Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

The applicant maintained a good academic record in a rigorous course of study, while simultaneously engaging in multiple and varied research opportunities. Research topics included analytical, instrumentation, and gender equity, and resulted in numerous publications (including four first author) and presentations. Letters affirm the applicants scholarly productivity, maturity, and overall potential. The potential of discovering the first exomoons makes excellent contributions to the field, and I appreciated the applicants reference to the 2020 Decadal Survey to support the importance of the work. Building upon work the applicant has already completed, the knowledge and mentoring support necessary to complete the work are available to the student. The instrumentation is already collecting data, and necessary telescope time is available, indicating the resources are available to see the project to completion.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

In addition to the research and publication on gender equity mentioned above, the applicant not only serves as a TA but is undergoing additional training to earn a Certificate of Practice in University Teaching. As an undergraduate, the applicant was active in Active in Marginalized Identities in Physics and Astronomy (MIPA), Women+ in Physical Sciences (W+PS), and the Society of Physics Students (SPS), and as a graduate student continues involvement in several equity focused organizations. Future plans involve creating a lecture series for the public and mentoring an undergraduate in a summer research project. The applicants track record and future plans are commendable. Regarding the research plan, it is difficult to overstate the importance and public interest that comes with possible discovery of the first exomoons. While the plan did not overly discuss the details, spectroscopic analysis of directly imaged exoplanets also has important contributions to understanding exoplanet atmospheres and the search for habitable worlds outside our solar system.

Summary Comments

This was a very strong application, both in terms of intellectual merit and broader impacts. The applicant has a bright future and is poised to make important contributions to science in the near term and beyond.

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

The applicant has a strong research record with two related research papers as first author and a second author paper submitted, in addition to other presentations and publications (in other fields). This multi-component interest and variety of experiences illustrate that the applicant has a range of skills and interests and can bring multiple types of projects to successful completion and publication. The proposed project involves the search for exomoons and is very well described. In particular, the applicant displays a clear understanding of the data processing and observational limitations imposed by the instruments. Even if no exomoons are discovered, the proposed work has the potential to inform our understanding of exoplanet system formation. The host institution has access to the Keck telescopes and observing time needed to complete the proposed project. Additionally, data are in hand so that significant work can be completed even if there is inclement weather. The applicant has displayed the needed observing and data processing skills, including Python coding, needed for the proposed activities.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

The applicant has a very strong record of broader impact activities related to inclusion, particularly among women in science, including participating in MIPA, W+PS, and SPS. There is also a record of leadership through serving on the board for GWiPMA. Another strength is that the applicant is pursuing a Certificate of Practice in University Teaching, which is an indication of a commitment to improve pedagogy. Not only this, but the applicant has also been involved in researching gender bias in publication timelines. Rather than the usual general interest in inclusion, this application clearly shows an interest in quantifying and understanding where gender biases are present and to what extent. The proposed activities for this project include a continuation of public outreach, lecture series, and mentoring of undergraduate research students.

Summary Comments

Overall the applicant is very strong in the needed skills and has a demonstrated history of commitment to outreach and inclusion in STEM. The proposed research has the potential for very high impact on the field of exoplanet system studies.

Intellectual Merit Criterion

Overall Assessment of Intellectual Merit

Excellent

Explanation to Applicant

Strengths: The proposed plan is creative, original and with a strong potential to obtain transformative results. The plan is well reasoned and organized. The applicant and team are uniquely qualified to carry out the proposed plan. The plan also includes expected outcomes. Finally, the applicant seems to have sufficient access to resources to carry out the plan. Weaknesses: None noted.

Broader Impacts Criterion

Overall Assessment of Broader Impacts

Excellent

Explanation to Applicant

Strengths: The applicant has demonstrated commitment to improve equity in the field. The applicant has also been taking steps to excel as instructor and mentor. The BI plans are detailed enough. Weakness: There is no plan in place to document the results of the BI efforts

Summary Comments

This is overall an outstanding candidate. The research plan is really strong and the BI plans are detailed. There is not plan in place to document the results of the later, but this is only a minor weakness.

