Concept study for a compact homodyne astrophysics spectrometer for Exoplanets (CHASE)

Sona Hosseini*[a], Chris Webster[a], Debra Fischer[b], Evgenya Shkolnik[c], Shouleh Nikzad[a], Gautam Vasisht[a], Wesley Traub[a]
[a]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA; [b]Yale University, 260 Whitney, JW Gibbs 259, New Haven, CT 06520; [c]Arizona State University, Tempe, AZ 85281

ABSTRACT

In this concept study, we are targeting to build a new instrument to sequentially observe exoplanet atmospheres and their parent's stellar spectra over a significant time in NUV and FUV. The Compact Homodyne Astrophysics Spectrometer for Exoplanets (CHASE) offers integrated spectra over a wide field-of-view (FOV~40arcsec) in high spectral resolution ($R>10^5$) in a miniaturized architecture using no (or a small < 1m) primary mirror. CHASE's wide FOV is compatible with the relaxed pointing requirements of current CubeSats and SmallSats which makes it readily qualifiable for space in a compact format and have the potential to enable major scientific breakthroughs.

Keywords: Exoplanets, Spatial Homodyne Spectrometer, SHS, interferometry, spectrometry,

1. INTRODUCTION

Here, we describe the concept study for a new compact, high-performance, high spectral resolution ultraviolet (UV) spectrometer for astrophysics science. Exoplanet science is now in its full expansion, particularly after the CoRoT and Kepler space missions. However, lack of data and knowledge of temporal variations in the parent star's stellar spectra and abundance of key photochemical species (e.g., O_3, H_2O, CO, etc.) in exoplanets has confined our detailed understanding to develop precise models of the exoplanet atmospheric chemistry. To address this, we need simultaneous observations at more than one wavelength region especially in near-ultraviolet (NUV) and far-ultraviolet (FUV). But so far the UV observations are done by HST, and nothing is planned after HST retires in 2019.

In this study, we are studying the concept to a new instrument to sequentially observe exoplanet atmospheres and their parent's stellar spectra over a significant time in NUV and FUV. The Compact Homodyne Astrophysics Spectrometer for exoplanets (CHASE) offers integrated spectra over a wide field-of-view (FOV~40arcsec) in high spectral resolution ($R>10^5$) in a miniaturized architecture using no (or a small < 1m) primary mirror. The architecture of CHASE combines the high étendue of a Fourier Transform Spectrometer (FTS) with higher optomechanical tolerance and simpler optomechanical design associated with grating spectrometers. With an all-reflective optical design, CHASE will target specific spectral features in NUV and FUV of multiple gases of exoplanet atmospheres. CHASE's wide FOV is compatible with the relaxed pointing requirements of current CubeSats and SmallSats which makes it readily qualifiable for space in a compact format and have the potential to enable major scientific breakthroughs.

Various configurations of instruments similar to CHASE have been developed as proof-of-concept laboratory prototype, ground-based instrumentation, and sounding rocket experiments in the Optical, NUV and FUV wavelengths. These studies have demonstrated high R and high sensitivity UV spectrometers can be built in ultra-compact configurations similar to CHASE with no or small aperture telescope for a variety of space science applications.

2. SCIENTIFIC OBJECTIVES OF THE UV OBSERVATIONAL PARAMETER STUDY

Exoplanets are now being discovered in profusion and have provided many fascinating surprises and puzzles. Given the youth of exoplanet science, the field is strongly driven by observations: the very first detection of an exoplanet atmosphere was in 2002 via STIS transmission spectroscopy of the close-in giant planet HD 209458 b that led to the detection of

sodium in the planet atmosphere [1]. Following this seminal detection, Vidal-Madjar et al. [2] used STIS-FUV *Ly-α* transmission spectroscopy of the same system to reveal that the planet possesses an extended hydrogen atmosphere that is escaping hydro-dynamically. This result led to the full realization that atmospheric evaporation is a key factor shaping planet evolution [3]. The needs to advance our understanding of exoplanets are comprehensively further detailed in the Exoplanet Exploration Program Analysis Group (ExoPAG) Reports [4, 5] and in the Exoplanet Handbook reports [6]. These reports identify specific goals that vary from obtaining data on diversity and demographic to interiors, surfaces, and atmospheres.

