Dear Harvard Students,

The Harvard-Smithsonian Center for Astrophysics (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.

Best wishes,

Karin Öberg,
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P-346

Exploring Star Formation in our Galactic Neighborhood

Advisors: Prof. Alyssa Goodman (agoodman@cfa.harvard.edu) and Dr. Catherine Zucker (catherine.zucker@cfa.harvard.edu)

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

Most of our knowledge about the formation of stars, and essentially all of our knowledge about the formation of planets, comes from observations of our solar neighborhood, less than 1 kpc from the Sun. Before 2018, accurate distance measurements needed to turn the 2D Sky into a faithful 3D physical picture of the distribution of stars and the interstellar clouds that form them were few and far between. Without distances, it is difficult to reliably measure the 3D mass and density of star-forming regions and to evaluate the relative importance of the mechanisms governing their evolution. Thanks to the launch of *Gaia* – which provided distances to 1 billion stars – it is now possible to build a physical 3D model of interstellar clouds and young stars in our corner of the Galaxy.

We propose two projects for interested students related to the local star-forming interstellar medium. In the first project, the student would apply a dendrogram algorithm (see https://dendrograms.readthedocs.io/en/stable/) to a new 3D map of the nearby interstellar dust distribution, to produce a high-resolution catalog of the 3D positions and physical properties (mass, size, density, etc.) of nearby molecular clouds. In the second project, the student would "zoom-in" on one or two famous nearby star-forming regions (e.g. the Orion nebula), and explore the question of *how stars leave home*. Specifically, using new datasets on the 3D positions *and* kinematics of young stars and clouds, the student would characterize how young stars formed in molecular clouds leave their birthplaces and eventually evolve into stars like our Sun. Both projects would involve hands-on experience with python programming and the latest data visualization tools, including the software *glue* (http://glueviz.org/), and we would be happy to discuss them with any interested students.

Recommended prerequisites: These projects are constructed with (rising) junior and senior students in mind. Some python coding experience basic knowledge of astronomy (AY 16 and 17) would be beneficial.

Star Formation in the Milkyway and Nearby Galaxies

Advisors: Prof. Alyssa Goodman (agoodman@cfa.harvard.edu) and members of the Goodman group: Dr. Catherine Zucker (catherine.zucker@cfa.harvard.edu), Michael Foley (michael.foley@cfa.harvard.edu), Angus Beane (angus.beane@cfa.harvard.edu), Eric Koch (eric.koch@cfa.harvard.edu), Sarah Jefferson (sarahjeffresonde@gmail.com), Shmuel Bialy (sbialy@cfa.harvard.edu)

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

Our group's work includes a wide range of projects revolving around the question of how the Milky Way and nearby galaxies turns gas into stars. We create, and make use of, various combinations of simulations, observational data, and statistical and visualization tools in our approaches to this question. A good recent example of our style of work is the discovery of "The Radcliffe Wave," described at http://tinyurl.com/RadWave.

One specific project we propose for interested students is to explore how the star-forming interstellar medium in nearby galaxies compares to our own Milky Way. The student will apply a new algorithm for identifying 3D filamentary structures in high-resolution maps of molecular gas of our Local Group neighbour Triangulum (Messier 33; M33), compare the properties of these filaments to the large-scale Galactic filaments in the Milky Way, and measure how flows along these filaments fuel star formation to produce new stellar clusters. The student will gain experience using python programming for research and the latest data visualization tools, including the software glue (http://glueviz.org/).

In addition to this specific project, members of our group would like to work with students this coming Summer on any of a variety of projects that involve: numerical simulations of the Milky Way Galaxy; statistical analyses of turbulence; analysis of observations and simulations of the topology of star-forming regions, and more. Please be in touch to learn more!

Designing and Building Instrumentation for Exoplanet Science

Advisor: Dr. Andrew Szentgyorgyi (aszentgyorgyi@cfa.harvard.edu)

Humanity stands at the threshold of quantitatively assessing the uniqueness of life on Earth. These investigations require state-of-the-art observational instrumentation to try to detect the presence of biomarker constituents in the atmosphere of planets beyond the Solar System, i.e. exoplanets. The range of research areas extends from building prototype instrumentation to optical design to modeling exoplanets to optimize searches for biomarkers. A particular area of interest, as I write is, the development of new reduction algorithms to optimize the sensitivity on exoplanet mass measurements. These projects range from the highly analytical to the very nuts-and-bolts, and I look forward to discussing them with any interested students.

