Unraveling Giant Planet Origins via Host Star Compositions

The compositions of giant planets and their host stars offer critical insights on the origins and evolution of planetary systems, but it is currently not well understood how these constraints can be used to trace the formation histories of planets. Although the primordial atmospheres of large, gas-rich planets were accreted from the protoplanetary disk as the planet formed, planetary atmospheric abundances (as a proxy for bulk composition) may differ from stellar abundances depending on the system's formation, migration, and evolution. Elemental abundance ratios thereby encode the formation histories of planetary systems, since these ratios correspond to the initial disk composition. In the Solar System, elemental and isotopic ratios for the gas and ice giants (Owen & Encrenaz 2003) have provided support for core accretion formation models (Pollack et al. 1996). Understanding the relationship between host star elemental abundances and the observed chemical compositions and cloud properties of exoplanets will thus provide key constraints on the formation and evolution of these systems.

As a Carnegie Earth & Planets Laboratory (EPL) Postdoctoral Fellow, **I aim to connect stellar elemental abundances and planetary atmospheric compositions to inform formation scenarios for gas giants.** Specifically, I will:

1. measure precise, differential elemental abundances for stars hosting giant planets that will be observed as part of scheduled *James Webb Space Telescope* (JWST) programs as well as planets with well-characterized atmospheres from current space-based and ground-based transmission spectroscopy surveys;
2. investigate empirical correlations in the measured stellar abundances, observed planetary compositions, and other system parameters to explore the influence of host star characteristics on planetary composition; and
3. expand equilibrium chemistry disk condensation models to explore stellar abundance patterns of refractory elements imprinted in the disk interior to the water snowline, which will provide the first constraints on where and how the planets in my sample formed.

In this way, I will begin to connect the observed diversity of exoplanet atmospheric compositions and cloud properties to the environments in which they formed.

To accomplish this goal, I will measure stellar compositions using spectroscopic observations of 50 giant planet host stars. This sample includes stellar hosts of planets that will be observed as part of the JWST Early Release Science (ERS) and Guaranteed Time Observations (GTO) programs, as well as stars hosting planets with transmission spectra already taken as part of the *Hubble* Panchromatic Comparative Exoplanetology Treasury (PanCET) survey and the ground-based Arizona-CfA-Católica Exoplanet Spectroscopy Survey (ACCESS) program.

For the past two years, I have been leading observational campaigns to obtain high-resolution (R~65,000), high signal-to-noise (SNR~150/pixel) optical (0.3–1 μm) spectra for giant planet host stars using Magellan/MIKE for southern targets and Keck/HIRES for targets observable from the north. This observational setup yields accurate elemental ratios (±0.1 dex) and an uncertainty on the absolute abundance of each element of about 0.05 dex, which corresponds to 0.5 mÅ precision in equivalent width. I have already obtained spectroscopic observations for all of the PanCET, ACCESS, and JWST ERS hosts. For the GTO targets, I have secured time on MIKE during the 2020B semester and have also applied for HIRES time in 2021A.

1. Measuring Stellar Elemental Abundances

In my first year as a Carnegie EPL Fellow, I will measure stellar chemical abundances of C, O, Mg, Si, Na, K, Ti, and V – elements that each play a critical yet not fully understood role in

the atmospheric chemistry of giant planets. I can measure the stellar C/O ratios from the C and O abundances, which provide key information about the planet's formation environment if compared with the precise planetary C/O values to be obtained with JWST (e.g., Öberg et al. 2011). Mg and Si abundances in the host star are useful for constraining planet cloud compositions, as magnesium silicate aerosols are considered key cloud-building species (e.g., Marley et al. 2013; Gao et al. 2020). Since planetary alkali abundances are directly observable in optical transmission spectra, stellar Na and K abundances can provide insights on clear atmosphere planets which – contrary to theoretical predictions (e.g., Seager & Sasselov 2000) – are often missing K absorption features (e.g., Nikolov et al. 2018). Stellar abundances of Ti and V are also useful for comparisons with observed planetary spectra because these species are informative for understanding rainout and atmospheric transport in giant planet atmospheres (e.g., Fortney et al. 2013).

