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 1). The young planets have larger radii given their predicted mass than the majority of the older planets, suggesting they have highly extended atmospheres. These highly extended, weakly bound atmospheres are likely to be eroded as the planets evolve.

One method of atmospheric removal is core-powered mass-loss, wherein the planetary core radiates the heat of its formation, thereby transferring energy to low-mass particles in the outer atmosphere Rogers & Owen (2021). Another method for atmospheric removal is photoevaporation, wherein the high energy radiation from the host star excites and removes low-mass atmospheric particles Owen & Wu (2017). Because young stars have higher X-ray and Ultraviolet (UV) luminosities than older stars of the same mass (Preibisch et al. 2005), photoevaporation is likely to occur only within the first 100 Myr. One key problem in exoplanetary science is understanding the contributions of each mechanism to atmospheric removal. **Now is the time to study young planetary atmospheres because we can observe mass-loss as a function of age**, as many of the young transiting planets have been discovered in the past few years (Mann et al. 2022). While these young planets have been targeted for follow-up spectroscopic observations, there have been no published detections of their atmospheres thus far (Feinstein et al. 2021). What is holding us back?

Young stars have large surface inhomogeneities and high stellar flare rates, both of which affect spectroscopic observations. **Only by understanding these manifestations of stellar activity can we tease out planetary atmospheric signatures via transmission spectroscopy.** As a postdoctoral fellow, I will (i) conduct an observational program to find the first evidence of extended young planetary atmospheres; (ii) use archival Far-UV (FUV) observations of young stars to build a statistical model for flare rates as a function of age; and (iii) expand upon theoretical atmospheric mass-loss models to include the contribution from stellar flares.

Objective 1: Young Planetary Atmospheres – The atmospheres of young planets are some of the most pristine tracers of planet formation, as they have not been significantly processed by their stellar environments. Thus, the C/O ratio 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.** Theory predicts that 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 ($a > 20$ 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. Because young planetary atmospheres are highly extended and rapidly evolving, they are promising targets for transmission spectroscopy.

I will lead this endeavor with novel JWST observations, which have already demonstrated an unparalleled ability to measure C/O and metallicity via exoplanet transmission spectroscopy (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, and NIRSpec PRISM 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. in prep). NIRSpec PRISM will extend out to $\lambda > 3\mu$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 (see Risk Mitigation section for more details).

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. Additionally, I have formed collaborations with Dr. Michael Gully-Santiago at the University of Texas Austin, which has guaranteed time on IGRINS. Through both the general and institutional calls for proposals, I will propose to observe young planets with this technique. 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.

Objective 2: The Role of Far-Ultraviolet Flares – Optical flare rates have been used as priors for modeling how atmospheric chemistry (Chen et al. 2021) and mass-loss (Feinstein et al. 2020) are affected by these short-duration high-energy events. 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. 2022b). However, 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.

For this objective, I will use publicly-available archival 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 on AU Mic (Feinstein et al. 2022b). I will use data from the ULLYSES[1] (Figure 2) program as well as from the HST Spectroscopic Legacy Archive (~ 50 pre-main sequence and T Tauri stars) as my sample. 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 young 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**.

During the upcoming proposal cycles, and throughout my fellowship, I will submit HST/COS proposals to build my sample of young stellar flares. This will include selecting

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

samples of young stars with high optical flare rates as observed with the TESS (sample description in Feinstein et al. 2022a) and young planet hosts with low optical flare rates, which may experience higher flare rates in the X-ray and FUV (Pillitteri et al. 2022). I will select stars which will be simultaneously observed with TESS for a direct comparison of flare rates and energies as observed in different wavelengths.

The FUV flare rates derived from Objective 2 will be used as priors for **Objective 3: Expanding Models of 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 in the presence of stellar flares and coronal mass ejections (CMEs). **I propose 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 (e.g. hydrodynamic escape due to X-ray and UV flux; Owen & Wu 2017) and do not account for non-thermal processes (e.g. interactions with energetic particles in stellar winds (SWs) and CMEs; Alfven 1950; Parker 1958). Young stars have frequent CMEs (Veronig et al. 2021) and strong SWs (Wood et al. 2021), which means that including these non-thermal effects in mass-loss calculations is essential for understanding the early stages of exoplanet atmospheric evolution. The stellar energetic particles from CMEs and SWs can result in atmospheric erosion via photochemical escape (Lammer et al. 1996), ion sputtering (Jakosky et al. 1994), ionospheric escape (Moore et al. 1999), and ionospheric ion pickup (Luhmann & Kozyra 1991). 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.

