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,
Director of Undergraduate Studies, Astrophysics
Professor of Astronomy
Harvard University
koberg@cfa.harvard.edu
617-496-9062
P-346

Star Formation in the Milkyway and Nearby Galaxies

Advisors: Prof. Alyssa Goodman (agoodman@cfa.harvard.edu) and Group Members

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

Prof. Alyssa Goodman and members of her research group are happy to supervise undergraduate research on topics related to:
physics of the interstellar medium; structure of the Milky Way; data visualization; and star formation. The group uses a wide variety of observational and computational approaches, and has special interest in many data science techniques, including visualization. Details of particular projects available upon request. Please be in touch to learn more!

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.

Determining CH4 and CO2 Abundances in Ocean World Atmospheres

Advisor: Dr. Amit Levi (alevi@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

Project introduction: Observations from Kepler and TESS and their follow-up ground observations discovered a very large number of exoplanets with sizes intermediate to that of Earth and Neptune. We have an estimate for the mass of some of these exoplanets which together with the size estimate yields an average density. The density tells us something about the planetary composition albeit with considerable uncertainty. Knowledge of the atmospheric compositions of these exoplanets can alleviate this uncertainty. This is if the internal planetary composition yields constraints on the atmospheric composition that differ substantially between the different types of planetary compositions imaginable. One type of exoplanet that is suggested to be common is the water world, where water composes a substantial fraction of the planetary mass. When close to their host star their outer surface is a deep ocean.

Project description: In this project we will derive constraints on the CH4 and CO2 atmospheric abundances for water worlds. These are observable chemical species (a potential biosignature pair) that may help pinpoint water worlds in the exoplanetary landscape. These constraints are a consequence of the solubility of CH4 and CO2 in liquid water and in high-pressure ice. We will calculate these solubilities by running a sequence of molecular dynamics simulations on a high-performance computer and perform a thermodynamic analysis.

The student will learn, using my codes and guidance, the basics of:
excessing and running software on the Harvard computer cluster
benchmarking the needed computer resources
converging a molecular system
executing a production run
analyzing a molecular trajectory and its thermodynamic context
publishing results in a scientific publication

Recommended prerequisites: Some basic python/MATLAB coding experience would be beneficial, as well as familiarity with basic thermodynamics.

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. These projects range from the highly analytical to the very nuts-and-bolts. Many student projects would align well with the interests of physics, applied sciences and engineering students. I look forward to discussing them with any interested students.

Simulating the stellar galactic X-ray emission

Advisors: Dr. Cecilia Garraffo (cgarraffo@cfa.harvard.edu)

Cool stars are, by far, the most common kind of stars in the galaxy, as they constitute ~99% of the stellar population. When cool stars rotate, they generate magnetic fields on their surface, so called magnetic activity. This activity results in X-ray emission, and it is determined primarily by the stellar mass and the rate of rotation.

X-rays, then, become a good tool to test stellar rotation models and their resulting magnetic activity. This is important, for example, to understand the space weather close-in exoplanets are exposed to, and the chances of a planet to host and retain an atmosphere. Stellar rotation evolution of cool young stars is still poorly understood. Recently, there has been growing consensus on the importance of the morphology of the magnetic fields on the angular momentum loss rates. Garraffo et al 2018 proposed a physics based model that takes this into account and successfully reproduces the distribution of rotation periods in open clusters.

In this project we will generate a synthetic galactic population using the Gaia Universe Model Snapshot and assign each star a rotation period using the Garraffo et al 2018 model. From the rotation period and stellar mass one can infer the X-ray emission of each star and then compare the stellar synthetic galactic emission with X-ray survey observations. This will allow us to calibrate rotation models, which will help, for example, estimate ages from their rotation periods, and to asses extrasolar planet's conditions as a function of stellar age and rotation period.

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) 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.

Cosmological large-scale structure and galaxy formation

Advisors: Prof. Daniel Eisenstein (deisenstein@cfa.harvard.edu)

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

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 millions of spectroscopic redshifts in just a few months. 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 use about 10% of the first year of the JWST mission to produce super-deep imaging and spectroscopy of faint galaxies, particularly at $z>3$. In the coming 21-22 academic year, we continue preparations for the survey, including the development of a novel GPU-accelerated photometric pipeline.

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

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. 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.