I will use the open-source Python-based iSpec code (Blanco-Cuaresma et al. 2014) to employ a line-by-line differential equivalent width technique, following the methods outlined in Bedell et al. 2014 and Meléndez et al. 2017. To facilitate a differential analysis and cross-calibrate the full sample, I have obtained solar spectra reflected off of Vesta from both MIKE and HIRES in the same observational configuration as my target stars. In anticipation of the transformative data that we will obtain with JWST, **I will assemble a catalog of precise, homogeneously derived elemental abundances for host stars of well-characterized planets – a critical deliverable for maximizing the science objectives of this future facility.**

2. Exploring Empirical Correlations in Stellar and Planetary Compositions

In the fellowship's second year, I will begin to investigate the impact of stellar characteristics on the outcomes of planet formation. I will first analyze empirical correlations in the measured stellar compositions as a function of observed planetary abundances published in the literature, stellar metallicity, orbital distance from the host star, and other system parameters that have been found to influence planetary composition (e.g., Fischer & Valenti 2005; Thorngren et al. 2016). Planet formation theories postulate that the stellar abundance pattern in the protoplanetary disk is imprinted on the compositions of planets (e.g., Öberg et al. 2011; Mordasini et al. 2016; Espinoza et al. 2017). I will provide the first direct tests of these theories with my empirical abundance comparisons. **These results will lay the groundwork for a new area of research connecting observed planetary and stellar abundances**.

3. Modeling Condensation Sequences in Protoplanetary Disks

Expanding on these empirical correlations for the remainder of the Carnegie EPL Fellowship term, I will develop a simple static disk condensation model akin to that presented in Öberg et al. 2011, but focused on exploring expected elemental abundances of refractory species (e.g., Na, K, Mg, Si, Ti, V) based on their condensation lines in the disk. In the solar nebula, a typical condensation sequence begins with refractory oxides and silicates, followed by iron and nickel, then alkali and chalcophile (sulfide-loving) elements, and finally volatile species (Morbidelli et al. 2016). Since condensation lines fossilize a planet's formation location in the disk, I will compare the observed stellar and planetary abundances to my model in order to discern possible formation locations and scenarios for the planets in my sample.

I will model disk elemental condensation sequences at distances between 1–5 AU for disks around stars of different spectral types (e.g., Öberg et al. 2011), assuming chemical equilibrium at these radii in the model. Refractory elements form interior to the water snowline (<3 AU), so the condensation sequences of these species can provide a detailed probe of atmospheric abundances for planets that formed within a few AU. This disk condensation model may also help explain any discrepancies in my empirical comparisons of the stellar and planetary abundances. For example,

if a planet has no visible detection of Na absorption in the atmosphere but its host star has high abundances of Na, then it is plausible that the planet formed interior to the Na condensation line. **Informed by observed stellar and planetary abundances, these results would provide the first formation history constraints for a statistical sample of giant planets.** This work will benchmark theoretical models of planet formation and disk chemistry informed by correlations between observed planetary and stellar properties, a key milestone for this project. Further, I will collaborate with cosmochemists and protoplanetary disk experts at EPL to move beyond chemical equilibrium and develop a kinetic disk chemistry model that includes refractory elements, as well as carbon and oxygen, to obtain a holistic view of the impact of stellar abundances on disk chemistry and resulting planet compositions.

Given my expertise in designing ground-based spectroscopic observations and analyzing and interpreting exoplanet atmospheric data, **I am uniquely poised to complete this project on connecting observed stellar and planetary abundances**. The proposed stellar composition measurements complement ongoing transmission spectroscopy surveys, while expanding upon theoretical work on planetary C/O ratios as a tracer for formation histories (Öberg et al. 2011, Mordasini et al. 2016). Although I will implement abundance analysis techniques similar to Teske et al. 2019 and Rice et al. 2020, my approach covers a strategically targeted sample of host stars for which optical to infrared transmission spectra (from PanCET and ACCESS) are already in hand and precise, high-resolution observations will be observed with JWST.