Reconciling the histories of the Milky Way told by stars near and stars far

Advisors: Prof. Charlie Conroy (cconroy@cfa.harvard.edu) and Rohan Naidu (rohan.naidu@cfa.harvard.edu)

The Milky Way, our home galaxy, has assimilated several smaller galaxies through its history. The stars from these foreign galaxies comprise the outer regions of our galaxy ("the stellar halo"). The stellar halo is challenging to study because it is distant. One common way to get around this has been to focus on stars in the solar neighborhood that are on halo-like orbits. The properties of the distant halo are then extrapolated from these "local halo" stars. This is clearly a biased way of studying the halo--we know this because we have observed entire accreted galaxies (e.g., the Sagittarius dwarf) whose stars have never made their way to the Sun. However, bound by practical constraints, this way of studying the halo has been the norm for the last couple decades, deployed in the most influential studies. More puzzlingly, despite the availability of several simulations of stellar halos, no one has quantified what exactly is lost to this "local halo" approximation. In this project, the student will (i) learn the basics of galactic dynamics (e.g., orbit integration), (ii) learn to navigate simulations, (iii) quantify what types of orbits/structures are lost to the "local halo" approximation. No matter what the student finds, we expect this project to lead to a short, useful paper.

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 MEarth Project consists of two arrays, one in Arizona and the other in Chile, each comprising 8 robotic telescopes, photometrically surveying several thousand nearby, small stars to search for small planets near the habitable zone. Due to their proximity to us and the small stature of their parent stars, the atmospheres of such planets are observationally accessible.

(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) The recently launched 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'd be happy to talk to any interested students about these projects.

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

Building and Exploring the Chandra Galaxy Catalog (CGC)

Advisor: Dr. Dong-Woo Kim (kim@cfa.harvard.edu)

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

Using the Chandra observations for the last two decades, the Chandra Source Catalog version 2 (CSC2, released in 2019) provides 317,167 unique X-ray sources with accurate positions as well as high quality photometric, spectral and temporal properties. CSC2 is the major X-ray source catalog with the most precise source position and with the least confusion ever built in X-rays. In this program, we will utilize CSC2 to build a large (about 10,000), clean (with least confusion and contamination) X-ray selected galaxy catalog. To obtain multi-wavelength data, we will cross-match CSC2 with the following sky survey catalogs covering from IR to UV: SDSS, Legacy, DES, GAIA, PanSTARRS, WISE, 2MASS, and GALEX.

We will classify X-ray sources and build the Chandra Galaxy Catalog (CGC). For the X-ray sources with optical spectral data, we rely on the spectroscopic classification, and we will further extract the galaxy properties (e.g., redshift, age, SFR, mass) from the spectral data. For X-ray sources with no spectroscopic observations, we will extract similar information (photometric redshift, age, SFR, mass) from the value-added catalogs for SDSS, Legacy, and DES. The primary classification schemes depend on the source extendedness, proper motion/parallax, and AGN strengths. Our preliminary results show that about 40K, 150K, and 100K of X-ray sources have counterparts from SDSS, WISE, and GAIA catalogs, respectively.

We expect to find more than 10,000 galaxies with multiple counterparts from other catalogs. The preliminary sample of galaxies (identified by optical spectra) has the redshift ranging from 0 to 1.6 with $<z> = 0.3 \pm 0.2$. We will further investigate focused galaxy sciences, which can be done only with a large, unbiased sample. They include the X-ray luminosity function of galaxies, X-ray scaling relations and unusual, but interesting types of galaxies (e.g., XBONGs, E+A galaxies). The student can be involved in (1) cross-matching CSC2 and other catalogs, (2) classifying matched sources to build Chandra Galaxy Catalog, or (3) to perform focused science projects on the catalog.