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

Advisors: Dr. Federico Fraschetti (ffrasche@email.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.

The Ionized Molecular Gas in Luminous IR Galaxies with SOFIA

Advisor: Dr. Howard Smith (hsmith@cfa.harvard.edu)

Open for Summer Research with external stipend

The ionized component of the warm interstellar medium (ISM) in galaxies plays a critical role in interstellar processes and galaxy evolution, particularly in luminous IR galaxies (LIRGs). Not only is the warm ionized component associated with the abundant warm dust responsible for the peak emission of LIRGs, it plays a critical role in the ISM chemistry because species like OH+ and H2O+ catalyze the production of numerous species that can affect the cooling rate of the gas, affecting collapse in star formation and other processes. The warm ionized gas has also been seen to trace massive outflows (and also inflows). Molecular outflows were discovered in via FIR molecular spectroscopy in neutral species including OH and at (sub)millimeter wavelengths in CO, HCN, HCO+, and CS and now have been seen in ionized gas. The outflows affect galaxies' metallicity, dust, chemistry, and play a key role in the lifecycle of galaxies and the shaping of cosmic structures, all central questions of 2020Decadal science.

The neutral components of the ISM are moderately well understood, but the warm, ionized, molecular material has not been well studied. Herschel PACS observations found galaxies and galactic outflows with unexpectedly abundant ionized molecular gas in at least three nearby LIRGs. Cosmic rays (CRs) were identified as playing a surprisingly large role in the gas excitation. Based on spectral modeling of PACS OH, OH+, H2O+, and H3O+ absorption lines in the galaxies Mrk 231, Arp 220, and NGC 4418, the energy bound up in CRs was found to be large - up to 1% of that in their AGNs or central starbursts. The reasons for such high CR energetics are not understood but may be caused by extreme local starbursts with pronounced outflows that generate CR-producing shocks in these LIRGs. CRs, along with X-rays, can penetrate large columns of gas, ionizing H and H2, following which a relatively simple chain of ion–neutral reactions leads to the formation of OH+ . LIRGs are powered by bursts of star formation and/or by contributions from their active galactic nuclei, and in local ULIRGs the activity can be triggered by mergers. Three O-bearing molecular cations OH+, H2O+, and H3O+ have rotational transitions in the far-IR and submillimeter domains and are suitable species to trace the ionization of molecular gas and to constrain the sources of that ionization. The equilibrium abundance of OH+ is sensitive to both the ionization rate over the hydrogen density and to the molecular fraction fH2, helping constrain the fluxes of CRs that permeate the gas. Hence studies of the ionized gas and OH+ will shed light on CR production and on all these other phenomena.

We have an ongoing program studying the warm, ionized molecular material in LIRGs using SOFIA, the Stratospheric Observatory for IR Astronomy and its 2.5-m telescope flying above 41,000'. The summer student will work with us in reducing and analyzing the spectroscopic data on ~12 nearby LIRGs using SOFIA software; familiarity with python is desirable but not essential. Depending on COVID and details of the observing schedule it may be possible to participate in an observing flight.

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+2021) 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 2021). 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.

Lunar Far-side Radio Cosmology Telescope Site Survey

Advisor: Martin Elvis (CfA-HEAD), and Phil Gläser (TU, Berlin) (melvis@cfa.harvard.edu)

Neutral hydrogen should be detectable from the time of the “Dark Ages”, after the Big Bang but before any stars or galaxies had formed. The key signature will be a highly redshifted “21-cm” line. Mapping out this line at high resolution over a wide range of redshifts will show how the topology of the large-scale structure in the Universe develops in its earliest stages and will put the ultimate limits on cosmological parameters (Silk 2016, 2018.)

The problem is that at redshifts of 20-30 the frequencies we need to observe at are those of terrestrial radio and TV broadcasts. As a result, detecting this signal from Earth is hopeless. For this reason, there has been a longstanding interest in putting a low frequency radio telescope on the lunar far-side, the one place in the Solar System shielded from these broadcasts. The recent upsurge of interest in returning to the Moon has brought new life into these plans, with NASA funding preliminary studies of a Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon (https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope/) ESA concepts for a Far-side Explorer have also been proposed (https://link.springer.com/article/10.1007/s10686-011-9252-3)

Any size telescope would be a great beginning but ultimately an interferometer at least 200 km diameter will be needed to extract all the information about the early universe. The radio array would be made up of 100s of dipole antennas linked by cables. Deploying such an array is greatly helped by locating it on a relatively smooth plain with minimal boulders.

