Summary of Previous & Current Research

There could be no transiting exoplanets without brilliant stars looming in the background. Exoplanet atmospheres are dramatically shaped by their host star, *especially* when they are young and the stars are extremely active. My research truly straddles the boundary between young stellar activity and the consequences it yields for close-in transiting exoplanet atmospheres. **Only through these interdisciplinary means can we shed light on the true nature of these systems.**

Young stellar activity manifests itself in a variety of ways. I am primarily interested in stellar flares, which are the radiation component of magnetic reconnection events on the surfaces of stars. With the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014), we now have the data to understand the evolution of stellar flares as a function of stellar age. In Feinstein et al. (2020b), I completed the first large statistical study of broadband optical-near infrared flare rates for young stars, using a sample of 3200 stars $< 800\,$Myr; stars were identified as high-probability candidate members of nearby young moving groups, associations, and clusters. We found that stars cooler than $T_{\rm eff} \leq 4000\,$K exhibit the highest flare rates and energies. Additionally, we saw no variation in the flare rates or distributions of these stars as a function of age. This indicates that planets around low-mass stars live in extreme environments for up to a billion years, yielding consequences for planetary habitability.

Along with international collaborators, we applied the flare-detection machine learning algorithm developed in Feinstein et al. (2020b) to all of the stars observed at TESS 2-minute cadence during the primary 2-year mission. We produced a catalog of $\sim 10^6$ flares across $\sim 10^5$ stars, producing one of the largest flare catalogs to date (Günther et al. incl Feinstein, in prep). From this catalog, I lead a study which measured the flare-frequency distribution (FFDs) slope as a function of stellar mass (Feinstein et al. 2022b). The objective of this study was to evaluate if stars with internal structures different to that of the Sun produced different distributions of flares. We found that stars with large convective envelopes and fully-convective stars exhibited shallower FFD slopes, meaning they produce more high-energy flares than stars with smaller convective regions. This inspired further work by Seligman et al. (2022) to derive a new theoretical framework to modeling flare-frequency distributions as a function of coriolis force, i.e. stellar rotation. I contributed a sample of stars for which I measured rotation periods and identified flares to this work. This work provided the first evidence of a relationship between FFD slope and stellar Rossby Number.

I have recently lead and completed a detailed study of far-ultraviolet (FUV) flares on the 23 Myr M dwarf AU Mic using the Hubble Space Telescope (HST) Cosmic Origins Spectrograph (Feinstein et al. 2022c). From these data, we were able to measure the continuum flux of AU Mic, which is not easily done for M dwarfs given their relative faintness. The continuum flux is the main source of error in exoplanet atmospheric photochemical modeling (Teal et al. 2022). We were able to accurately model the transmission spectra for AU Mic b and c, which will be used to motivate future JWST observations. Additionally, I measured flare energies, durations, and modeled flare morphologies for 13 flares observed in 5 hours, yielding an intense FUV flare rate of $\approx 2.5\,\mathrm{hour}^{-1}$. We detected flares with energies up to 2×10^{31} erg, which are comparable to the 1859 Solar Carrington event (Carrington 1859). I created spectroscopic light curves from emission features tracing different temperatures/formation locations in the stellar atmosphere to understand flare formation and cooling mechanisms and place these flares into the context of our Sun.

In addition to my flare publications, I am interested in detecting signatures of atmospheric escape for young planets. I have searched for optical/near infrared signatures of atmospheric escape for the 30-40 Myr super-Neptune V1298 Tau c (Feinstein et al. 2021). We found that the strength of Hα in absorption decrease with time throughout the transit, suggesting the planet is trailed by a hot wind of hydrogen, although we could not rule out stellar activity as the origin of the signal. In addition to this Hα investigation, we measured the spin-orbit alignment (projected obliquity, λ) of V1298 Tau c through Doppler tomography and found the planet to be well aligned ($\lambda = 5° \pm 15°$; Feinstein et al. 2021). The V1298 Tau system hosts one candidate long-period (> 40 days) planet with an unconstrained period (V1298 Tau e; David et al. 2019; Feinstein et al. 2022a). I am leading a collaborative effort with scientists at Harvard and the Flatiron Institute to finally constrain and confirm this young Jupiter-sized planet using ground-based facilities. When confirmed, this will be the longest-period young transiting planet to date, and will allow us to measure atmospheric mass loss as a function of orbital separation for the planets in the same system.