Observing and modeling exploding and colliding stars

Advisor: Prof. Edo Berger (eberger@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

The Dynamic Universe: The universe is a highly dynamic place teeming with the explosions of stars and collisions of neutron stars and black holes. These events can be studied with light and gravitational waves. In this context my research group provides several exciting opportunities for undergraduate research projects:

[1] Machine learning classification and study of supernova explosions, using on-going large-scale surveys and in anticipation of the revolutionary LSST survey.

[2] A comprehensive study of the energy source and progenitor systems of the mysterious class of Superluminous Supernova, the most energetic explosions in the visible sky.

[3] Observational and theoretical studies of neutron star and black hole binaries, the relation between their gravitational wave and electromagnetic emission. This is a new field of astrophysics enabled by the first operational gravitational wave detectors (LIGO, Virgo, and soon Kagra).

Recommended prerequisites: Basic python coding experience is important for this project. This project is designed with (rising) juniors and seniors in mind.

Instrumentation development for radio telescopes

Advisor: Dr. Edward Tong (etong@cfa.harvard.edu)

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

Instrumentation Development at Receiver Lab: At the receiver lab, we are at the forefront of instrumentation development for radio-telescopes. Our work spans from designing RF/microwave low noise amplifiers, to cryogenic ultra-sensitive detectors for the Submillimeter Array and sub-100mK wideband spectrometers, and development of automatic control of astronomical instrumentation. We would like to involve undergraduate students in our lab. If you would like to work with instrumentation development for radio-astronomy, we will be happy to get you on board in our team. There is no need of prior experience in hardware, just a motivation to work with and explore instrumentation work. I really enjoy working with undergraduates, so please reach out if this sounds interesting to you.

This project is designed with (rising) juniors and seniors in mind.

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. A large part of my research deals with the formation, cosmological evolution and observational signatures of the first population of black holes formed at redshift higher than 6. Shedding light on this primordial population is fundamentally important to understand the birth of the first quasars, their role in galaxy formation and the origin of the sources now detected via gravitational waves. With expertise in both theoretical modeling and observations, I developed some of the most advanced selection criteria and growth models for black hole seeds, formed when the Universe was very young. I also contributed, very recently, to the discovery of the first lensed quasar at z>6, and developed some theoretical models to interpret this observation. 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. This research focus is very timely given the commissioning of several new facilities, such as the James Webb Space Telescope (JWST), the 30-meter class telescopes, WFIRST and new X-ray (Lynx and Athena) and gravitational wave (LISA) 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.

Cygnus loop: test-bed for turbulence generated by low Mach number astrophysical shocks

Advisors: Dr. Frederico Fraschetti (ffrasche@lpl.arizona.edu) and Dr. John Raymond (jraymond@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY 99), Semester research for credit (AY 91R)

Shock waves driven by the remnants of supernova explosions propagate into an inherently inhomogeneous, or turbulent, interstellar medium (ISM). The surface of a supernova remnant (SNR) shock undergoes rapidly corrugation as it encounters the cold interstellar clumps and generates vorticity into the medium behind the shock. The vorticity leads to turbulence and this is arguably among the major contributors to the turbulence in the interstellar medium (ISM). Several studies investigated the collision of a shock with turbulent ISM when the shock is in non-radiative regime (Giacalone & Jokipii, ApJ, 663, L41, 2007, Fraschetti, ApJ, 770, 84, 2013), i.e. when radiative cooling of the downstream fluid is much longer than the typical hydro-dynamical timescale of the evolution of the SNR. However, little work has been done on shocks in radiative regimes. This regime can describe low Mach number shocks, such as Cygnus Loop shock, but also the broad category of interplanetary shocks. Recent direct observations allowed to infer the vorticity downstream of the Cygnus Loop shock (Raymond et al., ApJ, 894, 108, 2020) and might provide a unique probe of these shocks and test of models under development.

The project will calculate analytically the vorticity downstream of a shock wave with an MHD approach. The project would essentially follow the calculation in (Fraschetti, 2013) on the vorticity generated downstream of SNR shocks but in the radiative regime, thus adding a cooling term in the conservation of energy. The Rankine-Hugoniot jump conditions will be projected onto a local orthonormal reference frame on the corrugated surface of the shock as streamlined in the paper above. The vorticity and the magnetic field downstream of the shock will be calculated. The synchrotron emission in the downstream magnetic field will be predicted.

