1. Science aim/goal

Direct imaging and characterization of true exoplanet analogs of Jupiter and Saturn, young gas giants and ice giants, as well as ice giants at habitable temperatures (~300 K).

2. (i) Scientific Importance:

One of the highest scientific priorities for the astrophysical community in the next decades is to identify and characterize analogs of our own Solar System, and determine how common its features and characteristics are in the zoo of exoplanetary systems. While significant effort will go into finding Earth-analogs, the related objective of searching for, and characterizing analogs of our cool giant planets, Jupiter and Saturn, is critical for understanding the origin and evolution of exoplanetary systems like our own. Finding ice giant and gas giant planets around young (<100 Myr), intermediate age (100 Myr-1 Gyr), and old (>1 Gyr) stars will let us trace the evolution of planetary systems over time.

In order to do that, we have to develop observational capabilities for detecting, as well as characterizing the atmospheres of, Jovian planets orbiting older stars at separations of 5-20 AU. Such planets are cool, 150-300 K, with spectral energy distributions peaking beyond 10 micron. True Jupiter analogs have proven to be very difficult to detect. They are cool, so they have very low contrast relative to their parent star at short wavelengths (<10 micron), and their orbits are too wide for efficient radial velocity or transit detections. A mid- to far-infrared cold space telescope with a high contrast spectro-imaging instrument will be able to directly image such cool planets with masses less than 1 MJup orbiting at 3 AU around old stars within 6 pc, and 5-50 AU for intermediate age stars within 20 pc, and young stars within 100 pc, and will be able to measure the molecular composition of their atmospheres. Further, spectrally dispersed mid-infrared coronagraphy will allow OST to uniquely characterize the atmospheres of cool (200-300 K) Neptune-sized planets at ~10-50 AU separation, opening up a major new reservoir of exoplanets for direct imaging and characterization. Spectral dispersion allows for direct measurements of molecular abundances (NH_3, CO_2, O_3, H_2O and possibly CH_4).

(ii) Measurements Required:

The goal requires high-contrast spectro-imaging with an inner working angle (IWA) of 0.2” at 10 micron (1 lambda/D for a 9m aperture), and scaling with wavelength. This IWA is needed to detect a 300 K Neptune-sized planet around an old star at 5 pc at a 1-2 AU separation, and the contrast should be 10^{-6} to detect Saturn at 10 pc (~1 microJy @ 24 micron, 2 lambda/D for 9m aperture) with R~10. The maximum spectral dispersion should be sufficient to resolve the 15 micron CO_2 band (R~500). Direct imaging of exoplanets requires a coronagraph to separate the host star’s light from the target planet. Characterization of exoplanet atmospheres requires a spectrograph to identify key spectral features in the mid-infrared.

(iii) Uniqueness to 10µm to few mm wavelength facility:

No current facility is able to detect true exo-Jovian analogs and measure the molecular composition of their atmospheres. In particular CO2 and nitrogen-bearing species (NH3) are unique to the mid-infrared, and molecular bands at longer wavelengths are less blended, allowing for more quantitative characterization. Future ground-based facilities like TMT are likely to be limited to wavelengths of 10 microns and bluer. Distinctions between CH_4-dominated vs. CO-dominated atmosphere constrains the phase space of the underlying atmospheric chemistry.

(iv) Longevity/Durability:

The Transiting Exoplanet Survey Satellite (TESS) mission is scheduled to launch in December 2017. TESS will survey approximately 500,000 nearby stars and is expected to detect transits from about 3,000 systems. While TESS will not detect Jovian analogs in wide orbits, any TESS systems will be ideal targets for direct imaging searches and spectral characterization with OST.

The James Webb Space Telescope (JWST) is scheduled to launch in October 2018. JWST will provide extensive spectral characterization of planetary atmospheres of TESS planets in short orbits, but will not be able to detect and characterize many giant planets (other than the youngest, high-mass planets found by ground-based NIR direct imaging) at 5 AU, as this is within the inner working angle and limiting contrast of JWST-MIRI (0.33" at 10.65 micron, contrast of a few 10^{-4}, Boccaletti et al. 2015). Further, there is no spectrally dispersed high-contrast mode on JWST.