Since the planetary atmospheric abundances are derived from low-resolution transmission spectroscopy, a potential risk for this project is that the uncertainties for the most precise planetary abundances (~0.3 dex; Welbanks et al. 2019) may be too large to make adequate comparisons to the elemental abundances measured from the stellar spectra (~0.1 dex). Nonetheless, the proposed project will lay the groundwork for subsequent planetary atmospheric studies with JWST. Even if I do not find any strong correlations in the abundances as a function of stellar parameters, such a result would provide interesting insight on current planet formation theory.

During the duration of this three-year fellowship, the proposed project will yield unique and impactful deliverables, including a catalog of precise, homogeneous host star elemental abundances as well as a predictive model of giant planet formation. The measured stellar elemental abundances for this sample will directly address outstanding questions regarding planet formation and the impact of system parameters on planetary composition. From the host star spectra, I can also measure the Ca II H & K line strengths as a proxy for stellar UV fluxes (e.g., Melbourne et al. 2020) to select targets for follow-up atmospheric escape observations via the 1083 nm He line.

Beyond the timeline of this fellowship, it is also possible to expand this work to measure elemental abundances for stellar hosts of sub-Neptunes and super-Earths. The stellar abundances for smaller planets are critical for breaking degeneracies in bulk compositions and providing vital insights on planet interiors (e.g., Unterborn et al. 2017, Dorn et al. 2017). Further, although high-resolution spectroscopy has not yet yielded planetary atmospheric abundances, newly developed retrieval algorithms (e.g., Brogi & Line 2019) will soon yield this information. Ultra-hot Jupiters (UHJs) have been observed at high-resolution to have atomic refractory elements in their atmospheres (Hoeijmakers et al. 2018), and I will test my disk model using UHJs with abundances from high-resolution data when these constraints are available.

The analysis proposed here will provide key constraints on theoretical models of planet formation via correlations between observed planetary and stellar compositions, opening a unique and valuable window into the formation and evolutionary histories of the large gas-rich planets in my sample. **The results of this work will constrain crucial information about gas giant**

formation locations, identify correlations in stellar and planetary parameters, and establish stellar compositions as a vital diagnostic tool for tracing giant planet origins. This study will provide invaluable insights into the chemical compositions of gas giants, a critical blindspot in the characterization of exoplanet atmospheres and the key to unraveling their formation and evolution.

Relevance to Carnegie Facilities

The telescope facilities at the Carnegie Observatories are critical to several aspects of successfully completing the proposed project. This work hinges upon high-resolution, high signal-to-noise spectra of giant planet host stars taken with Magellan/MIKE. While I already have a sample of MIKE spectra in hand, the project will require ongoing MIKE observations of stellar hosts as we obtain more planetary atmospheric observations through ongoing space-based and ground-based transmission spectroscopy surveys.

Magellan/IMACS can also obtain precise optical planetary transmission spectra (e.g., Weaver et al. 2020; McGruder et al. 2020), so facilities at Las Campanas Observatories (LCO) will enable expanding the sample of exoplanet observations for which I can measure atmospheric abundances. It is also possible to obtain high-resolution planetary spectra via the Doppler technique (e.g., Hoeijmakers et al. 2019) for my sample of giant planets using the FIRE and MIKE instruments. High-resolution spectroscopy for giant planets will complement the low-resolution transmission spectra obtained with IMACS and HST. With new retrieval modeling techniques (Brogi & Line 2019), we will soon be able to extract planetary abundance measurements from high-resolution observations.

Further, the WINERED instrument that will soon be available at Carnegie will allow for observations of escaping exoplanet atmospheres via observations of the 1083 nm helium (He) absorption line. This instrument will not only allow for He searches of southern hemisphere targets (complementary to my ongoing He programs on the Keck Telescope), but also will be critical for fully contextualizing the evolutionary histories of the planets in my sample.

As a Carnegie EPL Postdoctoral Fellow, I look forward to collaborating with the vibrant community of research scientists at EPL working on planetary atmospheres, disk modeling, and stellar abundances – three integral facets of my proposed fellowship project. In particular, Dr. Johanna Teske's interests in exoplanet compositions and the chemical environments of planet formation are well-aligned with my research program, and Dr. Alycia Weinberger's expertise on planet formation and protoplanetary disks dovetail nicely with my own research agenda. These clear scientific synergies render EPL an ideal research environment for carrying out this work.

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