The student will be mostly mentored by Dr. Fraschetti. Dr. Raymond will contribute the cooling function and help with the physical interpretation of the results. The findings will be compared with multi-wavelength observations of Cygnus Loop. There is much physics to learn in this project including a new method to treat analytically no-ideal no-planar shocks and also mechanisms of radiation of energetic electrons. Finally understanding the role of the vorticity generated by shock can help shed light on the role of energetic particles at shocks, that also generate turbulence via excitation of instabilities as they stream in front of the shock; in particular, the non-resonant instabilities that are linked to the strong magnetic field inferred in SNR from, e.g. X-ray observations, were also discovered with a solution to MHD equations (Bell, MNRAS, 353, 550, 2004).

Recommended prerequisites: Familiarity with basics hydrodynamics or magnetohydrodynamics. This project is primarily geared towards junior and senior students.

Science and Mathematics Education Research

Advisor: Dr. Gerhard Sonnert (gsonnert@cfa.harvard.edu)

Open for Senior Thesis (AY 99), Semester research for credit (AY 91R), Paid semester research for work-study eligible students

Gerhard Sonnert works on large-scale survey studies in the area of science and mathematics education. Current projects include an examination of the factors influencing students' success in college calculus, a study of what predicts beginning college students' career interests, and an investigation of the extent to which professional development institutes for middle school life science teachers actually improve their scientific knowledge and pedagogical skills. He is particularly interested in the gender aspects of science careers, and would be happy to meet with any students interested in this subject.

Recommend prerequisites: Some familiarity with statistics. This os designed with junior and senior students in mind.

Hunting for exoplanets using microlensing

Advisor: Dr. Jennifer Yee (jyee@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

My research focuses on studying cold planet populations using the microlensing technique. I lead the Spitzer microlensing parallax project, which uses the microlens parallax technique to show where planets are located in our galaxy. The ultimate goal of the project is to measure the distribution of planets as a function of Galactic distance. In order to do that, we have observed almost 1,000 microlensing events with Spitzer to create a statistical sample of planets (and events without planets) that also have measurements of the microlens parallax. Although the sample has several known planets, it has not been systematically searched for planetary signals. I would welcome an undergraduate interested in undertaking such a search.

This project is open to undergraduate students at all levels.

TESS optical photometry of a prototype new class of Ostar - Black Hole (BH) X-ray binaries in our Galaxy.

Advisors: Prof Josh Grindlay (jgrindlay@cfa.harvard.edu) and Sebastian Gomez

This observational project is to confirm a new class of BH X-ray binaries in which the BH produces X-rays by accreting (swallowing) gas from the "weak wind" of a main sequence or sub-giant O or B star more massive companion. In the last decade, it became clear that most O stars have a less massive O or B star binary companion. Most O star (and some massive B stars), when super-giants, collapse to form BHs. The first BH discovered, Cyg X-1, is a very bright X-ray binary with a 13 solar mass BH accreting from the strong wind of a 19 solar mass O9Iab super-giant O star and is the prototype of a Black Hole High Mass X-ray Binary (BH-HMXB). Since the super-giant phase of an O star is <3 x 10^5 years, there should be >10-100 more BH-HMXBs with main sequence O9V stars with ~5My lifetimes and "weak winds", and so much less luminous in X-rays. The first was discovered with X-ray data from NuSTAR (Grindlay+2020) and identified as a 7 solar mass BH and 26 solar mass main sequence O star with optical photometry (AAVSO and CTIO) and spectroscopy from Magellan (Gomez and Grindlay 2020). This project will do photometry analysis of new optical images from the TESS satellite (repeated coverage) to measure a new light curve (brightness vs. time) of the O star donor (HD96670) over several orbits, particularly at radial velocity phase interval (0.7 - 0.8) in the 5.3 day orbit where the accreting BH and its hot surrounding disk is aligned in front of the O9V star. Repeated optical brightening (~0.04mag above the expected sinusoid) at only this phase is attributed in our accretion model to decreased opacity of the stellar wind at this phase when our line of sight view of the O star is maximally heated by X-rays; it cannot be due to thermal emission from the accretion luminosity which is >10^3 below that of the O star. This brightening should recur at this phase each orbit. If not, the BH model for the system will be called into question. If this project interests you, please reach out to us — we are happy to meet with any interested student.

