Dear Harvard Students,

The Center for Astrophysics | Harvard and Smithsonian (http://www.cfa.harvard.edu/), or CfA, 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
calcock@cfa.harvard.edu

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.

Gravitational Lensing

Advisor: Kim-Vy Tran (kim-vy.tran@cfa.harvard.edu); see www.kimvytran.org

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.

Description: Gravitational lensing has matured into a powerful cosmic tool for exploring a wide range of astrophysical phenomena such as multiply imaging a single supernova, identifying the highest redshift galaxies, and mapping dark matter distributions. With upcoming all-sky surveys, we are at the brink of a revolution where deep high resolution imaging of vast cosmological volumes is becoming widely available.

I currently lead the ASTRO 3D Galaxy Evolution with Lenses (AGEL) Survey (Tran et al. 2022) to deliver a benchmark sample of new gravitational lenses that can be observed by both northern and southern hemispheres to obtain high quality follow-up with upcoming Adaptive Optics and space telescopes. Science goals include measuring the dark matter profiles of the foreground deflector halos; mapping the Circum-Galactic Medium associated with the foreground deflector; quantifying the changing conditions of the Inter-Stellar Medium of the background lensed sources; and measuring the Hubble constant for a subset of compound lenses that have two sources at different redshifts. The AGEL observations include an ongoing Hubble Space Telescope program to image 500 strong lenses, extensive ground-based spectroscopy of the deflectors and sources, and complementary multi-wavelength observing campaigns to capture the interplay between gas and stars.

I have supervised 30+ undergrads in research including Honors theses. I work with each student to develop a well-defined project that is appropriate to their interests and abilities, no previous experience is needed.

Liam Connor
Assistant Professor, Harvard Astronomy
liam.connor@cfa.harvard.edu

Radio Astronomy Hardware : Global Radio Explorer (GReX)

In 2020 the brightest radio pulse ever discovered was captured by a small radio antenna at the Owens Valley Radio Observatory. It was found to come from a known magnetar in the Milky Way, establishing a strong connection between the mysterious extragalactic fast radio bursts (FRBs) and magnetized neutron stars.

My colleagues and I have built a successor instrument to find more of these ultra-bright Galactic FRBs. It's called GReX (rhymes with T-Rex). The hardware is sitting in my office and I'd love to work with an ambitious undergraduate to assemble the telescope, set it up on the roof of the CfA, and start looking for signals! The student would learn the fundamentals of radio astronomy, signal processing, and FRB searching in the most hands-on way possible.

Machine learning for 3D reconstruction of cosmological fields.

Modern AI/ML techniques in computer vision have made significant advances in reconstructed 3D fields using sparse 2D data (e.g. NeRFs, diffusion models). I would like to work with a student to build a neural network that can reconstruct cosmological fields such as the baryon density and the dark matter distribution from galaxy surveys and other inputs. Ideally the student would have some familiarity with machine learning, although one need not be an expert by any means.

Searching for Planets and Flares at X-ray Wavelengths

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 is working in two major domains: cosmology using the large-scale structure of the Universe and high-redshift galaxy formation using the James Webb Space Telescope.

Our work on the large-scale structure in the Universe combines 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, https://www.desi.lbl.gov, a major new facility now operating at Kitt Peak National Observatory in Arizona. DESI has already collected over 30 million spectroscopic redshifts in its first three years of operation. This data set is ripe for analysis, including for student projects.

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 led the development of the Abacus N-body code and 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 upgrades to the Abacus code or analysis of outputs.

Separately, my group is active in the James Webb Space Telescope (JWST) Advanced Deep Extragalactic Survey (JADES), https://jades-survey.github.io. JADES is conducting super-deep infrared imaging and spectroscopy of the GOODS-S and GOODS-N fields, designed to study galaxies at redshifts above 6. For example, we have published the first two spectoscopic confirmations at redshift 14. As the mission enters its third year of operations, these data sets are maturing well and are ready for a wide range of applications.

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.

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.

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'd be happy to talk to any interested students about possible projects.

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

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.

On particular project that we would be excited top 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.

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 supermassive ones.

See my website for additional information on my activities: www.fabiopacucci.com

Overall, my work addresses crucial questions about the nature and demography of black holes, their relevance for gravitational wave events, and ultimately, how black holes helped shape the Universe as we observe it now. Projects are available for theoretical modeling, data analysis, simulations, observations, and any combination!

If you are interested in working with me, projects are available on these broad research topics.

1) Formation, cosmological evolution, and observational signatures of the first population of black holes formed at redshift higher than 6, an undetected and fundamentally important class of black holes. New NASA's JWST telescope data provide fundamental constraints on this mysterious population of objects.