A secondary research goal of mine is to detect atmospheric molecules to constrain the formation location of young transiting gas giants. I am the PI of a Gemini-S/IGRINS proposal to measure the C/O ratio of HIP 67522 b, the youngest known transiting exoplanet (17 Myr). These high-resolution ground-based observations cover $\lambda = 1.45 - 2.45\mu$m, which includes broad water, CO, CO_2, and CH_4 molecular features. All of these molecules will be used to constrain the formation location of HIP 67522 b. I have applied for additional time on Gemini-S/IGRINS for this upcoming semester to obtain similar observations of a 50 Myr planet TOI-451 b.

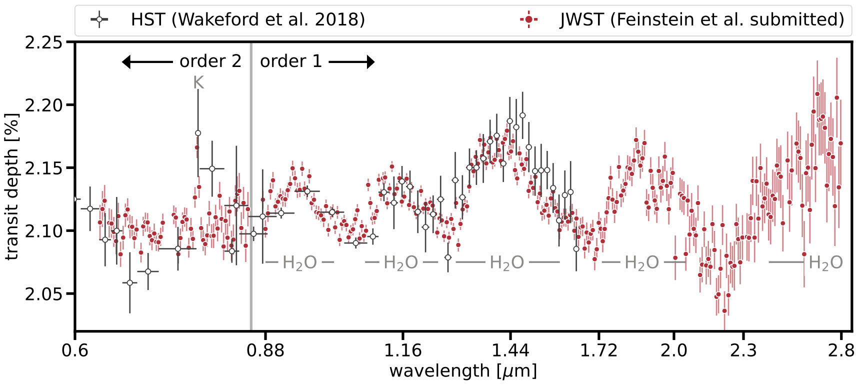

Figure 1: JWST transmission spectrum of WASP-39 b observed with NIRISS. The JWST data from my reduction pipeline are shown in red, while previous Hubble Space Telescope (HST) observations of WASP-39 b (Wakeford et al. 2018) are shown in white. We label the unambiguous signatures of absorption due to potassium and water vapour, and a 6.8σ detection of potassium at 0.768 μm.

To prepare for my own future JWST proposals, I joined the efforts of the JWST Transiting Exoplanet Community Early Release Science Team (JTEC; Stevenson et al. 2016) this past year. The goal of this community was to observe a transit of the same planet (WASP-39,) with all four JWST instruments, to provide a true panchromatic view of this planet's atmosphere. As part of this team, I am the first author of the observations of WASP-39 b using the Near Infrared Imager and Slitless Spectrograph (NIRISS). Independently of other team members, I developed my own data reduction pipeline to extract the stellar spectra. I worked closely with collaborators at University of Colorado, Boulder to create and fit the transit light curves for these data to produce the final transmission spectrum (Figure 1). Through this work, I have gained the skills necessary to propose for, analyze, and interpret beautiful JWST transmission spectra for my own programs moving forward. **This work is my 9th first-author paper as a graduate student, and is submitted to Nature.** In addition to my science contributions to the team, I was nominated and elected by my peers to serve on the JTEC Science Council, which organizes and aides in decision making for the entire team. I am **the only graduate student** serving on this council. This position has been an incredible opportunity to contribute scientifically to the team, and learn the skills necessary to lead a team of 300+ scientists across the world to achieve one common goal.