Starting college was a huge culture shock for me. I went from having mainly female teachers and classmates to collaborate and form relationships with to becoming a noticeable minority within all my classes. Although I was disheartened, one day I unexpectedly received an email promoting the Conference for Undergraduate Women in Physics (CUWiP). I decided that attending would help me determine if I wanted to continue getting a physics degree. At the conference, I was blown away by the sheer amount of diverse career scientists and students who identified as women pursuing physics, and the solidarity of those promoting diversity. Since I come from a background of mixed Vietnamese, Israeli, and German heritage, the representation of women and people of color at CUWiP truly resonated with me. I found a new vigor for pursuing my degree and felt like I now had a community supporting my academic path.

Intellectual Merit

Attending CUWiP inspired me to reach out to mentors and begin conducting research. I was interested in working with Professor Virginia Trimble at UC Irvine since I was inspired that she was one of the first women to graduate with a PhD in astronomy from Caltech, had published over 600 works in astrophysics, and even had an asteroid named in her honor. After speaking with Professor Trimble, we agreed to work on a project that mapped the history of papers concerning Newton's gravitational constant to understand the difficulty of finding a more precise value, even with international collaboration. I was tasked with leading the project and determining what methods we would use to best visualize the data. After publishing our findings as first author (Horstman, K. and Trimble, V. A, 2019, *Scientometrics*), I was selected to referee another work submitted to *Zeitschrift für Naturforschung A*., a German academic journal. I provided feedback on a basic torsion balance experiment used to calculate Newton's gravitational constant. This first research experience allowed me to lead a project, conduct and draw conclusions on research independently for the time, and understand the importance of scientific communication.

After I finished my project with Professor Trimble, I felt confident in my abilities to conduct research. I reached out to my former introductory astrophysics professor, Professor Alice Shapley at UC Los Angeles. Professor Shapley was my first female professor at UC Los Angeles and showed a passion for teaching undergraduates that seemed uncommon. Despite her obligations as a professor and the vice chair of the department, she still made time to work with interested students on research projects concerning galaxy formation and evolution. My next research project explored galaxy formation by comparing local (z~0) and high redshift (z~2) galaxies to explore our understanding of galaxy evolution and assembly. We aimed to determine whether high redshift (z~2), merging galaxies are characterized by higher star formation rates and diluted metallicities compared to non-merging galaxies because in the local universe and in cosmological simulations of galaxy formation, merging galaxies experience nuclear gas flows that both fuel star formation and dilute metallicity. To investigate this, I used existing data collected from the MOSFIRE Deep Evolution Field (MOSDEF) survey to explore trends between stellar mass, metallicity, and star formation rate and learned how to code in Python to establish a sample and analyze our data set. As I was starting to think about publishing this work, I noticed there was an inconsistency with one of my plots and the trend we expected to see from our data. Since I had little experience coding before this project, it took me several weeks to realize that I had fit a line to my full sample instead of the subset I was trying to fit. Although this did not change the main outcome of our project, it taught me the importance of verifying my process and investigating inconsistencies. After confirming the rest of my code's validity, I found my analysis indicated SFR enhancement and metallicity deficit for merging systems relative to non-merging systems for a fixed stellar mass at z ~ 2, though larger samples are required to establish these preliminary results with higher statistical significance (Horstman, K. et al. 2020 *MNRAS*). I worked on this project for over a year and having such a large time frame allowed me to deeply explore the topic and master techniques associated with cosmological observational research.

