National Aeronautics and Space Administration

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

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Program: FY22 R&TD Topics
Strategic Focus Area: Extra-solar planets and star and planetary formation

Objectives:

Demonstrate on-sky the ability to directly detect and spectrally characterize exoplanets at closer-in separations than ever before, using the Vortex Fiber Nulling (VFN) instrument deployed at the Keck II telescope in February 2022 and developed by our team members at Caltech and JPL.

Background:

The 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 than possible so far. 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 before the 30m+ telescopes come online in 5-15 years. VFN observations promise to more than double the current tally of exoplanets directly imaged and spectrally characterized, and greatly improve the current observational constraints on planet formation.

Approach:

First, the VFN is designed to provide high-contrast at much smaller angular separations (20-100 mas) than current state-of-the-art coronagraphs (> 300 mas). This specificity stems from the VFN 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 are interfered destructively with each other. Any residual (uncancelled) starlight, as well as light from a nearby off-axis companion (**Figure 2, panel c**) is then injected into a single-mode fiber (SMF) feeding the Keck high resolution near-infrared spectrograph (NIRSPEC, R~35,000). High spectral resolution is used to resolve distinctive molecular lines in the off-axis companion atmosphere, further boosting the detectability of faint off-axis companions in the presence of featureless stellar residuals.

Second, our targeted survey will have a high likelihood of success, as we cross-matched the latest Hipparcos-Gaia catalog of accelerations with the list of stars in young moving groups accessible from Keck to generate an initial list of 38 well-vetted young stars with high quality astrometric acceleration measurements compatible with the presence of a substellar companion between 0.01-5" from the star.

Results:

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, and aligned with its Pyramid Wavefront Sensor plate and near-IR ultra-low noise SAPHIRA detector. First on-sky VFN observations were conducted successfully in March 2022 (**Figure 3**). The SMF coupling efficiency was measured on the sky with the vector vortex coronagraph (charge 2), showing the expected radial pattern and a peak coupling efficiency of ~9%, in line with the theoretical prediction. First spectra of a bright target star were obtained with and without the VFN coronagraphic mask (**Figure 3, bottom right panel**), showing a starlight attenuation factor of order 100:1 at the center of K-band, also consistent with model predictions. To demonstrate the VFN approach to small separation companion detection, we then observed on June 15 2022 HD 178911, a G1V + K1V spectroscopic binary system with a ~3:1 K-band flux ratio and a separation of 50 mas. The K1V companion was easily detected when fitting the VFN-observed high resolution spectrum by a stellar template with the parameters listed in **Figure 4**, and our data analysis indicated that a companion 300 times fainter than the primary would have been detected under the same conditions. The next step for the VFN is to increase contrast performance, by improving pointing control, low order wavefront control and data reduction.

Significance/Benefits to JPL and NASA:

The development and demonstration of high contrast imaging/spectroscopic 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 exo-Earth direct imaging and spectroscopy mission recommended for technical and science maturation by the Astro2020 Decadal survey, and will further establish JPL/Caltech's position at the forefront of this rapidly evolving field. The VFN technical developments and direct observations of young EGPs will advance NASA's science goal to "discover and study planets around other stars and explore whether they could harbor life", as well as address NASA's Exoplanet Exploration Program (ExEP) science gaps #2 ("modeling exoplanet atmospheres") and #3 ("exoplanet spectral signature retrieval").

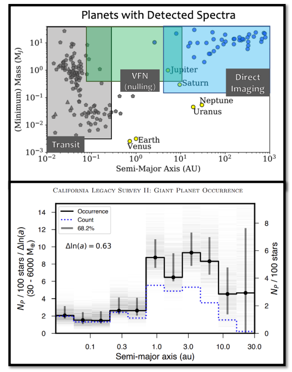


Fig. 1

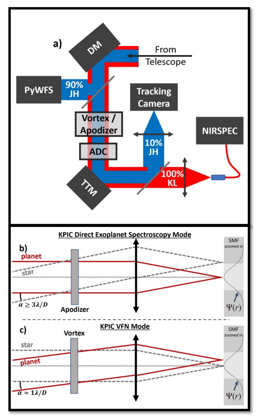


Fig. 2

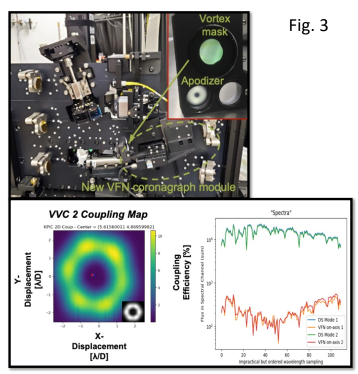
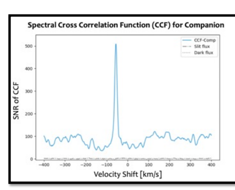


Fig. 3



Values from best fit to observed spectrum	
Teff	4760 K
log(g)	4.6
RV	-57 km/s
ΔRV	-14 km/s
V.sini	<1 km/s
Null	~3e-2

Fig. 4

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Clearance Number: CL#
Poster Number: RPC#R22106

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