Beyond my scientific goals, I am committed to open-source science and open data availability policies. To achieve these personal goals, I have developed two software packages to support exoplanet and stellar science. My first package is called `eleanor` and extracts time-series photometry from the TESS Full-Frame Images for any source in the TESS field-of-view (Feinstein et al. 2019). This publication has 130 citations thus far; the citing papers span exoplanets to supernovae. Additionally, 150 million `eleanor` light curves have been created and are hosted on the Mikulski Archive for Space Telescopes (Powell et al. 2022). My second package is called `stella` and is a machine learning framework for identifying flares in TESS 2-minute observations. `stella` includes the convolutional neural network models for flare identification, and modules for flare characterization and stellar rotation identification (Feinstein et al. 2020a,b). The resulting method allows for flare detection in a single light curve ($\sim 15,000$ data points) in about one second, making it easily scalable to large TESS data sets.

Over my five years of graduate studies at the University of Chicago, I have lead 9 first-author and contributed to 24 papers on exoplanets, young stars, and stellar activity. By approaching both exoplanet and stellar astrophysics equally in my research, **I am uniquely poised and qualified to achieve the interdisciplinary goals of my proposal.**

Commitment to Diversity, Equity, and Inclusion in Astronomy

I am committed to breaking down representation and financial barriers to astronomy. I recognize the lack of underrepresented minorities (URMs) at all stages in STEM careers, and recognize there are several approaches to fixing the leaky pipeline.[1] As a Hubble Fellow, I will focus on reforming graduate admissions and mentoring at my host institution.

I am the founder and lead organizer of the UChicago "Virtual Graduate Admissions Information Session" which improves transparency in our admissions process. This event allows potential applicants to chat with members of the admissions committee to gain insight into the admissions process. We directly advertised this event to physics & astronomy departments across 58 recognized historically Black and Hispanic serving universities.[1] All participants received application fee waivers to help ease the financial burden of applying to graduate school. This event is held over Zoom, allowing the participation of 134 interested applicants from 13 countries. I also led the Graduate Admissions Working Group, a group of students, postdocs, and faculty who advocate for changes in the admissions process. These changes have included removing submission of General and Physics GREs scores and providing resources on how to write an application. These changes resulted in nearly doubling the number of applications from URMs (from 26 to 47). This year, I am eager to serve as the student representative on the official Graduate Admissions Committee and advocate for URM applicants who would succeed at UChicago.

Direct mentorship and support of underrepresented students, even at the undergraduate and graduate levels, will help improve DEI at the graduate to faculty level.[2] As such, I have directly mentored an underrepresented undergraduate student at UChicago during

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[1] Rudolph, A., Basri, G., Agüeros, M., et al. 2020, Bulletin of the AAS, 51

[2] National Academies of Sciences, 2019, The Science of Effective Mentorship in STEMM

this past summer. I firmly believe no undergraduate should work without financial support, which can be a significant barrier for those from underrepresented groups wishing to pursue research opportunities in undergrad.[3] Because I do not have my own research budget, I actively put in several grants to ensure my student, Rowen, was funded. We were awarded $8,500 to support her for five months of research. I ensured the project would help her develop technical skills she wanted to improve before applying to graduate school. I will continue supporting Rowen as she applies to graduate programs and writes her senior thesis.

I will bring the skill set I have developed to improve DEI efforts to any of my host institutions. I will continue mentoring underrepresented undergraduate students at my host institution. These students will be funded through a variety of routes only available at Astronomy Summer Research Experience for Undergraduates, bridge programs, and internal undergraduate scholars programs.

Research Proposal

The Evolution of Young Exoplanet Atmospheres in the Presence of Extreme Stellar Activity

Detecting and studying young planetary systems is *essential* for piecing together the key questions of how planets form and evolve, as they are a means for looking back in time to the progenitors of the older and well-studied Kepler population (Figure 2). The radius distribution of young planets (≤ 100 Myr) indicates that their atmospheres are heavily inflated and will undergo significant mass loss. This means, that at their youngest ages, they have not undergone significant processing and still retain traces of where they formed. One process for atmospheric removal at young ages is photoevaporation, wherein the high energy radiation from the host star excites and removes low-mass atmospheric particles (Owen & Wu 2017). This is due to the fact that young stars have higher X-ray and Ultraviolet (UV) luminosities than older stars of the same mass (Preibisch et al. 2005). However, it has not yet been fully explored as to if or how stellar flares (short-duration, high-energy events) play into this story of atmospheric removal.