2) What are the infamous "Little Red Dots" popping out everywhere in JWST deep fields? These strikingly red and compact galaxies could contain the secret to understanding the early formation history of black holes.

3) 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 unique?

4) 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?

5) Is there a supermassive black hole at the center of Milky Way satellites? I am the Principal Investigator of an extensive observational campaign seeking to detect the second-closest supermassive black hole to Earth. I was recently awarded JWST time to observe one of such sources, and projects regarding this observation are available.

These topics are very timely, given new data from JWST and the upcoming commission of new observatories to probe the high-redshift Universe, the 30-meter class telescopes, WFIRST, Euclid, and, farther in the future, new X-ray and gravitational wave observatories. 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.

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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.

Revealing molecular complexity in planet forming disks with ALMA

Advisor: Dr. Alice Booth (alice.booth@cfa.harvard.edu) and Prof. Karin Öberg

Planet formation occurs on megayear timescales in the disks of gas, dust and ice around young stars. The composition of these forming planets, moons, and comets depends intricately on the chemical properties of the parent protoplanetary disk. With the Atacama Large Millimeter/submillimeter Array (ALMA) we can obtain a molecular inventory of these disks and spatially resolve the gas emission on 10’s of au scales. One fundamental avenue of research is to understand the level of chemical complexity present during planet formation. Complex organic molecules (COMs) are the building blocks of potentially pre-biotic molecules therefore, the inheritance, formation and survival of these species in disks is key to understanding planetary habitability.

Recent observations with ALMA have shown that disks around young A-type stars are partially rich in COMs with the common detections of methanol and methyl-cyanide. The goals of this project are to analyze new ALMA observations of a nearby protoplanetary disk around the young A-type star HD 163296. Although this is a well-studied system, these data cover a previously unexplored frequency range. The student will look for detections of different molecules including methanol, formic acid, cyanodiacetylene and dimethyl-ether. All of which would be a first for this system.

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)

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.

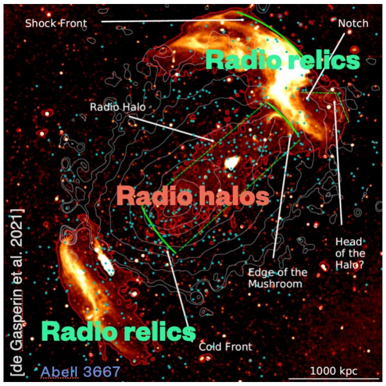
Dr. Williams (https://newton.cx/~peter/) is the lead developer of Tectonic (https://tectonic-typesetting.github.io/), an open-source project that aspires transform technical communication for the 21st century. In particular, it aims to bring the power of the venerable TeX typesetting software — still 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.

The largest particle accelerators in the Universe - turbulent re-acceleration of cosmic rays in galaxy clusters

Advisors: Paola Domínguez Fernandez (pdominguezfernandez@cfa.harvard.edu), Vadim Semenov (vadim.semenov@cfa.harvard.edu), John ZuHone (john.zuhone@cfa.harvard.edu)

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

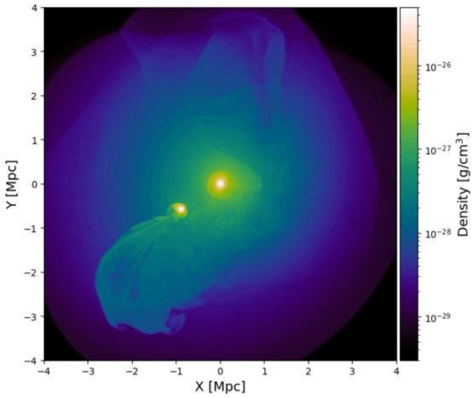
Galaxy clusters reveal Mpc-size diffuse radio emission permeating its center. This emission is evidence for relativistic electrons and magnetic fields in galaxy clusters. Nevertheless, these electrons need to be re-energized by some particle acceleration mechanism in order to explain the observed radio emission. Turbulence is naturally produced as galaxy clusters form and is expected to accelerate particles in the intracluster medium.