WFIRST's microlensing mission will be able to detect giant planets in Solar System orbits, but it will not be possible to follow up these detections with other facilities or characterize their atmospheres. However, once WFIRST has determined the frequency and mass distribution of Jovian analogs, it will be critical to develop instruments capable of characterizing this, still uncharted, population of exoplanets. The WFIRST coronagraph will be able to study ~1-5 AU Jupiter-mass and Neptune-mass planets around the closest stars in reflected visible light, but not the mid-IR molecular features that OST is sensitive to.

Table:.

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	µm	9µm to 40µm	5µm to 40µm	
Number of targets		100	1000	Depends on integration time required to resolve key spectral features

Survey area	deg.^{2}	N/A	N/A	
Angular resolution	arcsec	0.4”	0.2”	At 10 micron
Spectral resolution	$\Delta \lambda / \lambda$	200	500	To resolve the CO2 band
Bandwidth		10 micron	10 micron	
Continuum Sensitivity (1 σ)	μJy	1	1	To detect a Saturn analog
Spectral line sensitivity (1 σ)	W m^{-2}	N/A	N/A	
Signal –to-noise		10	10	To confidently detect molecular absorption bands
Field of Regard	sr	4pi	4pi	
Cadence		1 year	1 year	
Any other requirement	Contrast	10^{-6} @ 0.2”	10^{-7} @ 0.2”	To detect a Saturn analog or a warm Neptune

5. Key references:

Bell, Mamajek, and Naylor 2015 MNRAS 454 593
Boccaletti et al. 2015, PASP, 127, 633
Boccaletti et al. 2011, ASPC, 450, 163
Nielsen et al. 2013, ApJ 776 4
Seager & Deming 2010, ARA&A, 48, 631