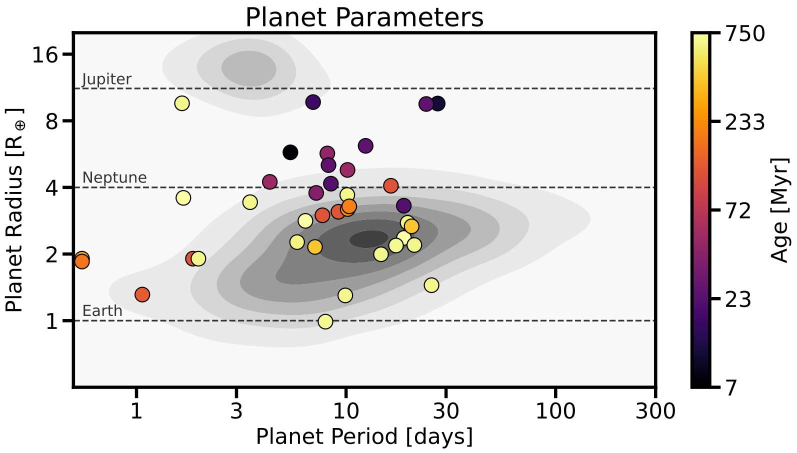

Figure 2: Radii and periods of young transiting exoplanets in the context of the older population highlighting the rarity of planets younger than 100 Myr (dots) relative to the older Kepler planets (gray contours). Given the high levels of irradiation from young stars, the young planets will likely undergo atmospheric mass loss and evolve into the Kepler population.

As a Hubble Fellow, I will explore three primary questions: (I) where did young close-in transiting planets originally form? (II) what are the FUV flare rates of young stars? and

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[3] Longmire-Avital, B. 2018, Seven Potential Barriers to Engaging in Undergraduate Research for HURMS

(III) what is the length of stellar cycles for young stars? Although seemingly disjointed, these three questions each play a role in our understanding of how close-in transiting planets form and evolve. The results of Objectives (II) and (III) will be used as crucial priors for analytically deriving the contribution of flare-driven atmospheric mass-loss to young planetary evolution. This work establishes the groundwork for a more complete view of how the demographics of older transiting planets have been shaped by their host stars.

I. Constraining the Formation Location of Close-in Planets

The atmospheres of young planets are some of the most pristine tracers of planet formation. Thus, the carbon-to-oxygen ratio (C/O) derived from infrared (IR) measurements of CO, CH_4, and H_2O is our best opportunity to learn about the formation location of young transiting planets with respect to the H_2O, CO and CO_2 snowlines. **I propose to pursue both space- and ground-based high-resolution observations to constrain the formation locations of young transiting exoplanets.** Large gas-rich planets ($R/R_\oplus \geq 4$) which form beyond the aforementioned snowlines and subsequently migrate inwards *after* the disk dissipates will have elevated C/O (> 0.8) and low metal enrichment. Giant planets which form in similar locations, yet migrate *within* the disk should have lower C/O (< 0.5) and more metal enrichment (Öberg et al. 2011). Planets at large orbital separations (e.g. HR 8799; $a > 20$ AU) that may have formed in situ via gravitational instability will have C/O dependent on their formation location (Madhusudhan et al. 2014). These considerations will be crucial for testing whether hot gas giants ($P < 10$ days) formed in situ or experienced inward migration. We can also place the young close-in transiting exoplanet population in context with the young directly imaged exoplanets via these proposed measurements. This will be the first *direct* comparison of planetary atmospheres of the same age at vastly different orbital separations. The differences in these observations will highlight the role of stellar activity in shaping close-in transiting exoplanets.