Astrochemistry and Planet Formation

Advisor: Prof. Karin Öberg (koberg@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, 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.

These projects are open to undergraduate students at all levels.

Characterizing Star Clusters in M31

Advisors: Dr. Nelson Caldwell (ncaldwell@cfa.harvard.edu) and Prof. Charlie Conroy (cconroy@cfa.harvard.edu)

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

The M31 PHAT survey (Dalcanton et al 2012) was an HST imaging survey of about 1/3 of the disk of M31. Among many other things, it produced a catalog of star clusters, nearly all of which are young disk clusters. Integrated light photometry was performed, and a paper deriving ages from resolved star color-magnitude diagrams was written (Johnson, Seth 2016). Over the last 9 years I have obtained optical spectra of about 800 clusters with the MMT and Hectospec. Nearly all of these clusters have not had spectra taken before, and as such these spectra are available to measure ages and of course velocities. I published a small sample of such clusters in 2009 using a simple analysis code. The new plan would be for a student to use Conroy's stellar population modelling code to derive velocities and ages, taking into account stochastic effects for the lower mass clusters.

After comparing the derived ages with those of the color-magnitude work, the student would describe the cluster age distribution, and study the deviation of cluster velocities with local H I gas velocities.

Transforming Technical Communication

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

Open for Semester research for credit (AY 91R), Paid semester work for work-study eligible students, Summer Research with external stipend

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

The world deserves excellent technical documents, chock-full of beautiful equations, abundant cross-references, interactive graphics, and runnable code. But most of the documents created by scientists are intended for printing on little rectangles of paper, static and dead. Why? Modern displays are capable of so much more, but we just don't have the tools to create the documents that can take advantage of them.

Dr. Williams (https://newton.cx/~peter/) is the lead developer of Tectonic (https://tectonic-typesetting.github.io/), an open-source project that aspires to do nothing less than 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 ninja programmer, but given the time constraints, substantial previous coding experience is required. If this applies to you, please reach out!

Recommended prerequisites: Extensive coding experience, preferably including compiled languages, not only scripting languages like Python. Adequate preparation would include the bulk of the undergraduate CS curriculum including systems and PL classes, or equivalent such as a track record of involvement in open-source software projects.

Massive star formation at millimeter and radio wavelengths

Advisor: Dr. Qizhou Zhang (qzhang@cfa.harvard.edu)

As one of the building blocks in the visible universe, massive stars dominate the appearance and the evolution of galaxies. However, their formation is not well understood. My research focuses on studying different evolutionary stages of massive star and stellar cluster formation using high-resolution radio and sub-millimeter interferometers as well as infrared telescopes. Possible projects for undergraduate research involve processing and analyzing data taken from the Submillimeter Array (SMA), Atacama Large Millimeter/Submillimeter Array (ALMA), Karl Jansky Very Large Array (VLA), and Herschel Space Telescope. Depending on time availability, these projects can be tailored to fit the time frame of summer research, junior tutorial or senior thesis. If schedule permits, the student will travel to Mauna Kea, Hawaii for one-week observing. I'd be glad to meet with any interested student to discuss this project.

Machine Learning and the Chandra Source Catalog

Advisor: Dr. Rafael Martínez-Galarza (juan.martinez.galarza@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY99), Semester research for credit (AY 91R)

I am an astrophysicist with the Chandra X-ray Center. I am in charge of maximizing the scientific output delivered by Chandra data, for example by curating the Chandra Source Catalog, that includes all the X-ray sources detected by the observatory from the beginning of the mission. One possible way to harvest the immense amount of data from X-ray binaries, AGNs, young stellar objects, and other types of X-ray emitters is by mining the Chandra Source Catalog with Machine Learning. One aspect that remains largely unexplored is temporal variability of X-ray sources. This is important because many sources that are relevant for the study if compact object physics, such as kilonovae and gravitational wave progenitors, behave as X-ray transients. An exciting project for an enthusiastic Harvard undergrad would be to apply recently developed machine learning algorithms for the study of time variability, such as auto-encoding recurrent neural networks, in order to characterize and classify hundreds of thousands of X-ray light curve, and to use the derived representations to find the most scientifically compelling objects, such as Tidal Disruption Events and ultra-luminous X-ray sources. This project should open new research avenues in the high energy astrophysics community, and I'd be very happy to discuss it with students.

