National Aeronautics and Space Administration

FY23 Topic Areas Research and Technology Development (TRTD)

Close-in Exoplanet Characterization using High-Dispersion & High-Contrast Nulling Coronagraphy

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Strategic Focus Area: Extra-solar planets and star and planetary formation

Objectives: Our proposed work aimed to demonstrate on-sky the ability to directly detect and spectrally characterize faint companions, and ultimately exoplaents, at closer in separations than ever before, using the Vortex Fiber Nuller (VFN) instrument developed by our team members at Caltech and JPL and that we deployed at the Keck II telescope in February 2022. The Keck VFN will be the first high-contrast direct imaging instrument providing sensitivity to exoplanets located at a very small "inner working angle" (IWA) equal to half the telescope diffraction limit, and retaining acceptable throughput down to a tenth of it.

Background: Direct imaging promises great progress in the physical characterization of exoplanetary systems, complementing radial velocity (RV) and transit techniques in terms of accessible planetary ages and physical separations. However, that potential has yet to be realized, with only ~ a dozen young EGPs emerging from imaging surveys of hundreds of young (<~300 Myr) nearby stars with the best ground-based coronagraphs so far. The Keck Telescope Vortex Fiber Nulling (VFN) instrument was designed to detect and spectrally characterize extrasolar giant planets (EGPs) at typically 5 to 10x closer-in separations from their host stars (~20 to 100 mas) than previous state-of-the-art high contrast exoplanet imaging systems. Given the results of previous radial velocity, transit and coronagraphic surveys of exoplanets (**Figure 1**), this corresponds to the region around nearby (< 150 pc) stars where the bulk of the giant exoplanet population resides, which no other existing or planned direct imaging instrument can reach until 30m+ telescopes come online in 5-15 years. With over 20 new young EGPs expected to be spectrally characterized, Keck VFN observations promise to more than double the current tally of exoplanets directly detected and spectrally characterized, and greatly improve the current observational constraints on planet formation.

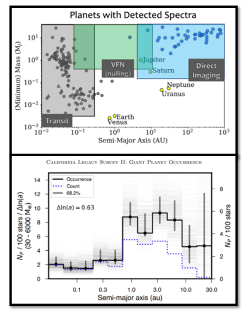

Fig. 1: VFN uniquely accesses the circumstellar region where most giant planets orbit

Approach and Results: The VFN's sensitivity at small separations stems from its interferometric nature: when inserting a vector vortex coronagraph mask in an intermediate pupil plane (**Figure 2**), the starlight beams collected by diametrically opposed parts of the Keck primary mirror interfere destructively with each other. However, due to residual wavefront aberrations - notably pointing errors -, the starlight cancellation provided by the vortex coronagraph is imperfect. The next step is to inject the residual uncancelled starlight as well as light from a nearby off-axis companion (**Figure 2, panel c**) into a single-mode fiber (SMF) feeding the Keck high resolution near-infrared spectrograph (NIRSPEC, R~35,000). NIRSPEC's high spectral resolution allows to resolve distinctive molecular lines in the off-axis companion atmosphere, further boosting the detectability of faint exoplanets in the presence of featureless stellar residuals. After the detailed lab characterization of the K-band VFN module was completed at Caltech, the KPIC/VFN instrument module was installed inside the Keck II Adaptive Optics bench in February 2022. First on-sky VFN observations were conducted successfully in March/April 2022and the VFN approach to small separation companion direct spectroscopy was first demonstrated in June 2022 on a binary system with a ~3:1 K-band flux ratio and a separation of 50 mas (1.1λ/D). On May 5 2023, less than a year later, the Keck VFN made the highest contrast direct detection to date of a companion at the diffraction limit of any telescope, detecting a close companion around a solar type star (suspected from GAIA measurements), at a separation of only 1.1λ/D again, but this time with a 2.2 um flux ratio of ~400:1 (**Fig. 3**). Finally, we have concentrated the last 6 months of our RTD effort on 3 key technical aspects that will enable further contrast performance improvements. In priority order: reduction of pointing jitter, of non-common path wavefront errors and of NIRSPEC's spectral fringing effects. The VFN pointing jitter reduction effort (**Fig. 4**) is crucial, as it will enable VFN observations of exoplanets at smaller separations and higher throughput with the new vector vortex coronagraph purchased in August 2023 by our Caltech team members.

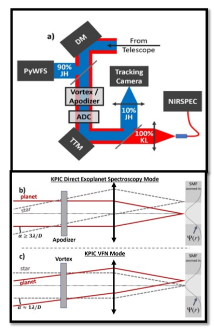

Fig. 2: VFN uses a vortex coronagraph to cancel starlight and feeds the residual light + any exoplanet light from within ~λ/D to the Keck II Telescope high res (R~35,000) IR spectrograph

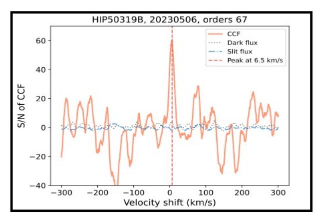

Fig. 3: May 2023 VFN observations of a binary (SB1) system. After canceling light from the primary star, a companion ~400 x fainter and 1.1 λ/D away is revealed through spectral cross-correlation. The max correlation is found with the spectrum of an M4 companion blue redshifted by 6.5 km/s, in line with prior orbital info.

To our knowledge, this is the faintest companion ever directly detected at the diffraction limit of a telescope.

Significance/Benefits to JPL and NASA: The development and demonstration of high contrast imaging/spectrocopic capabilities at or within the diffraction limit of large telescopes will have a tremendous impact on the design (telescope size, spectral resolution) and scientific yield (strong function of inner working angle) of the HWO exo-Earth direct imaging and spectroscopy mission recommended for technical and science maturation by the Astro2020 Decadal survey, and will further establish JPL/Caltech position at the forefront of this rapidly evolving field. Given the potential impact of the VFN high spectral resolution approach on the design of coronagraphic instruments for HWO (and TMT), we recommend that the Keck/VFN optimization and in particular jitter reduction effort led by JPL pointing control experts, be continued in the future in collaboration with the Caltech team (e.g., via a FY 24 PDRDF).

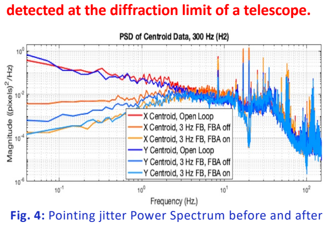

Fig. 4: Pointing jitter Power Spectrum before and after control

Publications:

- Echeverri, D. et al. 2023, " Vortex Fiber Nulling for Exoplanet Observations: Implementation and First Light", accepted for publication in the Journal of Astronomical Telescopes, Instruments and Systems and Instrumentation (JATIS). https://arxiv.org/abs/2309.06514
- Echeverri, D. et al. 2022, "Phase II of the Keck Planet Imager and characterizer: system-level laboratory characterization and preliminary on-sky commissioning", SPIE Proc. 12184. https://arxiv.org/abs/2210.15915

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