I will lead this endeavor with novel JWST observations, which have already demonstrated an unparalleled view of exoplanet atmospheres (The JWST Transiting Exoplanet Community ERS Team et al. 2022). I will propose to use JWST's Near Infrared Imager and Slitless Spectrograph (NIRISS; $\lambda = 0.6 - 2.8\mu$m), with which I have extensive experience[4], and NIRSpec G395H observations to probe C/O as a function of planetary age. The wavelength coverage of NIRISS is sufficient to constrain C/O, and break the cloud/metallicity degeneracy previously affiliated with the shorter wavelength coverage of Hubble Space Telescope (HST; Feinstein et al. under review at Nature). NIRSpec G395H will extend out to $\lambda = 3 - 5\mu$m, which will allow us to directly measure the CO_2 ($\lambda = 4.2 - 4.6\mu$m) abundances for each planet. In the case we are not awarded any JWST time in the next three cycles, I will focus on analyzing already accepted proposals of young planets and combine these observations with already-obtained complimentary high-resolution data.

Second, I will continue to submit proposals for ground-based spectroscopy every semester in addition to my already-obtained data sets. For the 2023A semester, I proposed to observe the 50 Myr $4.8R_\oplus$ planet TOI-942 b. Through general calls for proposals, I will propose to observe more young planets with this technique. These observations will be complimentary to the JWST observations. IGRINS will be reinstalled on the Harlan J. Smith Telescope at McDonald Observatory and IGRINS-2 will be commissioned on Gemini-N in 2024. These new changes and additions will enable observations of new young targets currently outside of the field-of-view of Gemini-S, which I am eager to add to my sample.

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[4] Feinstein et al. submitted to Nature; `https://github.com/afeinstein20/nirhiss`

II. Measuring Young Far-Ultraviolet Flare Rates

One key problem in exoplanetary science is understanding the contribution of photoevaporation compared to other methods of mass removal. Young stars have elevated stellar flare rates (Feinstein et al. 2020b). The effects of these high-energy short-duration events on atmospheric removal have yet to be fully explored. Optical flare rates have been used as priors for modeling how atmospheric chemistry (Chen et al. 2021) and mass-loss (Feinstein et al. 2020b) are affected by stellar flares. However, flares emit the majority of their energy in the X-ray and UV. As an example, AU Mic is a 23 Myr star with an optical flare rate of 2 day^{-1} (Gilbert et al. 2022) and an FUV flare rate of 2.2 hour^{-1} (Feinstein et al. 2022c). There has been no constraint on how the optical flare rate compares to the FUV flare rate across a large, statistical sample of young stars. The flare rates of individual stars, such as AU Mic, can be used to study the evolution of particular systems. **But, in order to truly model how atmospheres of young planets respond to the intense activity of their host star, we need a better prior on the FUV flare rate of young stars as a population.** As a Hubble fellow, I will use archival Far-UV (FUV) observations of young stars to build a statistical model for flare rates as a function of age, and expand upon theoretical atmospheric mass-loss models to include the contribution from stellar flares.

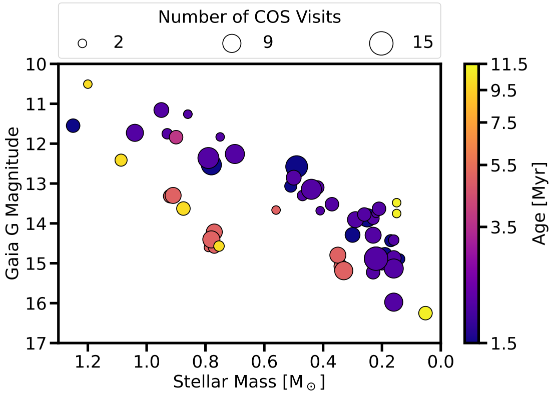

Figure 3: A sample of 56 stars younger than 15 Myr with archival HST/COS observations. I will measure the FUV flare frequency distribution of young stars. The results of this study will inform models of planetary atmospheric mass-loss.