Timeline – A summary of papers can be found in Figure 3. During my first two years, I will gather infrared transmission spectra of 10 young planets to fulfill Objective 1. I will perform a demographic study of atmospheric compositions of young planets. During my first year, I will focus on archival HST/COS observations to achieve the goal of Objective 2. During my second year, I will build the models described in Objective 3.

Risk Mitigation – Objective 1 is the highest-risk objective because I do not have an accepted JWST program. I will continue to propose for both ground- and space-based observations throughout my three year postdoctoral fellowship. In the event that the proposed observations are not allocated any telescope time or are lost to bad weather, I will focus on analyzing publicly available data for young planets obtained in JWST Cycle 1 (GO 2149, 2498), and used already-obtained high-resolution observations to yield further insight into these systems. This project would explore how the two methods compliment and strengthen detections of particular molecules. Objective 2 uses publicly available archival observations of young stars to measure FUV flare rates. This project can be extended to search the XMM-Newton data archive for observations of young stars to extract flare rates in the highest energy regime. Objective 3 focuses on developing analytical models of non-thermal mass-loss to understand the role stellar flares have on shaping close-in exoplanet atmospheres. This does not require any new observations and is a self-contained project.

Impact on the Field – We know that some planets will lose their atmospheres as they age. My proposed research focuses on *how*. How extended are young planetary atmospheres after they form? How does the extreme stellar environment of young stars affect the rate of atmospheric mass loss? And how do stellar flares affect young planetary atmospheres? I am trying to understand the earliest stage of planet formation and evolution. This work will not only bring insight into how the vast population of hot-Neptunes and Jupiters came to be, but can also be extended to terrestrial planets and their ability to host life.

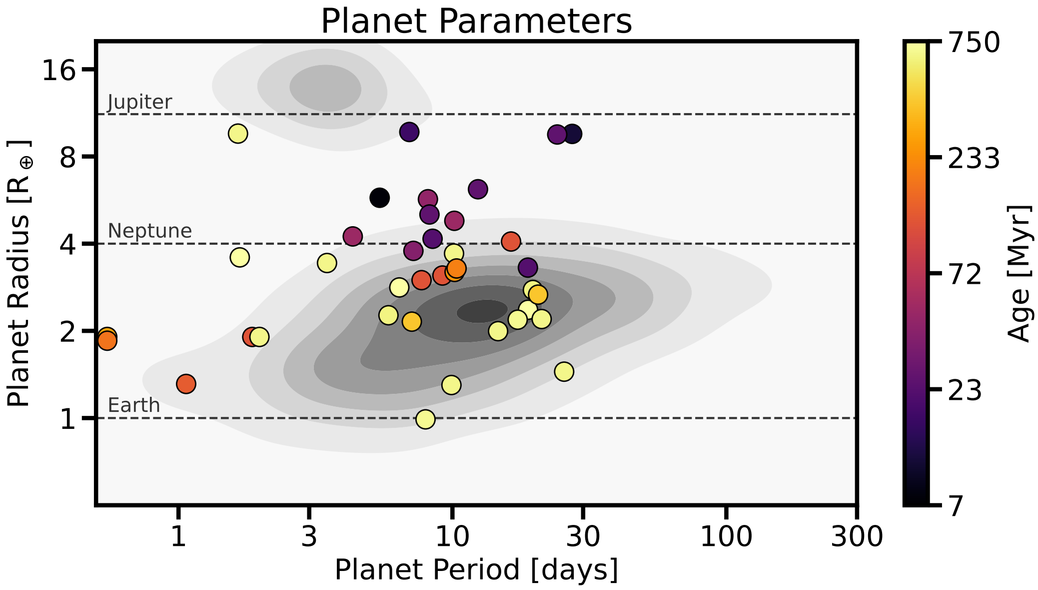

Figure 1: Radii and periods of young transiting exoplanets in the context of the older Kepler population. A period-radius diagram highlighting the rarity of planets younger than 800 Myr (colored dots) relative to the older *Kepler* planets (gray contours indicating planet occurrence). Most of the known youngest planets have radii between $4 \leq R_p/R_\oplus \leq 10$, indicating potentially significant inflation. Given the high levels of irradiation from young stars, they will likely undergo atmospheric mass loss during the next ~ 1 Gyr and evolve into the Kepler population.