Working with my two female mentors gave me the confidence and direction to reach out to other professors for research opportunities related to my newfound interests. From my research with Professor Shapley, I became curious about how distant galaxies are imaged. I learned about imaging techniques in the near infrared (NIR) and consequently discovered that NIR instrumentation and imaging is also used to detect exoplanets. The summer of my junior year, I participated in the Caltech Summer Undergraduate

Research Fellowship (SURF) program and worked with Professor Dimitri Mawet on the Palomar Radial Velocity Instrument (PARVI), a diffraction limited, fiber fed, high resolution spectrograph at the Palomar Observatory. To help PARVI achieve one of its main science goals, confirming the dynamical masses of candidate planets discovered by the NASA TESS mission, I actively added to the PARVI Data Reduction Pipeline (DRP). I worked on extracting radial velocities from one dimensional spectra using forward modeling techniques. I learned how to verify each component that creates model spectrum and practiced isolating individual components to understand how they were incorporated into the model. Through modeling PARVI's spectral data, I was able to learn more about how spectrographs function and understand how to translate physics and optics concepts into models that match observational data. Tangentially, I started work on another instrumentation project with Professor Michael Fitzgerald at UCLA related to the DRP for OH Suppressing InfraRed Imaging Spectrograph (OSIRIS) at the W.M. Keck Observatory. The goal of the project was to explore the signal processing method, Non-negative Matrix Factorization (NMF), to separate blended spectra produced by an integral field spectrograph. Having well separated spectra is important so astronomical objects, such as exoplanets or stars in the galactic center, are characterized by the proper flux at each discrete wavelength. It was a welcome challenge to understand a new DRP and try to apply signal processing methods to data that is not normally compatible with the pipeline. I found applying NMF to calibration scan data showed reduced crosstalk, or the physical manifestation of blended spectra on the detector, of up to 26.7% ± 0.5% while not adversely impacting the signal-to-noise ratio (Horstman, K. *et al* 2022, *PASP*). <u>From working with astronomical instruments, I learned I enjoy projects that straddle the intersection of science and engineering and developed technical skills and the instrumentation knowledge necessary to understand how astronomical data is reduced.</u>

Since starting graduate school at Caltech, I have been involved with a variety of interdisciplinary projects, extending the work I started as an undergraduate with Professor Dimitri Mawet. I have continued to work on DRPs by contributing to characterizing the wavelength solution of the Keck Imager and Characterizer (KPIC), a high contrast imaging suite attached to a high-resolution spectrograph, at the W.M. Keck Observatory (Keck) and have participated in multiple observing runs at Keck. Through these projects, I have had the opportunity to work with both engineers and physicists to gain a deep understanding of high contrast imaging and high-resolution spectroscopy. Using data from KPIC observing runs, I started a new project looking at the possibility of discovering exomoons, or moons outside our solar system, around directly imaged planets to learn more about circumplanetary disks and planet formation. Collaborating with those in the Division of Geological and Planetary Sciences and groups specializing in precision radial velocity measurements at Caltech, I have explored the prospects of searching for exomoons with future instrumentation and telescopes, such as the spectrographs HISPEC and MODHIS planned to be on Keck and the Thirty Meter Telescope (TMT) respectively. <u>I was able to apply my previous experience working with DRPs and spectrograph data to create predictions for future, detectable exomoon masses, significantly contributing to the wider collaboration and a submitted publication (Ruffio, J.B., Horstman, K., Mawet, D., et al 2002, *submitted to AJ*).</u>

<u>Broader Impacts</u>

Underrepresented Minorities in STEM: Wanting a way to explore diversity within the astrophysics community, I started another research project with Professor Trimble looking at the correlation of time from submission to acceptance of astronomical papers for men versus women lead authors. I used data scraping techniques and a gender determining application program interface to determine the gender of around 4000 different first authors who published papers in 1998 and 2018. Using a Kolmogorov-Smirnov (KS) test to decide if the two differing distributions for females and males come from the same parent distribution, we found that on average, in the years 1998 and 2018, there was a 2-week difference in elapsed time from submission to acceptance for male versus female first authored papers. We believe that although a 2-week difference may not be a substantial enough period to cause concern, it raises other issues within the community that must be addressed, such as the role nationality and intersectionality play in discrimination regarding academic literature (Horstman, K. and Trimble, V. A, 2020, *BAAS*). In addition to my academic research, <u>I will continue to be involved with research efforts exploring bias in astrophysics</u>

during my graduate studies because I believe it is important to monitor the progress of diversity, equity, and inclusion efforts, address potential discrimination, and inform existing efforts as a member from within the community.