I will use publicly-available HST/Cosmic Origins Spectrograph (COS) data of young pre-main sequence and T Tauri stars to create and analyze FUV light curves to search for flares. This builds upon my previous work (Feinstein et al. 2022c). I will use data from the ULLYSES[5] program as well as from the HST Spectroscopic Legacy Archive ($\sim$ 50 pre-main sequence and T Tauri stars) as my sample (Figure 3). Each target has $2-40$ HST visits, totaling from $1-22$ hours. Therefore, there is an opportunity to analyze as many as tens to hundreds of FUV flares in these data. If there are no FUV flares detected, or there is a lower flare rate in the FUV than the optical, this will provide evidence that early (< 5 Myr) accretion onto the stellar surface disrupts the formation of stellar flares. However, if a high flare rate is observed in the FUV for these stars **this would show that the early stages of planet formation – and the consequent chemical make-up of the building blocks of planets and planetary atmospheres – are shaped by stellar flares**.

These data will also systematically be searched for evidence of affiliated coronal mass ejections (CMEs). CMEs have been shown to compress planetary magnetospheres (Cohen et al. 2014) and strip planetary atmospheres (Lammer et al. 2007). However, evidence of CMEs in FUV observations have only begun to be explored (e.g. Veronig et al. 2021; Loyd et al. 2022). This proposed work will be the first large-scale search of flare-affiliated CMEs around young stars and provide constraints on the occurrence of CMEs on stars other than the Sun. CMEs have been theorized to increase atmospheric mass-loss and result in variable

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[5] Hubble UV Legacy Library of Young Stars as Essential Standards

transit depths over time (Hazra et al. 2022). Understanding the CME rate for young stars will help us interpret the transit depths observed during the ongoing extensive follow-up of these young planets, especially those which have already been observed by HST (e.g. GO 16163, 16194, 15836) and will be observed in JWST Cycle 1 (GO 2149, 2498).

Complimentary to these archival data sets, I will submit HST/COS proposals to build my sample of FUV flares. This will include selecting young stars with high optical flare rates (Feinstein et al. 2022b) and young planet hosts with low optical flare rates, which may experience higher flare rates in the FUV (Pillitteri et al. 2022). By selecting known planet hosts, we can better constrain the atmospheric evolutionary tracks of these planets. I will propose targets which will be simultaneously observed with TESS for a direct comparison of flare rates and energies in different wavelengths.

III. Uncovering the Length of Stellar Cycles with Flares

Instantaneously, stellar flares can have detrimental effects to atmospheric chemistry and mass-loss rates. However, in the context of understanding the full evolution of planets, longer timescales must be accounted for: that of stellar cycles. It is through long-term monitoring of the Sun that we learned the Sun goes through solar cycles, or 11-year timescales of higher and lower magnetic activity (Schwabe 1844). Through these cycles, the Sun is seen to have an increased number of and stronger solar flares; it is believed that other stars go through these long-term cycles as well (Donati et al. 2003). Therefore, when evaluating the long term evolution of exoplanets which account for the high-energy luminosity of the star, the cycles of magnetic activity and flare rates/energies must be accounted for.

While we know an inordinate amount about the Sun, it is still unclear what drives the solar cycle. **By searching for signatures of stellar cycles on other stars, I hope to not only better understand the effects of longer timescale activity cycles on atmospheric removal, but also shed light on the mechanisms driving our own Sun.** It is currently believed that the timescale of the solar cycle is proportional to the rotation period of the Sun and inversely proportional to the convective turn-over timescale, or stellar mass (Wright et al. 2011; Distefano et al. 2017). Stars are known to spin-down as they age (Soderblom 2010). If stellar cycles are correlated with the rotation period of a given star, then the stellar cycles for young, rapidly rotating stars should be shorter than the 11 year cycle we see for the Sun ($P_{\rm rot} \approx 30$ days). Using stellar flares to approximate cycles of strong and weak magnetic activity is one of the only ways to approach the question that has alluded us for so long: **what drives the length of stellar cycles?**