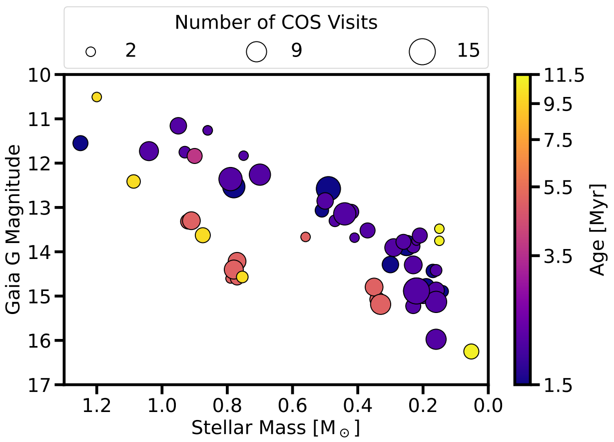

Figure 2: A sample of 56 stars younger than 15 Myr with archival HST/COS observations. I will systematically create and search the light curves of these stars to measure the FUV-frequency distribution of young stars. The results of this study will inform models of planetary atmospheric mass-loss and models of stellar flare formation and propagation through the stellar atmosphere.

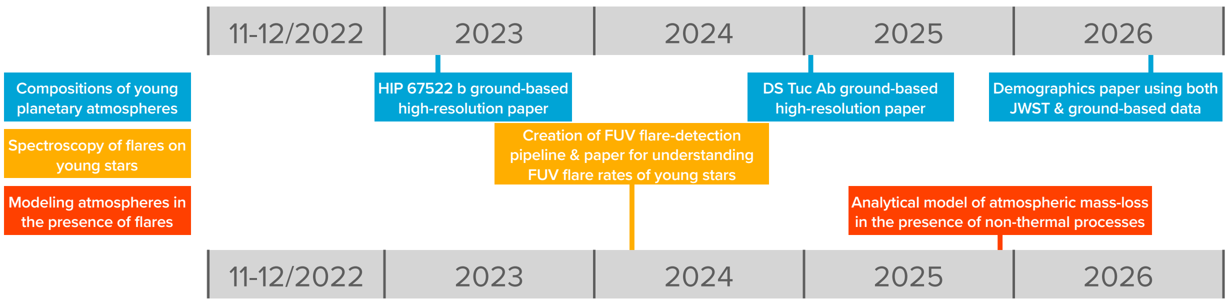

Figure 3: Proposed Research Timeline. Lines to the timeline indicated proposed submission dates per each of the five laid out papers achieving each described Objective above. The fellowship would begin in September, 2023.

Alfven, H. 1950, Cosmical electrodynamics
Chen, H., Zhan, Z., Youngblood, A., et al. 2021, Nature Astronomy, 5, 298
Feinstein, A. D., Montet, B. T., Ansdell, M., et al. 2020, , 160, 219
Feinstein, A. D., Montet, B. T., Johnson, M. C., et al. 2021, , 162, 213
Feinstein, A. D., Seligman, D. Z., Günther, M. N., & Adams, F. C. 2022a, , 925, L9
Feinstein, A. D., France, K., Youngblood, A., et al. 2022b, , 164, 110
Gilbert, E. A., Barclay, T., Quintana, E. V., et al. 2022, , 163, 147
Jakosky, B. M., Pepin, R. O., Johnson, R. E., & Fox, J. L. 1994, , 111, 271
Lammer, H., Stumptner, W., & Bauer, S. J. 1996, , 23, 3353
Luhmann, J. G., & Kozyra, J. U. 1991, , 96, 5457
Madhusudhan, N., Amin, M. A., & Kennedy, G. M. 2014, , 794, L12
Mann, A. W., Wood, M. L., Schmidt, S. P., et al. 2022, , 163, 156
Moore, T. E., Lundin, R., Alcayde, D., et al. 1999, , 88, 7
Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011, , 743, L16
Owen, J. E., & Wu, Y. 2017, , 847, 29
Parker, E. N. 1958, , 128, 664
Pillitteri, I., Argiroffi, C., Maggio, A., et al. 2022, arXiv e-prints, arXiv:2208.07415
Preibisch, T., Kim, Y.-C., Favata, F., et al. 2005, , 160, 401
Rogers, J. G., & Owen, J. E. 2021, , 503, 1526
The JWST Transiting Exoplanet Community ERS Team, Ahrer, E.-M., Alderson, L., et al. 2022, arXiv e-prints, arXiv:2208.11692
Veronig, A. M., Odert, P., Leitzinger, M., et al. 2021, Nature Astronomy, 5, 697
Wood, B. E., Müller, H.-R., Redfield, S., et al. 2021, , 915, 37