Recommended prerequisites: Some python coding experience. This project is designed with (rising) junior and senior students in mind.

Supermassive black holes and their host galaxies

Advisor: Dr. Rainer Weinberger (rainer.weinberger@cfa.harvard.edu)

Open for Junior Thesis (AY98), Senior Thesis (AY99)

Why do the galaxies we see in the universe look the way they do? What is the underlying physics that shapes their appearance, and how do they evolve?

I am interested in developing, running, and analyzing sophisticated computer simulations that are able to model the formation of galaxies, thereby studying the physics governing their evolution. My main focus is the role of central supermassive black holes on their host galaxies, commonly referred to as active galactic nucleus (AGN) feedback. While evidence for the importance of this process is significant by now, the details of how, when, and in which form these black holes impact their surroundings are unclear. One reason for this remaining uncertainty is the absence of direct observational signatures, making indirect signatures, both in the galaxy as well as in the supermassive black hole population the most promising avenue for progress.

Potential projects are linked to this topic of supermassive black holes and their connection to their host galaxies. Some examples are the statistical properties of simulated AGNs or the properties of galaxies during the times they experience significant AGN feedback.
All projects are theoretical in nature, but can have some degree of connection to observational work.
More informations about the simulations that could be used for these projects are here: www.tng-project.org. Prior programming knowledge (Python, C, C++) beneficial, willingness to spend time to learn/improve your programming skills is essential. If this applies to you, please reach out, and I'd be happy to discuss the project further.

Recommended prerequisites: Some python coding. Basic astronomy (AY 16 and 17).

Computer Simulations of Black Hole Accretion

Advisors: Prof. Ramesh Narayan (rnarayan@cfa.harvard.edu), Dr. Matthew Liska, and Sophia Sanchez-Maes.

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,

Magnetized gas accreting on black holes powers some of the most spectacular objects in the universe: quasars, blazars, gamma-ray bursts, X-ray binaries. Often, strong magnetic flux concentrates around the black hole, leading to a so-called Magnetically Arrested Disk (MAD). The collected flux couples with the rotation of the black hole to produce relativistic jets. The amount of flux that acculumates, and hence the jet power, depends on the mass accretion rate on the black hole, but it is not clear what additional factors are involved. One possibility is that the geometrical thickness of the disk plays a role. The proposed project is to design and run computer simulations of black hole accretion disks with different thicknesses to explore the effect of disk thickness on the MAD phenomenon. If this interests you, please reach out, and we'd be happy to discuss the details of the project with you.

Recommend prerequisites: A background in special relativity, electromagnetism, and basic astrophysics. Previous experience in computations, e.g., Python, is also highly desirable. This project is designed with junior and senior students in mind.

EUV and X-ray Laboratory Astrophysics

Advisor: Dr. Randall Smith (rsmith@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

My group works at the interface of atomic physics and EUV/X-ray astrophysics, as the maintainers of the primary database of atomic data for modeling X-ray emitting and absorbing plasmas. We collect and verify atomic data, using it to create plasma emission models, and we will soon be making laboratory astrophysics measurements using the CfA Electron-Beam Ion Trap (EBIT). We test our data by trying to understand complex astrophysical plasmas, such as those found in supernova remnant shock fronts, symbiotic stars, and clusters of galaxies. Opportunities exist for both short-term and long-term projects of an observational, theoretical, or experimental nature. Note that due to US law, experimental work may be restricted to US citizens or green card holders, although we will attempt to accommodate anyone. I am always happy to meet with students to discuss potential projects, so please don't hesitate to reach out.

Recommended prerequisites: Python coding experience. This project is designed with juniors and seniors in mind.