However, cosmologists have not proposed any particular location for this cosmology telescope. Finding a site is not easy given the mountainous nature of the Far-side. Very few places on the farside are more-or-less flat over 200 km scales. There are 6 possibilities: Mare Moscoviensis, Mendeleev, Mare Ingenii, and the Korolev, Hertzsprung, Apollo craters (Elvis et al. 2021). (Mare Orientale is a 7th possibility, but libration makes much of it exposed to Earth some of the time.)

This project would use laser altimeter (LOLA) data from the Lunar Reconaissance Orbiter (LRO) to create digital terrain maps (DTMs) of the 6 or 7 potential sites to find the most suitable. From the DTMs we will derive several parameters, e.g. slope maps and roughness maps on different length scales to compare the sites to each other. These results will be written up for publication and may be presented at a Royal Society meeting in 2022. The results will emphasize the need to establish a protected “radio-quiet” zone on the lunar far-side.

Elvis, M., Krolikowski, A., & Milligan A., 2021, “Concentrated lunar resources: imminent implications for governance and justice”, Philosophical Transactions of the Royal Society A, Volume 379, Issue 2188, article id.20190563
Silk, J., 2016, Challenges in Cosmology from the Big Bang to Dark Energy, Dark Matter and Galaxy Formation, arXiv:1 611.09846v2.
Silk, J., 2018, Towards the Limits of Cosmology, Found Phys (2018) 48:1305–1332.

Prerequisites: Basic python coding will be needed. This project is best suited to a Senior thesis, although a Junior thesis should be enough to set up the method and try it on one case.

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.

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.

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.

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.

The Dynamical Effects of Self-Gravity in Protoplanetary Disks

Advisors: Dr. Sean Andrews (sandrews@cfa.harvard.edu) and Dr. Rich Teague (richard.d.teague@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

The disks of gas and dust that orbit young stars are the birthplaces of planetary systems. The potential for forming planets in these disks is fundamentally controlled by how much gas is available. Unfortunately, we do not yet have a robust approach to directly measure the gas densities in disks. One challenging, but attractive, option would be to measure the subtle deviation from normal orbital motion in the gas disk imposed by its own gravitational potential, using high resolution observations of molecular spectral line emission. This project will have a student develop tools to simulate such observations and identify the optimal physical conditions and observing strategy for measuring the contribution of self-gravity to the gas disk velocity field. Ultimately, that tool will be deployed on real data from the Atacama Large Millimeter/submillimeter Array (ALMA) interferometer to assess our sensitivity to this kinematic constraint on the spatial distribution of gas disk densities.

This project has many good "off ramps" and is easily extensible for different work timescales. Our expectation is that the minimum productive effort is ~1 semester of research time, in a Junior Thesis, Senior Thesis, semester of research, or summer internship. The student researcher is strongly encouraged to have some familiarity with Python programming to get the most out of the project.

Predicting James Webb Space Telescope observations of high-redshift galaxies

Advisors: Dr. Sirio Belli (sirio.belli@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 Blue Jay survey (https://www.cfa.harvard.edu/~sbelli/bluejay.html) is a medium-size program with the James Webb Space Telescope (JWST) that will obtain spectra and images of high-redshift galaxies in 2022 or 2023. The lack of atmospheric contamination will yield spectra of unprecedented quality, from which we will be able to measure several physical properties including the galaxy ages, their past history, and their metal abundances.

In order to prepare for the exquisite quality of the JWST data, we need to develop models and predictions starting from state-of-the-art numerical simulations of galaxy evolution, such as IllustrisTNG, and libraries of stellar population synthesis, such as FSPS. Available projects include:

1. Simulating JWST/NIRSpec spectra of z~2 galaxies including realistic star formation histories and metal abundances.

2. Predicting the strength of individual absorption lines (such as those produced by magnesium and iron) for different values of stellar ages and abundances

3. Predicting the strength of individual emission lines (such as those produced by hydrogen, oxygen, and sulfur) for different conditions of the interstellar medium

4. Testing the recovery of physical properties from simulated JWST data via spectral fitting and/or analysis of line indices