Outside of this project, to help foster a community for underrepresented junior scientists in physical sciences, I was an active participant in Marginalized Identities in Physics and Astronomy (MIPA), Women+ in Physical Sciences (W+PS), and the Society of Physics Students (SPS) at UCLA. At Caltech, I have continued to be involved with organizations representing minorities in STEM, such as serving on the leadership board for Gender Minorities and Women in Physics, Math, and Astronomy (GWiPMA). Additionally, I was invited to speak at FUTURE Ignited, a one-day conference designed to support underrepresented young scientists and allies through providing insight into life as a graduate student and exploring what makes a successful graduate school application. I spoke to future graduate students about my academic journey and graduate school experience so far. One of the greatest benefits to these organizations, and one of the reasons why I am still in physics today, is because these groups foster an inclusive community. They provide a place for others to reach out to mentors, find collaborators, and become a mentor themselves. It is imperative that throughout my graduate study that I continue to be a leader and mentor within diversity groups by forming personal relationships, leading workshops, and hosting events for those traditionally underrepresented in STEM.

STEM Education and Outreach: Another way I participate increasing STEM diversity is through encouraging youth involvement in science and promoting STEM education. When I was a senior in high school, volunteers at a solar viewing event encouraged me to become involved with my local observatory because they noticed I was interested in both learning and teaching others about space. As a docent, I conducted stargazing events, learned how to operate a telescope, and taught the public about astronomy, leading me to pursue an astrophysics degree. This experience changed my academic trajectory and led me to seek out a career in STEM. Now, as a graduate student, I see the importance of experienced students in communicating science through outreach and educational experiences. As a graduate student, one of my responsibilities is to work as a Teaching Assistant (TA) to help undergraduate students understand material taught in introductory physics and astronomy courses. To learn how to be a more effective instructor, I am currently in the process of obtaining the Certificate of Practice in University Teaching (CTLO) at Caltech. This program teaches those interested in effective methods for teaching and learning, how to assess and implement a teaching philosophy, and how to refine teaching pedagogy through feedback and self-evaluation. As part of the program, I am encouraged not only to lead my TA sessions, but to also develop guest lectures and materials for courses of interest. In addition to my regular TA responsibilities, I plan to develop guest lectures for both introductory astrophysics courses, through CTLO, and the public, through the established Stargazing Lecture Series at Caltech, to explain basic concepts behind exoplanet science and instrumentation to encourage STEM involvement.

Future Goals

Working with multiple mentors on a variety of projects has allowed me to explore the interdisciplinary nature of astrophysics. I have learned the importance of how science is communicated within the field, studied the evolution of some of the largest structures in the universe, investigated gender bias within academia, and worked with state-of-the-art instruments to study exoplanets. I now realize how vast and varied the field of astrophysics is, and that I have a place in it.

The next step in my academic journey is to complete my PhD at Caltech so I can continue advancing my understanding of astrophysical instrumentation and exoplanet science. I feel fortunate to be a graduate student continuing my career in astrophysics not only because I love the work I do, but also because I have the opportunity to become a role model for others within the field. Being awarded an NSF graduate research fellowship will allow me to become an established scientist within the field and provide me the resources to continue advocating for diversity and retention within astrophysics through established programs and teaching.

Discovering exomoons from RV measurements around self-luminous planets

Keywords: *exoplanets, exomoons, direct imaging, radial velocity, data reduction pipeline*

Until the mid-1990s, we did not have concrete evidence that planets existed outside of our solar system. Now, exoplanet demographic studies emphasize the wide diversity of planets that exist, such as Super-Earths, mini-Neptunes, and hot Jupiters. Recent technological advances promise a similar shift as we expand our search for moons outside our solar system, or exomoons. As an NSF Graduate Research Fellow, I will search for the first exomoons around directly imaged planets and brown dwarfs, and constrain their occurrence rates, contributing to 2020 Decadal Survey on Astronomy and Astrophysics' goal of exploring exoplanet and circumplanetary disk formation, placing our solar system in context, and providing new worlds to search for habitability.