We need to regularly explore and precise the observational, technological, and theoretical requirements to properly characterize exoplanets (of all types). A comprehensive study done by various groups [7, 8] show having optical and infrared (IR) stellar spectra data doesn't necessary provide accurate knowledge in UV regions. A key resolution to this dilemma is to collect a treasury data archive of UV transit observations for a sample of systems selected on the basis of their stellar, planetary, and orbital characteristics [7, 9, 10]. Sequential UV data set of exoplanetary systems will provide a significant observational back-bone for the below objectives:

Simultaneous observations in various wavelengths allow correlation of data sets to identify variability in highly active stars and provide robust input to planetary models. The stellar UV flux, especially the extreme-UV (EUV) and FUV components is one of the main energetic inputs for planetary upper atmospheres [9] and the uncertainties can lead to biased estimates of fundamental atmospheric parameters [11]. Stellar activity features such as spots and plages in different wavelengths creates difficulties in determining planetary parameters, produces anomalies in the transit light curve and may lead to inaccurate estimation of transit duration, depth and timing [11, 12]. *This problem becomes quite critical since the UV flux of parent stars is often very poorly known [13, 14]*.

Stellar winds play a major role in the formation and evolution of planetary systems [15]. The FUV radiation has an impact on the atmospheric photochemistry of the planet [16] and allows one to empirically estimate the stellar EUV flux responsible for the heating of the planet atmosphere [17].Constraining stellar winds is crucial to understanding planet evaporation, but because of their optically thin nature, they are exceptionally hard to observe and study [18]. UV transit observations of planets with CHASE will provide the unique opportunity to constrain the wind physical properties (temperature, density, and velocity), particularly around the crucial transition region where the wind is accelerated, which is otherwise observable only for the Sun [19, 20].

High R measurements over a very narrow spectral range and targeting atomic and molecular band features in a planet's atmosphere that are otherwise jumbled together at lower resolution has been demonstrated by Snellen et al. [21]. Observations of transit of the hot giant exoplanets in the unresolved H I Ly-α line show signs of hydrogen escaping the upper atmosphere with significant temporal variations in the physical conditions of its evaporating atmosphere [22]. Atmospheric mass loss primarily affects low-mass exoplanets, leading to the suggestion that hot rocky planets might have begun as Neptune-likes, however, no confident measurements have hitherto been available. Although the phenomenon of evaporation had been anticipated [23, 24] and calculated [2, 25], independent follow up study on the low resolution HST data confirmed, due to the planetary disk, the transit depth in Ly-α is significantly greater than the transit depth [3, 12, 26, 27]. CHASE will obtain UV transit light curves of a variety of planets with different characteristics and give us the best possible opportunity to study planet evaporation. This is key to understanding, for example, the gap observed by Kepler for intermediate-mass planets with a short orbital separation [28-30].

With UV transit observations of different close-in planets over a long time we can constrain and provide accurate boundary conditions to the various models [31-33] of the early-ingress planetary atmospheres. The WASP-12 b observations led to the detection of a thick circumstellar cloud formed of material lost by the planet. Observational [34] and theoretical [35] studies suggest that this is a common feature of many close-in planets. Because different stellar emission lines effects the circumplanetary clouds differently, FUV observations from CHASE would allow us to directly detect the clouds and characterize physical properties.