Appendix

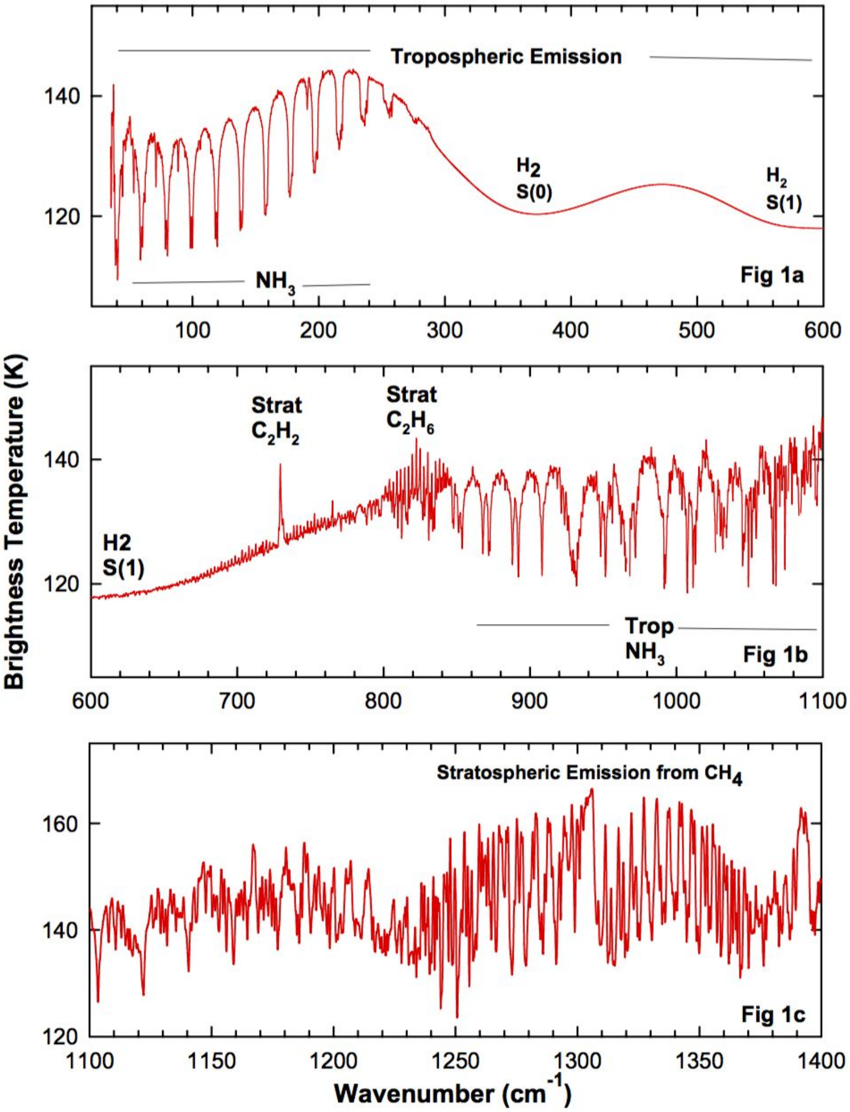

Figure 1: Emission spectrum of Jupiter, as observed by Cassini (Kunde et al. 2004). Note the dominance of water, ammonia and hydrocarbons.

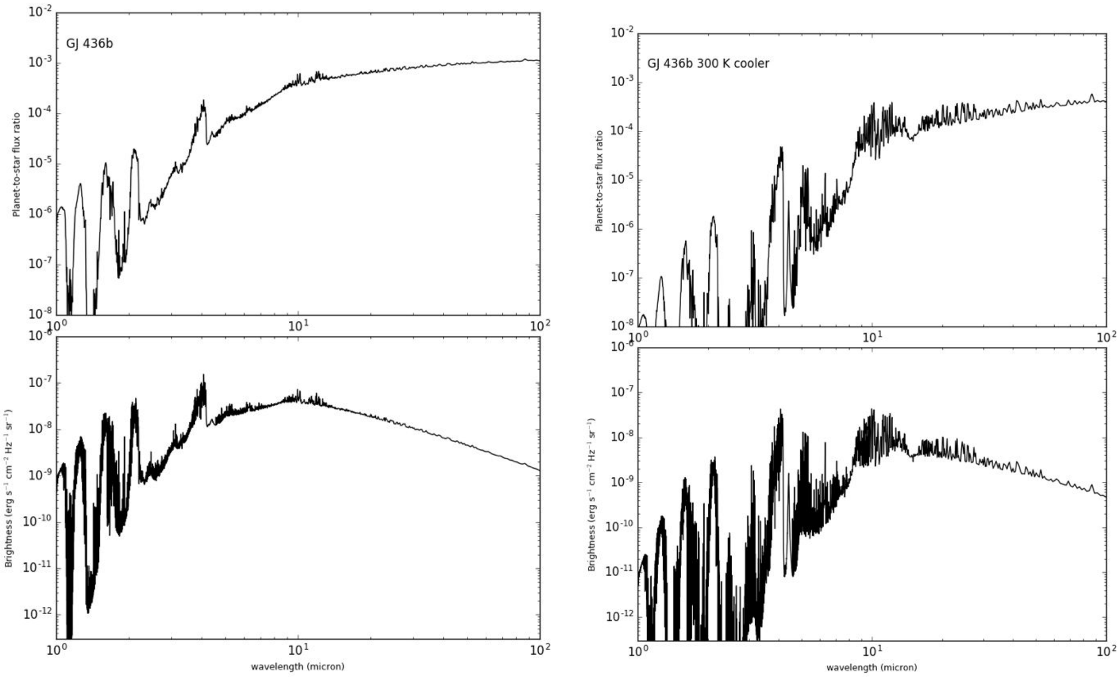

Figure 2: Model emission spectra of GJ 436B at 700 K (left) and 400 K (right), showing how the contrast of cool planets is high only beyond 10 micron (M. Agundez).

