the detection of small aromatic molecule such as benzonitrile is also very recent. Such molecules were detected in cold and dense molecular cloud with abundances higher than expected. The detection of benzonitrile in the ISM suggests that its parent molecule benzene should be abundant as well and that it may undergo derivatization to form phenol, benzaldehyde, and toluene in addition to benzonitrile.

The broad aim of this project is to study and characterize ices of benzene, toluene, phenol, benzaldehyde, and benzonitrile in the laboratory. The work will be carried out at in the Öberg lab, where the student will be using one of the experimental set ups. These set ups consist of an Ultra High Vacuum (UHV) chamber designed to perform Infrared Spectroscopic (IR) detection and characterization in icy samples. The set-ups also allow for collecting Mass Spectrometry (MS) data of gas-phase molecules during ice desorption.
For this project the student will be preparing benzene ice samples at cryogenic temperature (~10K), followed by a temperature programmed desorption (TPD) experiment. For the whole length of the experiment both IR and MS data will be collected. The collected IR data will be used to determine and characterize the IR signature of the molecule at 10K as well as any changes due to increasing temperature. The MS information will be used to precisely determine the desorption temperature of benzene and its associated physisorption energy.

Dependent on the length of the project, the student project will either focus on the experimental characterization of benzene ices, or if the time allows also on the characterization of ices of functionalized benzene molecules (benzene derivatives).

This work will provide the community with state-of-the-art experimental data on benzene ice (and its derivative) which will be useful for the detection and for the prediction of the chemistry of such molecules in astrochemical environments.

Black holes

Advisor: Dr. Fabio Pacucci (fabio.pacucci@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester research for credit (AY 91R), Summer Research with external stipend

My research focuses on "all things black holes", from local ones to the farthest ever discovered, from the small to the super-massive ones. Overall, my work aims at addressing crucial questions about the nature and demography of black holes, their relevance for gravitational wave events, and ultimately how black holes helped to shape the Universe as we observe it now. With expertise in both theoretical modeling and observations, I developed some of the most advanced growth models for black holes and contributed to the discovery and understanding of the first lensed quasar at redshift higher than 6.

Projects are available in these broad research topics:
1) Formation, cosmological evolution and observational signatures of the first population of black holes formed at redshift higher than 6, a yet undetected and fundamentally important class of black holes.
2) The formation and evolution of high-redshift quasars, the population of farthest and heaviest supermassive black holes ever detected. Why did they grow so fast, and what makes them special?
3) The elusive population of intermediate-mass black holes, nowadays found in dwarf galaxies. Were they remnants of the first population of black holes, or did they form more recently? Also, are there intermediate-mass black holes in the Milky Way galaxy, and how do we find them?

These topics are very timely, given the upcoming commission of new observatories to probe the high-redshift Universe, such as the James Webb Space Telescope, the 30-meter class telescopes, WFIRST, Euclid and, farther in the future, new X-ray and gravitational wave observatories. Theoretical models and simulations are needed now more than ever to: (i) plan new observations, and (ii) interpret the unprecedented amount of high-quality data that current and future facilities will provide. Research projects are always available in the fantastic world of black holes, and I would be glad to meet with interested undergraduates to discuss possible common research interests.

Recommended prerequisites: Basic python coding experience and astronomy knowledge (AY 16 and 17) are recommended, but the project is open to all undergraduate students.

How did the Solar System form and evolve?

Advisor: Dr. Rosemary Pike (rosemary.pike@cfa.harvard.edu)

The outer Solar System beyond Neptune is populated with small, icy objects, which are the remnants of planet formation. These Trans-Neptunian Objects (TNOs) are the least thermally altered bodies in the Solar System, but their orbits have been significantly altered by the migration of the giant planets. The outward migration of Neptune transported many of these objects out to their current locations. These small TNOs have a large variety of orbit types, including some nearly-primordial TNOs and some which have been dynamically excited by Neptune. These dynamically excited objects include TNOs in resonance with Neptune- their orbital periods have an integer ratio with Neptune's orbital period. For example, Pluto is in the 3:2 resonance with Neptune, so it is protected from close encounters with Neptune when it comes to pericenter inward of Neptune's orbit. The characteristics of resonant TNO populations can provide a unique insight into the specifics of Neptune's migration, because different numbers and types of objects are trapped into resonance depending on the mode of Neptune's migration. Our team has recently discovered ~150 objects in the Large inclination Distant Object Survey (LiDO). We are tracking these objects to constrain and classify their orbits.

Possible projects include: determining the color and surface type of TNOs from photometry data in order to constrain their formation location; Measuring the precise position of TNOs in telescope data, determining their orbits, and predicting their orbital classification; N-body simulations of resonant TNO orbits to determine their stability and robust classification, population modeling for TNO sub-populations and testing using a survey simulator.