[de Gasperin et al. 2021]

Tasks:

1. Work with AREPO simulations of galaxy cluster mergers
    a. The student will learn how to analyze data from simulations using Python
    b. There will be a possibility for the student to run AREPO simulations
2. Characterize turbulent motions
    a. Quantify the properties of turbulence in the intracluster medium using common statistics like power spectrum, velocity structure functions, and the ratio of solenoidal and compressive modes.
    b. Use high-resolution turbulence simulations to quantify the dependence of the solenoidal and compressive modes on the spatial scale, and use this relation to predict these properties on unresolved scales in a cluster-scale simulation
3. Discuss its application for turbulent re-acceleration mechanisms (Fermi-II mechanisms)



Open for all undergraduate students

The student will learn about galaxy clusters, the largest gravitational systems in the Universe, radio emission, turbulence and magnetic fields. The student will learn Python scripting to analyze simulation data, about the AREPO code and use the yt package also for the analysis and visualization of the simulation data.

Protecting Sites for Super-Telescopes on the Moon.

Advisor: Martin Elvis <melvis@cfa.harvard.edu>

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

The imminent return of humans to the Moon has spurred ideas for novel "super-telescopes" using some special sites on the Moon: The lunar farside can be home to low frequency radio investigating hydrogen in the Dark Ages, before there were stars or galaxies and for advanced SETI; "cold traps" that are permanently colder than 50 K, make a low background far-IR telescope to measure distortions in the Wien tail of the microwave background spectrum; larger "permanently shadowed regions" offer low noise places to listen to the gravitational waves from pairs of black holes months or more before they finally merge; optical interferometers could image stellar disks and measure geometric distances to quasars to determine the metric of the universe. We call these "sites of the extraordinary scientific importance (SESIs)" and they are rare.

But all these SESIs are easily disturbed by human actions, such as mining for water in the same cold traps, or operating heavy machinery to build a base, or even just landing rockets on the surface. The protection of SESIs has been realized to be something to get on the international agenda before the opportunity for doing this unique science is lost. As vice-chair of the IAU working group on "Astronomy from the Moon", creating a registry of these SESIs to forward United Nations COPUOS* efforts to preserve them.

The essential first step is to create a "SESI Registry" of all the candidate locations and then to see which ones are the best. To build the SESI Registry requires data analysis of lunar orbiter satellite data on e.g., the coldest polar cold traps (T<50K) for IR telescopes, lava tubes for human bases or bio-vaults, the few large sites for radio telescopes on the (presently) radio-quiet farside. Student projects would tackle pieces of this puzzle with a goal of having publishable results.

[* COPUOS = Committee on the Peaceful Uses of Outer Space]

TEMPO Science Studies

Advisor: Atmospheric measurement group; Main contact: Dr. Huiqun Wang (hwang@cfa.harvard.edu)

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

The atmospheric measurements group at the Center for Astrophysics | Harvard & Smithsonian leads the TEMPO (Tropospheric Emissions: Monitoring of Pollution, tempo.si.edu) satellite mission. TEMPO uses the UV/visible spectroscopic technique to monitor atmospheric pollution across North America from geostationary orbit hourly at high spatial resolution. TEMPO has been collecting spectra since first light on 2 August 2023. TEMPO spectra are used to retrieve a suite of products important for air quality and climate, including O_3, NO_2, H_2CO, SO_2, $C_2H_2O_2$, H_2O, BrO, aerosols, cloud parameters, and Ultraviolet B (UVB) radiation. TEMPO data can be used to conduct scientific research that encompasses a wide range of air quality and climate related topics. In particular, the revolutionary datasets enable the diurnal variations of trace gases over North America to be revealed for the first time. A few science applications are listed below. For a more complete list please refer to the TEMPO green paper (https://weather.ndc.nasa.gov/tempo/green_paper.html).

(1) The Great American Eclipse from TEMPO's perspective. This rare event was captured by TEMPO from orbit. It happened on Monday April 8 and drew millions of travelers to watch in addition to those directly underneath the path. The pollutants associated with traffic emissions over the weekend and on the day were monitored by TEMPO, and are anomalously high with respect to the normal pattern. This project seeks to quantify the anomaly in trace gases associated with this event, providing a unique perspective.

(2) Changes in trace gases under extreme weather conditions. Hurricanes, droughts, heat waves, dust storms, Atmospheric Rivers (AR) are well known weather phenomena. However, little is known about the changes in chemical composition under these environments. This project seeks to illustrate how various trace gases evolve before, during and after the extreme weather conditions.

(3) Wildfires' influence on air quality. Wildfires emit large amounts of pollutants which depend upon source materials and environmental conditions. This project investigates the variation, transport and transformation of pollutants.

Please reach out if you are interested in using TEMPO data to pursue any of the science studies here or in the TEMPO green paper.

These projects are open to all undergraduate students and require experience with programming languages, e.g., Python, Matlab, or IDL.

Observing Exoplanets

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

Professor Charbonneau is on sabbatical for 2024-2025 and not advising undergraduate research.