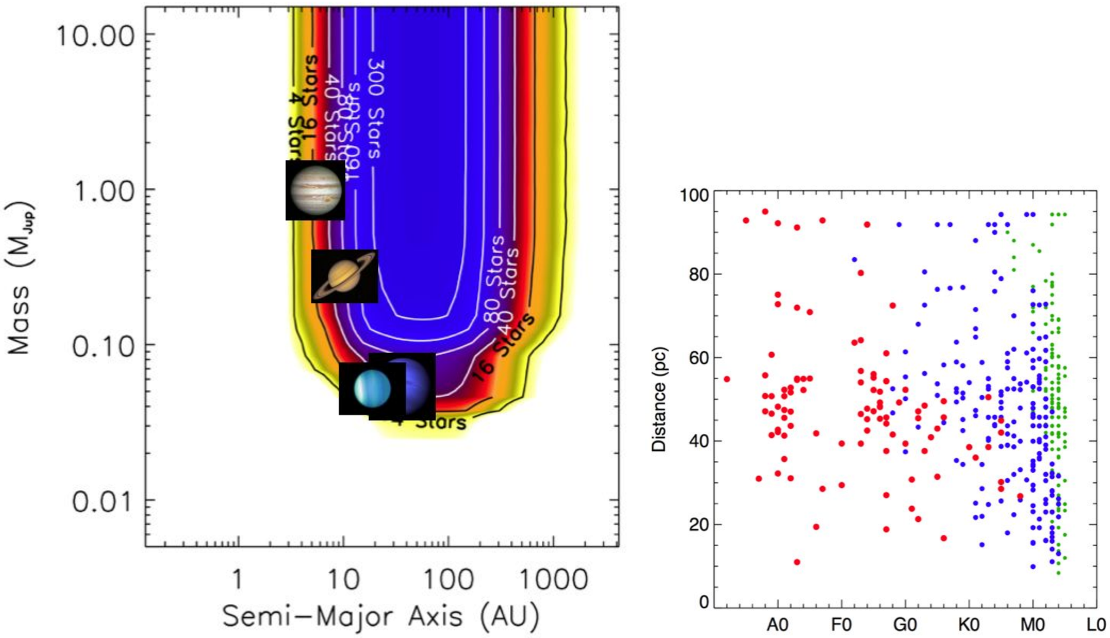

Figure 3: (left) Sensitivity to gas giant and ice giant planets around 490 young, nearby stars (right) from Bell et al. 2016, assuming an IWA of 2 lambda/D, 9m aperture, and contrast of 10^{-6}.

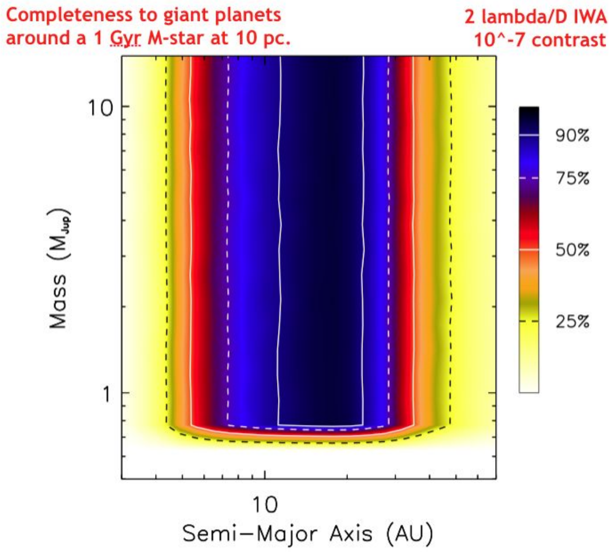

Figure 4: Completeness to gas giant planets around a 1 Gyr, 10 pc M star, assuming the optimistic case of 10^{-7} contrast and an IWA of 2 lambda/D.

Table 1: Estimated brightnesses, separations and contrasts of Jupiter and Saturn around a G2 star at 10 pc, with D=9m.

	8 um	15 um	24 um
Jupiter flux density (uJy)	0.01	2.1	10.3
Jupiter contrast	4.E-09	2.E-06	3.E-05
Jupiter separation (lam/D)	3.5	1.9	1.2
Saturn flux density (uJy)	0.00003	0.07	1
Saturn contrast	1.E-11	8.E-08	3.E-06
Saturn separation (lam/D)	6.5	3.4	2.1