Intellectual Merit

Introduction: We predict exomoons to primarily form in the circumplanetary disk (CPD) surrounding an exoplanet or from gravitational instabilities. Focusing on the in-situ case, CPDs are an expected outcome of planetary formation, since material not used in formation remains around the planet. The typical CPD total dust mass relative to the planet is around 10^{-4} [1,2], which is consistent with the mass ratio of the Galilean satellites, suggesting the ubiquity of Galilean moon analogs around Jupiter mass exoplanets. Similar to binary star formation, gravitational instability can create companions with mass ratios close to unity and are thought to form in bound systems as often as ~45% of the time when orbiting a host star [3]. By understanding binary planets of BDs formed through instability versus exomoons formed in the CPD, we can learn about the different formation pathways of planets.

Directly imaged companions could be a promising place to look for exomoons since they have unique formation and migration history that may make them more likely to retain satellites [4]. Only a few exomoon candidates have been proposed using transits and direct imaging, but none have been confirmed [5,6,7]. To explore a complementary parameter space to continue the search for exomoons, we couple high resolution spectroscopy with high contrast imaging to directly measure the RV of the planet. This can be achieved by using a new class of spectrograph, currently represented by the Keck Imager and Characterizer (KPIC) at the W.M. Keck Observatory (Keck). KPIC combines high contrast imaging with high resolution spectroscopy (R~35,000 in K band) to study directly imaged exoplanets in unprecedented detail.

To constrain the current capabilities of KPIC, we used observations of the BD companion HR 7672B targeted over a full night to find that KPIC is sensitive to exomoons with a mass ratio of 1-4% at separations similar to the Galilean moons around Jupiter [8]. To investigate prospects of searching for exomoons with future instrumentation and telescopes, such as the spectrographs HISPEC and MODHIS planned for use at Keck and the Thirty Meter Telescope (TMT) respectively, I constrained recoverable moon-to-planet mass ratios for simulated directly imaged planets. For more massive planets (>10 M_{Jup}) and BDs, we expect TMT/MODHIS to reach the RV sensitivity needed to look for close in exomoons. TMT/MODHIS will be capable of detecting mass ratios smaller than 10^{-4} for a median system age of 30 Myr, showing that our preliminary work is foundational to the future of detecting exomoons.

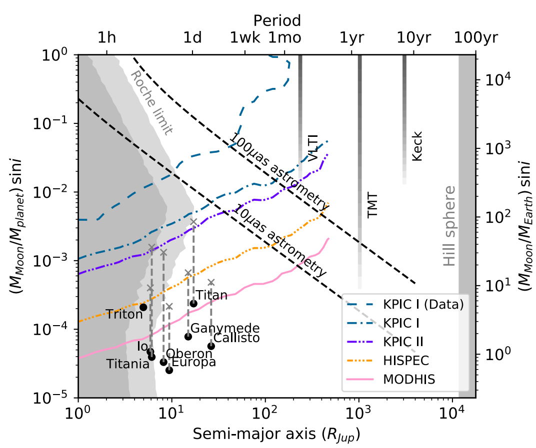

Figure 1: Detectable moon-to-planet mass ratio for different instruments around brown dwarf HR 7672B. Simulated sensitivities are shown in colored curves assuming 6 nights of observations over 25 days. The sensitivity demonstrated in this work from ~ 1.5 nights of KPIC observations is labeled as KPIC I (Data).

Research Plan: As a Caltech graduate student working with Professor Dimitri Mawet, I have access to the twin 10-meter telescopes at Keck. Historically, our group receives 6+ nights of observation a semester on KPIC and we currently have over two years of data on directly imaged planets and BDs.