To achieve this objective, I will build upon my previously developed machine learning flare detection algorithm (Feinstein et al. 2020a,b) and use publicly available TESS light curves to uncover the timescales of stellar cycles for young, rapidly rotating ($\mathrm{P}_{\rm rot} < 20$ days) stars. Now is the opportune time to investigate this question, as TESS will have completed six years of operations before the completion of this fellowship. This grants us a six year baseline, longer than that of the Kepler mission, to search for changes in flare frequency distributions over time. Additionally, TESS' broad field-of-view will allow for the analysis of thousands of young stars, resulting in a large sample of stellar flares to search for statistical evidence of flare rate changes.

I will focus my work on young stars within the TESS Continuous Viewing Zone (CVZ). The orientation of the TESS cameras results in one year of continuous monitoring for stars in the CVZ, located in the ecliptic north and south poles, for Years 1, 2, 3, 5, and 6, with slightly shorter coverage during Year 4. I will measure the rotation periods of my sample via starspot modulation, and identify and measure the energies of flares within the light curves to build my sample. I will use more accurate updated TESS flare models to ensure high-fidelity energy measurements for my flare catalog (Tovar Mendoza et al. 2022). From these data, I will construct the respective flare frequency distributions per each star and compare if they have changed in a statistically significant way over the six years of observations. If no statistically significant changes are discovered in these observations, **this could demonstrate that the majority of planetary atmospheric mass will be stripped in the early lifetimes of close-in exoplanets** while the host star is in a prolonged period of heightened flare activity.

Both Objectives II and III will be used to expand upon models of flare-driven atmospheric mass-loss. While significant work has been done to improve our understanding of flare-driven chemistry in terrestrial exoplanet atmospheres (Chen et al. 2021), little has been done to quantify mass-loss rates of gas-rich exoplanets in the presence of stellar flares. As a consequence of these observations, **I will work closely with my current theorist collaborators, as well as new collaborators at my host institution, to expand these models to understand atmospheric erosion for young planets in the presence of flares.** The majority of mass-loss calculations focus on thermal processes removing the atmosphere (Owen & Wu 2017, e.g. hydrodynamic escape due to XUV flux) and do not account for non-thermal processes (Alfven 1950; Parker 1958, e.g. interactions with energetic particles in stellar winds (SWs) and CMEs). Young stars have frequent CMEs (Veronig et al. 2021) and SWs (Wood et al. 2021), which means that including these non-thermal effects is essential for understanding the early stages of exoplanet atmospheric evolution. Non-thermal processes are dependent on particle mass; these newly developed models will yield interesting results for the removal of H_2 and He, and heavier molecules like H_2O and CO_2, which are currently used as tracers for planet formation locations. These models can be extended down to terrestrial planets to address questions of habitability.

My proposed research will complete the first comprehensive view of how stellar activity shapes early exoplanet evolution through a variety of observations spanning from the FUV to the IR. This work will provide accurate priors for theoretical frameworks of atmospheric mass-loss. My previous work on all of these seemingly disconnected projects have **made me uniquely qualified to connect stellar, exoplanet, and Solar astrophysics to truly understand the early lives of young exoplanets.**

Fellowship Timeline

- January 2023: JWST Cycle 2 Proposal Deadline. Time will be requested for transit observations of a dozen young planets with NIRISS and NIRSpec G395H.
- Fall 2023: NHFP begins; IGRINS transit of HIP 67522 b paper submitted (Paper I)
- Winter 2023 – Spring 2024: Creation of flare detection and modeling pipeline for measuring the FUV flare rates of young stars (Paper II)
- January 2024: JWST Cycle 3 Proposal Deadline. Time will be requested for additional young planets which have been confirmed since Cycle 2.
- Summer 2024 - Winter 2025: Atmospheric demographics paper of young planets using both JWST & ground-based data (Paper III)
- Winter 2025 - Fall 2026: Measuring flare rates and looking for statistically significant evidence of stellar cycle lengths using TESS flare rates (Paper IV)

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