Asteroid families: a powerful tool to understand our Solar System

Advisor: Dr. Federica Spoto (federica.spoto@cfa.harvard.edu)

Open for Junior Thesis (AY98)
Senior Thesis (AY 99)Summer Research with external stipend

Asteroids are bits of building material remaining from the formation of the Solar System, which means that they have witnessed all the different phases of the formation and evolution of our system. The study of the asteroid population is thus the key to better understand our Solar System and as a consequence also other planetary systems, how the life formed on our planets, how collisions happen in space and how to mitigate hazards given by possible collisions of the so-called Near Earth Asteroids (NEAs) with our planet.

A powerful tool to turn back time and understand what happened during the early phases of the formation of the Solar System is given by asteroid families. These are groups of objects generated by past collisions between asteroids that now shares similar dynamical (or physical properties). My research focus on the identification of the largest number of families and on the computation of the time of their initial collision (or age of the family) to obtain the most accurate chronology of the impacts in the Solar System.

Recent improvements in orbit accuracy (the Gaia mission) and number of objects discovered presented new and exciting challenges in the characterization of asteroid families. Undergraduate projects are available in both areas of identification and characterization of asteroid families: we want to use new machine learning techniques to identify new families or update existing ones, we would like to include physical properties from the Gaia mission into the algorithms of identification of families, and improve methods to compute asteroid family ages using high-precision astrometry.

If all or some of the previous arguments seem fascinating to you, please reach out. I am always to meet interested student and the fields is evolving so quickly that more and more discoveries of asteroids are making the research even more exciting.

Black Holes and 100 kpc Jets: Two Ends of One Phenomena

Advisor: Dan Schwartz (das@cfa.harvard.edu), with participation by collaborators.

Open for Senior Thesis (AY 99),

1. X-ray structure of a supermassive black hole.
Use gravitational lensing to probe milli-arcsec X-ray structure and astrometry in high redshift quasars. Analyze archival Chandra X-ray data of strongly lensed, quadruply-imaged quasars. Many sources have 10 Chandra observations spanning more than 10 years. The student will use existing GAIA or VLBI data to construct a lens mass model and compare the X-ray location(s) to the resulting radio or optical position.

2. Physical parameters of 100 kpc X-ray Jets. Studies of archival Chandra X-ray jets in quasars. These jets are detected on scales of a few arcsec, which correspond to > 10 kpc at the quasar redshift, and are inferred to be at a small angle to our line of sight and thus have de-projected lengths of order 100 kpc. Details of their emission mechanisms and derivation of physical parameters remain to be clarified: Synchrotron emission from Lorentz factor 10^8 electrons, or inverse Compton scattering on the cosmic microwave background from 100 MeV electrons?

Basic python coding experience, and familiarity with Mathematica will be useful and needed, but are not formal prerequisites.

Are you interested not just in astronomy itself but in the tools we use to do modern science? Are you an experienced coder?

Advisor: Dr. Peter Williams (pwilliams@cfa.harvard.edu)

The world deserves excellent technical documents, filled with beautiful equations, abundant cross-references, interactive graphics, and runnable code. And with the digital displays that we use every day, all of these things and more are possible. But most of the documents created by scientists are designed using centuries-old approaches — approaches that assume that a document's "true" form is a bunch of ink printed on little rectangles of dead tree.

Dr. Williams (https://newton.cx/~peter/) is the lead developer of Tectonic (https://tectonic-typesetting.github.io/), an open-source project that aspires transform technical communication for the 21st century. In particular, it aims to bring the power of the venerable TeX typesetting software — still the world's best for authoring demanding technical documents — to the Web. In this project, you will develop the systems that will coax HTML output from the classical TeX engine. You will learn about the guts of TeX (mind-expanding), modern Web technologies (useful!), the Rust language (totally awesome), and open-source software development (noble!). You don't need to believe that you're a programming ninja, but given the time constraints, substantial previous coding experience is required.

Instrumentation Development for Submillimeter Astronomy

Advisors: Dr. Edward Tong (etong@cfa.harvard.edu), Dr. Paul Grimes (pgrimes@cfa.harvard.edu), and Dr. Lingzhen Zeng (lingzhen.zeng@cfa.harvard.edu).

Open for Junior Thesis (AY98), Senior Thesis (AY 99), and Summer research.

Observations at submillimeter wavelengths increase the understanding of the universe from star formation, early galaxies, planets and black holes. The Submillimeter Receiver Lab has a long history of developing instrumentation for the Submillimeter Array (SMA) and other submillimeter telescopes. One of our recent focuses is the wideband SMA upgrade (wSMA) which will significantly improve the throughput of the SMA. We are also working on the instrumentation for the next generation Event Horizon Telescope (ngEHT), Cosmic Microwave Background experiments and future space telescopes. With all these ongoing projects, there is a lot of technical work in our lab to push the frontier of submillimeter instrumentation. Much of our ongoing work is at low temperatures, using superconducting detectors in a cryogenic environment: that is to say, we have a lot of cool stuff going on in our lab.