Research Goal 1: KPIC is in the process of receiving upgrades, including a Laser Frequency Comb (LFC) with an expected calibration accuracy of <10 m/s, which should provide substantial gains in RV accuracy. The addition of an LFC to KPIC was heavily influenced by its effective implementation on the Palomar Radial Velocity Instrument (PARVI), a diffraction limited, high-resolution spectrograph at Palomar Observatory. My previous work on the data reduction pipeline (DRP) of PARVI and my current work on the KPIC DRP related to wavelength stability naturally lends itself to creating a dedicated RV extraction pipeline for KPIC data. Once the LFC commissioning begins in September 2023, I will begin work on the RV DRP for high-contrast companions, incorporating lessons learned from modeling dense telluric lines in the near-infrared and combating strong contamination from the host star not found in typical optical RV DRPs. Additionally, I will develop a python package that will extract RVs for any target planet imaged by KPIC. Once precise RVs are extracted, other well-established python packages, such as RVsearch [9], can be used to search for periodic exomoon signals in planetary RVs and calculate the detectable mass ratio between the moon and planet.

Research Goal 2: While working on the RV pipeline, I will carry out deep observations of GQ Lup B to begin searching for exomoons formed in the CPD. Currently, KPIC has several epochs of data available for GQ Lup B, a 10-36 M_{Jup} companion with signs of a potential moon carving out a gap in its CPD [10]. We estimate, based on KPIC's empirical performance and the instrument simulator PSIsim [11], that 6x0.5 nights with KPIC would be sensitive to a moon-to-planet mass ratio of ~$2x10^{-3}$ or a ~$13M_{Jup}$ companion mass at the measured CPD radius of $65R_{Jup}$. I will reduce the current data available and combine it with additional observations to create an RV time series of GQ Lup B. I will then analyze the data to search for periodic exomoon signals from planetary RVs to identify the detectable mass ratio, as done in Figure 1.

Research Goal 3: To start exploring high mass ratio systems currently detectable with KPIC, I propose to carry out a snapshot survey to look for satellites formed through gravitational instability. I plan to conduct a 3-year survey, observing one epoch per target, to look for spectroscopic BD binaries around the > 20 planets directly imaged by KPIC. To identify equal mass binaries, we can discern unique spectral line shapes based on the different spin of each object using Cross-Correlation Function (CCF) analysis [12]. For binaries with mass ratios less than 1 and orbital periods of less than a year, we expect RV variations of > 1 km/s, based on RV semi-amplitude equations, which is easily detectable by KPIC.

Research outcomes: I will constrain satellite occurrence rates, and possible detections, from the first RV survey of exomoons around directly imaged planets and BD companions and build a dedicated RV pipeline for high-contrast companions. Establishing a process to look for detectable exomoons is an important step in preparing to find Galilean moon analogs with the next generation of telescopes and instrumentation, and even if no moons are found, can place the first upper limits of moon masses able to form in CPDs.

<u>Broader Impacts</u>

Both scientists and the public are invested in the search for life on potentially habitable planets, or even moons, to answer the question: are we alone? As a Caltech student, I will utilize existing organizations to continue public outreach and STEM education related to my field of study. I will participate in the established Stargazing Lecture Series at Caltech to teach the public about the search for biosignatures and how my current research is related. Additionally, I will help undergraduate students explore their interest in exoplanet science through mentoring students in the Caltech SURF program, a paid 10-week fellowship for any undergraduate student to conduct research over the summer. I will mentor a student to work on a project adjacent to my current work and teach them how to use the KPIC. Along with individual mentoring, I will host the established Exoplanet Society of Students, a weekly meeting for SURF students that invites guest speakers and schedules lectures to explain exoplanet science and promote professional development.

References: [1] Canup & Ward, et al., Nature, 441, 834 (2006); [2] Batygin & Morbidelli, ApJ, 894, 143 (2020); [3] Burgasser, et al., AJ, 129, 2849 (2005) ; [4] Spalding, et al., ApJ, 817, 18 (2016); [5] Teachey, et al., AJ, 155, 36 (2018) ; [6] Kipping, et al., NatAs, 6, 367 (2022); [7] Lazzoni, et al., A&A, 641, A131 (2020) ; [8] Ruffio, Horstman, Mawet, et al submitted AJ (2022); [9] Rosenthal, et al., ApJS, 255, 8 (2021); [10] Stolker, et al., AJ, 162, 286 (2021); [11] https://github.com/planetarysystemsimager/psisim [12] Konopacky, Q. M., et al., ApJ, 750, 79 (2012).