Dedicated high resolution observations in multi-wavelengths will be essential if exoplanet spectroscopy is to realize its true potential for exoplanet atmospheric characterization [7, 10]. As different wavelengths probe different planet atmospheric depths [9], observations obtained in the UV (HST), optical (HST), and IR (HST/Spitzer/JWST) give us the unique opportunity to consistently constrain models (temperature, pressure, and dynamical structure) of a whole exoplanet atmosphere, currently possible just for a few Solar System planets and HD 209458 b. CO, CO_2, NH_3, N_2, C_2H_2, C_2H_4, PH_3, H_2S, O_2, O_3, N_2O, and HCN have all been proffered as exoplanet atmosphere gases [7], however the only atmospheric

species that have clearly been identified in transit are water, sodium, potassium and a haze [36, 37]. Clearly the field is in its spectroscopic infancy: a set of UV transit observations by CHASE together with future JWST data will provide the necessary set of observational constraints for the advance of planetary atmospheric models.

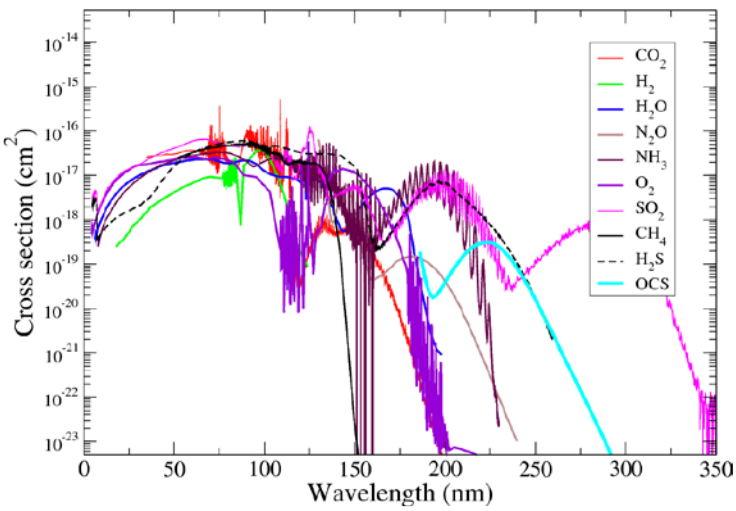

Figure 1. The photodissociation cross sections of key trace atmospheric molecules in terrestrial planet atmospheres as a function of wavelength. It shows the importance of UV flux on planetary atmosphere photochemistry. More UV flux data from planet hosts are needed to have a detailed understanding of the photochemistry process.
(Image credit: Shkolnik and Hu et al. 2012)

A planet's habitability, including atmospheric retention, is strongly dependent on the parent star's UV emission, which chemically modifies, ionizes, and even erodes the atmosphere over time including the photodissociation of important diagnostic molecules, e.g. H_2O, CH_4, and CO_2. The UV spectral slope of the parent star can enhance atmospheric lifetimes, and increase the detectability of biologically generated gases. But, a different slope may lead to the formation of abiotic oxygen and ozone producing a false-positive biosignature for oxygenic photosynthesis. In the case of M-dwarfs studies have shown most have FUV/NUV flux ratios 1000 times and 2-3 orders of atmospheric O_2 and O_3 content greater than that of Sun-like stars [38, 39]. Realistic temporal and long term measurements over a significant number of transitions and constraints on the incident UV flux over a planet's lifetime are necessary to explore the cumulative effects on the evolution, composition, and fate of a habitable zone planetary atmosphere. With further UV observations from CHASE we can constrain the numerous planetary atmosphere evolution models that are currently used to study and determine habitability.

3. THE CHASE INSTRUMENT CONCEPT

CHASE is a compact reflective two-beam cyclical interferometer that produces a 2-D fizeau fringe pattern from which the input UV spectrum can be obtained via a Fourier transform. The basics of CHASE is based on a compact reflective variation of a class of technology known as Spatial Homodyne Spectrometers (SHS) [40-42]. Reflective SHS [41] combines the high étendue ($\acute{E}$= telescope effective area (A_{eff}) × *FOV*) and high *R* of FTS with higher opto-mechanical tolerance and simpler opto-mechanical design associated with grating spectrometers. The importance of high étendue for the CHASE is in achieving high *R* spectra with small aperture telescopes. SHS-based instruments have been used in a series of ground and space-based projects for observations of atmospheric and interstellar emission line features [43, 44]. To date, the majority of the SHS projects are in the Michelson SHS format [42] in which the mirror in each interferometer arm was replaced by a grating [42, 45], and a two-dimensional camera CCD detector imaged the fringes [42, 43, 46, 47].