We have current projects potentially suited to committed undergraduates ranging from design, development, testing, characterization and calibration of submillimeter components and systems. Most of these involve hands-on activities, while others may be linked to creating software control of instruments under development. Part of the lab's mission is to educate the next generation of instrumentation scientists. Regardless of whether you've had any past exposure to instrumentation work, if you are interested in instrumentation development, and you would like to work on such a project, you are welcome to come to visit the lab. We will be happy to show you the different projects we are working on and to discuss potential projects that would suit you.

Examples of past projects:

1. Grant Meiners, "Measuring optical properties of dielectrics at ambient and cryogenic temperatures for use in CMB telescopes," Harvard senior Thesis 2023.
2. Lorenzo Russotto, "Study and Improvement of a 300 GHz Optically controlled silicon attenuator," Freshman Harvard College Research Program Summer Internship, 2022.
3. Beverly Brown, "A Tunable Waveguide Filter for low noise local oscillator module for wSMA receivers," Harvard senior thesis, 2020.

Advisor: Dr. Garrett Keating (garrett.keating@cfa.harvard.edu)

Open for Junior Thesis, Senior Thesis

One area of research is developing systems for correcting for atmosphere effects on interferometers like the Submillimeter Array (SMA). Just like their optical counterparts, radio telescopes are sensitive to fluctuations in the atmosphere, which in most cases limiting the resolution of the instrument or otherwise reduce it's efficacy. I am presently working on a couple of projects in this domain, one of which includes developing models of the atmosphere for a "radio adaptive optics" system -- folding in measurements from ozone radiometry, barometry, and lower-frequency interferometer arrays to correct for these atmospheric fluctuations. I am also working to involve the SMA phased array system, which enables the SMA to act like a large single-dish telescope, used during observations with the Event Horizon Telescope. Students interested either project would analyze data taken from existing measurements and help develop predictive models that could be used with submillimeter interferometers like the SMA.

Separately, I work on a number of efforts -- both observational and theoretical -- related to "intensity mapping", wherein galaxies that are too faint and distant to be detected in aggregate, which can then be used to probe the evolution of these galaxies across cosmic time, as well as the structure of the Universe. Most of my research in this domain is focused on the use of emission lines such as CO and CII, which are used as tracers of the cool gas that helps to fuel star formation. Students interested in either data analysis of current/upcoming experiments, or simulation work to explore futuristic experiments would be welcome.

Prerequisites: Some coding experience (particularly Python, C, or MATLAB) is recommended, but not required.

Bridging Cosmic Scales: An AI Approach to Understanding Star Formation Clustering

Advisors: Dr. Sarah Jeffreson (sarah.jeffreson@cfa.harvard.edu), Dr. Carolina Cuesta-Lazaro (carolina.cuesta-lazaro@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester research for credit (AY 91R), Summer Research with external stipend.

Galactic winds and outflows play a key role in many aspects of galaxy evolution, including the regulation of the star formation rate and the chemical enrichment of the intergalactic medium. As such, any model for the star formation rate of galaxies in cosmological simulations must be coupled to a model for galactic winds, driven by the supernovae from these stars.

Recently, it has been found that the energy and mass-loading of galactic winds depends strongly on the spatial and temporal clustering of supernova explosions in a galaxy. In turn, this star-formation clustering is set by the masses and densities of cold, star-forming 'giant molecular clouds 'on scales much smaller than can be resolved in cosmological simulations. Due to our inability to achieve the required resolution in cosmological simulations, these processes are usually modeled via simple analytical relations known as subgrid models. While an average star formation rate can be predicted in terms of the density or mid-plane pressure, as yet there is no theory for its small-scale distribution. Any such dependence is likely too complex to capture in a simple analytic theory, due to the large number of physical processes (e.g. galactic dynamics, stellar feedback) that may contribute.

Alternatively, we could use AI to learn these relations from accurate simulations of isolated galaxies, which would help us bridge the scale gap between galactic-scale physics and cosmological scales. In this project, we will train normalizing flow models on a set of six high-resolution numerical simulations of galaxies with resolved star formation and molecular clouds, to predict the clustering of star formation, stellar feedback and the resulting mass-loading of galactic outflows in terms of the large-scale properties of the galaxies, such as density, mid-plane pressure and rotation speed. We will answer the question: *Can star formation clustering be predicted in terms of large-scale galaxy properties that are resolved in cosmological simulations?* Regardless of whether the answer to this question is 'yes 'or 'no', the result will be of interest to the star formation and cosmological simulations communities.

Recommended prerequisites: Basic python coding experience and astronomy knowledge (AY 16 and 17) are recommended, basic knowledge of statistics and machine learning would also be recommended, but the project is open to all undergraduate students.

Background reading:
[1] Springel V., Hernquist L., 2003, MNRAS, 339, 289
[2] Fielding, D., Quataert, E., Martizzi, D. 2018, MNRAS, 481, 3325
[3] Smith M. C., Bryan G., L. Somerville R. S., et al. 2021, MNRAS, 506, 3882
[4] Jeffreson S. M. R., Semenov, V. A., Krumholz, M. R., 2023, submitted
[5] https://lilianweng.github.io/posts/2018-10-13-flow-models/ Flow-based generative models