Gravitational wave astrophysics, and large scale hydrodynamic simulations of galaxies

Advisor: Dr. Razieh Emami Meibody (razieh.emami_meibody@cfa.harvard.edu)

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

I have been focusing on different topics in astrophysics including gravitational wave astrophysics as well as the connection between the galaxies and stars and other topics, and have multiple projects available for students at different stages that I'd be glad to discuss with any interested student.

1) to develop some techniques in studying a variety of different star clusters around super massive black holes (SMBH) which are located at the center of different galaxies such as Milky Way. The goal would be to study the impact of the metallicity and thus the initial mass function of stellar mass black holes on the rate of EMRI as well as the tidal disruption rate. We can use some of the hybrid tools that we have been developing recently which connect stars with different metallicities to different BH populations and use them in some simulations of stellar cluster. This setup can be then put in some post processing codes and compute the rate of the inspiral for the BHs at different environments. For each of these environments we may use the most recent observational data for the density profile of stars and compute the signal etc. Some environments such as post star burst galaxies may give us larger signals and this is very timely to estimate how may this be related to the properties of the PSB galaxies.

2) I have also some tools for studying some hierarchical BH systems, such as triple and 4-body systems in the presence of the SMBH that can be used to study the impact of hierarchical BH binaries in the gravitational wave signals. We can also investigate the impact of stellar evolution in the signal.

3) Currently, I am using some large scale hydrodynamical simulations (TNG project) to study Milky Way like galaxies to compute the shape and morphology of different galaxies in our sample. We have been working a lot on developing some tools that can be further extended and be used for different environments and different morphologies. Since the Galaxy shapes are being affected by a number of different processes and is connected to the stars, dark matter and gas in the galaxy as well as their merger history, it would be very fascinating to check the impact of each of those in the shape and make a connection among them. We are hoping to make the connection between such theoretical estimations and some real data and thus have some juniors that are interesting in such sciences would be beneficial to our growing team.

Beside the above developed tools, I am interested in a number of other topics such as the clustering of massive neutrinos as well as the gravitational lensing, most of which are at the stage of development and thus having more senior students that can help such developments would be desired.

Recommend prerequisites: Some experience with Python coding.

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.

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.

How did the Solar System form and evolve?

Rosemary Pike (rosemary.pike@cfa.harvard.edu)

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Galaxy evolution

Advisor: Dr. Sandro Tacchella (sandro.tacchella@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 the formation and evolution of galaxies. I'm curious to understand how the first galaxies in the early universe form, how the bulge and disk components in galaxies buildup, and how star formation in massive galaxies ceases. I'm using both observational and theoretical tools, including the Hubble Space Telescope, the 6.5m MMT telescope, cosmological simulations, and empirical models.

I would like to welcome undergraduate students on a variety of observational or theoretical projects related to galaxies. Specifically, projects include:
(i) Studying recently obtained spectra of distant galaxies in order to determine their metallicity content;
(ii) Working with a state-of-the-art cosmological simulation to shed light on star-formation variability in galaxies;
(iii) Developing an empirical model for the size growth galaxies;
(iv) Making clustering predictions of the first galaxies for the upcoming James Webb Space Telescope using a newly developed empirical model.

Recommend prerequisites: Some Python coding experience. This project is designed with (rising) Junior and Senior students in mind.

Theoretical cosmology

Advisor: Xingang Chen (xingang.chen@cfa.harvard.edu)

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

I am a theoretical cosmologist specializing in early universe models and their observational consequences in the cosmic microwave background and large scale structures. Recent years of astrophysical observations have revealed some special patterns of the distributions of light and matter in the largest scales of our Universe. We find that these structures have all evolved from some special initial conditions at the beginning of Big Bang. Our research projects include early universe model-building and data analyses that allow us to look for the causes of these special conditions in terms of fundamental physics, and to make new proposals for theoretical model building and predictions for future experiments. Some of the projects will provide for undergraduate students introductions to more advanced subjects in cosmology and high-energy physics. Due to the nature of the research, students are advised to have some background in general relativity and quantum field theory and have interests learning such subjects. Interested students are encouraged to talk to me.

Recommended prerequisites: General relativity and quantum field theory. This project is designed with junior and senior students in mind.