But a major weakness of Michelson SHS instruments is their use of transmitting elements, which limits their usefulness in shorter wavelengths (UV).

CHASE will be best suited to studies of sources where temporally tracing specific spectral features sensitivity and spectral resolution are of higher significance than spatial fidelity (in this case *Ly-α* and NUV). SmallSats are lower cost, faster to

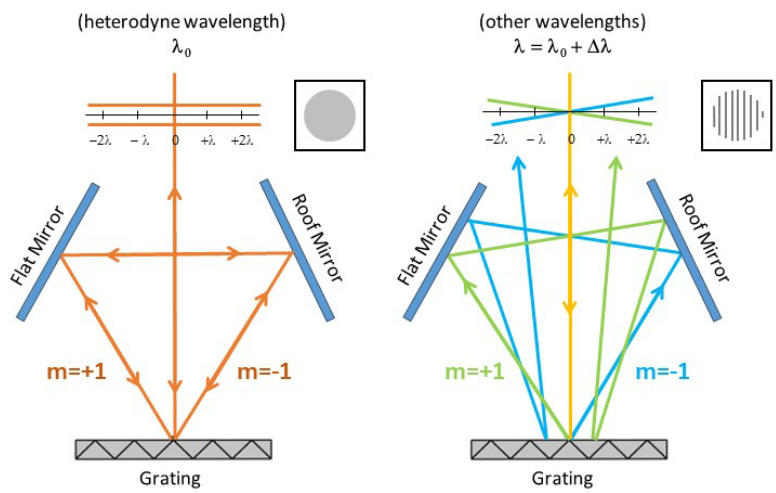

Fig. 2 (Left) CHASE is based on a simple cyclical design. The incoming collimated light hits the grating at normal incident, splits to two orders, travel in opposite directions, and diffract off the grating before exiting. For the tuned wavelength λ_0 everything is symmetric, there is no path or phase differences between the emerging beams. **(Right)** However the exiting wave fronts of other wavelengths ($\lambda=\lambda_0+\Delta\lambda$) are rotated in respect to each other producing a fringe pattern.

build, relatively easy to correct and upgrade. CHASE could be implemented on a dedicated SmallSat or ISS that can sit and stare at targets for long duration of time that cannot be done from the ground or on big missions. High R spectrometers are usually limited by the telescope aperture size and complicated opto-mechanical tolerances for UV regions but that's not the case for CHASE. A miniaturized CHASE from space platforms orbiting Earth will provide measurements of full disk of planetary system for significant amount of time to reveal the temporal behavior of *Ly-α* global abundance and variability over time in addition to sequential mapping of the parent star's UV spectra over time. CHASE measurements will add to the observations to date from HST UV data set, and will be able to resolve questions concerning the exact abundances, and their variations over time. In all approaches CHASE will provide an integrated spectra over *FOV* at very high spectral resolution (R~150,000) in NUV and FUV in a compact package with only one moving spectrometer part.

Table 1. Compared to commonly used high-*R* spectrometers CHASE is among the highest étendue instruments and in supreme group for grasp values allowing it to observe by small-aperture telescopes.

Instrument	Telescope	Bandpass (nm)	~FOV (arcsec^2)	Resolving Power	Étendue (m^{2}arcsec^2)	Grasp x 10^5
CHASE	0.5m / off-axis	120.9-122.3	40 x 40	108,000	314	340
CHASE	1m / off-axis	120.9-122.3	20 x 20	108,000	314	340
CHASE	0.5m / off-axis	192-194	40 x 40	108,000	314	340
CHASE	1m / off-axis	192-194	20 x 20	108,000	314	340
Hamilton	Shane 3m / Lick	340-1100	2 x 2.5	60,000	35	20
HIRES	Keck / Mauna Kea	300-1000	8 x 0.7	60,000	440	200
SOPHIE	1.93m / OHP	380-690	3 x 3	75,000	105	80
STIS	Hubble 2.4m	115-1030	0.5 *x* 52	9000	117	10
ALICE	Rosetta 0.04 m	70-205	180 *x* 7200	137	1630	2

3.1 CHASE Optical Design

We can coarsely sort the performance of narrow bandpass imagers or traditional dispersive grating spectrometers into two classes of instruments with large A_{eff} that emphasize spectral resolution (e.g, HST-STIS or Keck-HIRES) and those with large étendue (e.g., Cassini UVIS). The most common instrument to obtain high R in UV is the classical grating spectrometer, but their high *R* implementations are physically large and require large aperture telescopes to overcome the small *FOV* of the apertures required. In grating spectrometers, *R* is derived from both the dispersion relation at the detector and the width of the aperture in the diffraction plane. This convolution drives the *R lower* if the size of the instrument is reduced and/or its *FOV* is increased. Thus, the typical high *R* (~50,000) spectrometer is quite large, has a very narrow *FOV* and is attached to a large telescope (2.4 m HST), while the typical low-resolution spectrograph on a remote probe (e.g., Voyager-UVS or New Horizon-ALICE) is compact, has a wide *FOV*, and *low R* (<1000). The *FOV* in CHASE is not convolved with spectral response and therefore, to a large degree, the *R* is decoupled from the size of the area that is being sampled. This allows CHASE to sample closer to the full theoretical *R* of the grating.

Interferometry is another technique that is used to obtain high étendue measurements at high *R*. They emphasize sensitivity for long term temporal studying at high *R* from wide *FOV* (e.g., planetary disks, nebula, large galaxy structures, interstellar medium, etc.). Some technologies that demonstrate the utility for these targets include Hydrogen absorption cells (e.g., SOHO-Solar Wind experiment [48]), field-summing instruments such as FPIs (e.g., Wisconsin H-alpha Mapper [49]), and scanning FTSs. However, below 300 nm many commercially available glasses begin to become opaque and the transmitting optics issue dominates around 100-130 nm. The number of transmitting crystals, especially below 160nm, is sharply reduced and performances degrade. The last known transmitter, LiF, becomes opaque at ~105 nm, and is difficult to make optically flat beam splitter or etalon. Getting spectra below 100 nm requires Boron-Carbide or Silicon-Carbide coatings (≤35% reflectivity) [50] or multi-layer coatings for narrow-band filters. Therefore these designs are limited at different points in UV by their use of transmitting optics, demanding low opto-mechanical tolerances, a narrow acceptance bandpass, and/or physical size [42, 48, 49, 51, 52].

CHASE is a cyclical interferometer where the two beams travel a *common-path* in opposite directions through the interferometer (similar to a Sagnac Interferometer). This coupling of the optical paths has many positive aspects that makes it attractive for spaceflight, namely: (1) It is easier to optically align; (2) It contains less optics and is less constrained on opto-mechanical tolerances; (3) The common path configuration is more stable to thermo-mechanical effects; (4) The lack of transmitting optics permits its use in shorter wavelengths into the FUV; and (5) the wide FOV capability is compatible

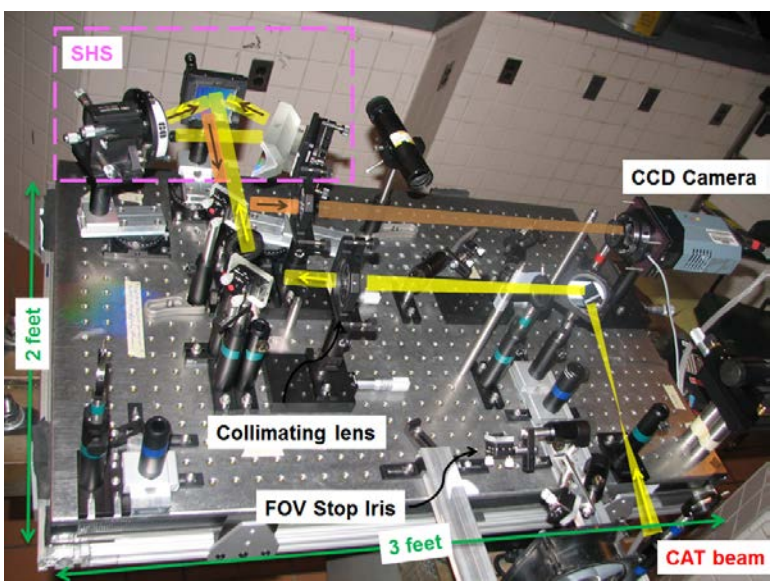

Figure. 3. The PI has developed the basic concepts of the reflective tunable optical SHS under the PIDDP program at Mt. Hamilton during 2010-15. Shown here is the optical bench layout of the instrument that demonstrated measurement capability coupled to the 0.6 m Coude Auxiliary Telescope (CAT).

with relaxed pointing acquisitions of SmallSats. In CHASE deisgn, (Fig. 1) the grating diffracts an incoming collimated beam into ±m orders following the grating equation for normal incidence $[\sin\beta_{in}+\sin\beta_{out}]\cos\Phi=m\lambda G$, where λ is the wavelength, G is the groove density and Φ is the diffraction angle. The incoming light beam hits the grating in normal incident and splits to two diffraction order (m=±1). Both orders anti-symmetrically traverse the optical path, converge back on the grating, and diffract for the second time before exiting the system. By using a right angle 'roof' mirror for one of the mirrors the incoming and outgoing beams, are separated into parallel plane below (or above) the incoming optical path. For the tuned wavelength λ_0, called the homodyne wavelength, the optics are aligned in such a way to have both orders exit the grating in normal angle: their wave-fronts exit parallel in respect to each other and hence create no fringes [41, 53]. This case is referred to as the 'homodyne condition'. At all other wavelengths ($\lambda=\lambda_0+\Delta\lambda$) there is a dispersive rotation introduced to the merging wave-fronts and results in the formation of a 2-D Fizeau fringes with a frequency dependent on $\Delta\lambda$ [41]. The Fourier transform of the 2-D fringe pattern recovers the original power spectrum in units of $\Delta\lambda$. Alignment of CHASE involves the rotation of one or both of the transfer mirrors to set the angles such that a chosen wavelength satisfies the homodyne condition (λ_0) [41, 53].

The data fringe pattern forms at a location called the *Fringe Localization Plane* (*FLP*) and is imaged onto an imaging 2-D detector [41]. *FLP* is defined by following the diverging exiting beams from the interferometer, and is a virtual plane located at distance z_0 behind the grating on the z-axis [54]. For a complex spectrum, each wavelength diffracts in different angle, resulting in a superposition of fringes in different frequencies and intensities. Herein lies the homodyne aspect of CHASE: the interferometer essentially homodynes the entire input beam with itself keeping the zero-frequency fringe for the tuned λ_0 homodyne wavelength as reference. The Fourier transform of the interference pattern imaged onto the detector recovers the power spectrum of the input light.

The quantity of étendue is widely used to express the sensitivity of an optical instrument. However, for practical reasons in building new instruments, usually the goal is to optimize g*rasp* per cost. Grasp [41, 55] is defined as $G = \text{Étendue} \times R$ and it is used to quantify the overall potential of an instrument considering the input aperture, *FOV*, and resolving power. One of the implementations of low grasp in common high *R* spectrometers is the steep trade-off between *R* and *FOV*; by increasing the *FOV* the instrument loses the *R* sensitivity.

The significance of the wide *FOV* for CHASE is that it increases the *étendue* of the instrument, the capability of an optical system to accept and gather light. Therefore CHASE can target NUV and FUV spectral regions of multiple gases of exoplanet atmospheres using smaller aperture telescopes and can go to relatively longer exposure times (shot noise permitted). Since the data is an integrated spectra over FOV, the wobbling of the SmallSat wouldn't create a problem as long as the target stays in the FOV. This is of great instrument engineering and observation ease and is compatible with the relaxed pointing requirements of current SmallSats. However, one side effect of wide *FOV* is the possibility of observing other sources inside the *FOV* which will be easily distinguished and removed due to high spectra *R* and pointed Doppler shifts. In the same way, the parent star's features will always be present in the spectra and can be used for

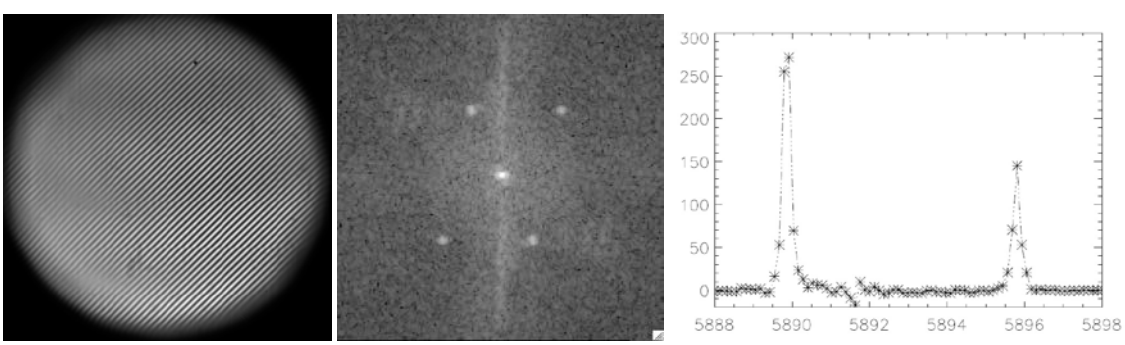

Figure 4. (Left) Fringe pattern from Na Hollow Cathode Lamp when the ground-based tunable reflective SHS built by PI at Mt. Hamilton (shown in Fig. 1). The interferometer is tuned to the vicinity of the Na D lines at λ_{D1}= 5895.9 Å, λ_{D2}= 5889.9 Å. This image contains two set of fringe patterns each for one of the Na D lines. **(Middle)** The reduced power spectra shows both lines indicating both fringe pattern are present in the data. The top half of the 2D FFT is the repetition of the bottom half which an inverse wave-vector sign. **(Right)** The Na D lines' power spectra: the separation of $\Delta\lambda$=5.97 Å, indicates a resolving power of R~48000 which is same with the calculated R.

calibration purposes. The other issue is that the data obtained by CHASE is not immune from the multiplexing noise, the inherent nature of the interferometers. That means, a noise somewhere in the bandpass will contribute to the spectrum everywhere in the bandpass. For that reason, the CHASE concept may have to pass some challenges before accommodating practical signal to noise ratio observation criteria. And therefore it is key to choose the bandpass and duration of the observations carefully.

4. SUMMARY

In this study we used a series of measurements using high *R* spectroscopy focused on specific atomic and molecular features [21] in NUV and FUV over small bandpasses over a significant amount of time to emphasize on three visionary aspect of exoplanet research: 1) maybe we can develop new clever methods unanticipated in roadmap documents and decadal surveys using SmallSats. 2) Maybe, with CHASE, we are able to measure and map some exoplanets without the high contrast imaging techniques that are now emerging to compete. 3) Maybe we can use the inherent nulling property of CHASE to null the star light in a specific spectra feature in a very small bandpass and detect the Doppler shift in the planet spectra moving around the homodyne wavelength. The detectability of the emissions depends mainly on the signal to noise ratio and thus of both the total flux received from the system and the line profile. Various studies investigate conditions that would make the direct detection of a planetary $Ly\text{-}\alpha$ emission possible [13, 56] and has been estimated that the planetary emission can be due to dayside scattering of the stellar line [57].

5. ACKNOWLEDGMENT

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