Characterizing Giant Exoplanet Atmospheres with the Nancy Grace Roman Space Telescope Coronagraph Instrument

Zarah Brown[1], Ty Robinson[1], Sarah Moran[1], Mark Marley[1]

[1]University of Arizona, Lunar and Planetary Laboratory (LPL), Tucson, AZ

LUNAR & PLANETARY LAB

Direct Imaging

Direct imaging captures a 2D image of light emitted by objects in space, including exoplanets. The major challenge of direct imaging is capturing faint planets adjacent to their intensely luminous host stars. Current direct imaging efforts are limited in the targets they can observe, focusing on planets that are easier to detect and are:

- **Massive** (super-Jupiters)
- Far from their host stars (**Wide Orbits**)
- **Young** (less than 100 million years old). These planets glow brightly in infrared (IR) due to their residual heat of formation, a wavelength range where the stellar companion is not as bright.

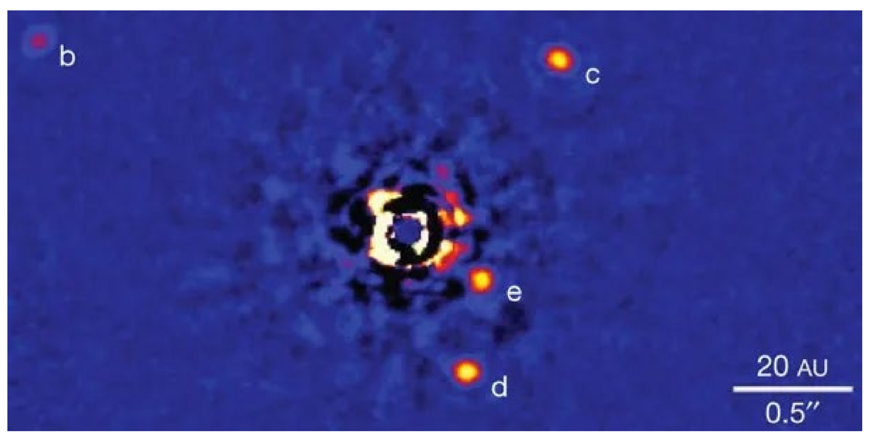


Figure 1. Direct image of four planets orbiting the star HR 8799, Marois et al. (2008)[1].

Advancements are needed in order to be able to image cooler, older jovians and eventually terrestrial-sized planets.

The Nancy Grace Roman Space Telescope

The Nancy Grace Roman Space Telescope represents a significant advancement in space observation, building upon the achievements of both the Hubble and JWST missions. Originally designated as WFIRST (Wide-Field Infrared Space Telescope), it was renamed in 2020 to honor Nancy Grace Roman, NASA's first female executive and a key figure in the development of the Hubble Space Telescope. Scheduled for **launch by 2027**, the telescope will orbit the Earth's L2 point, boasting a primary mirror 2.4 meters wide, comparable to that of the Hubble.

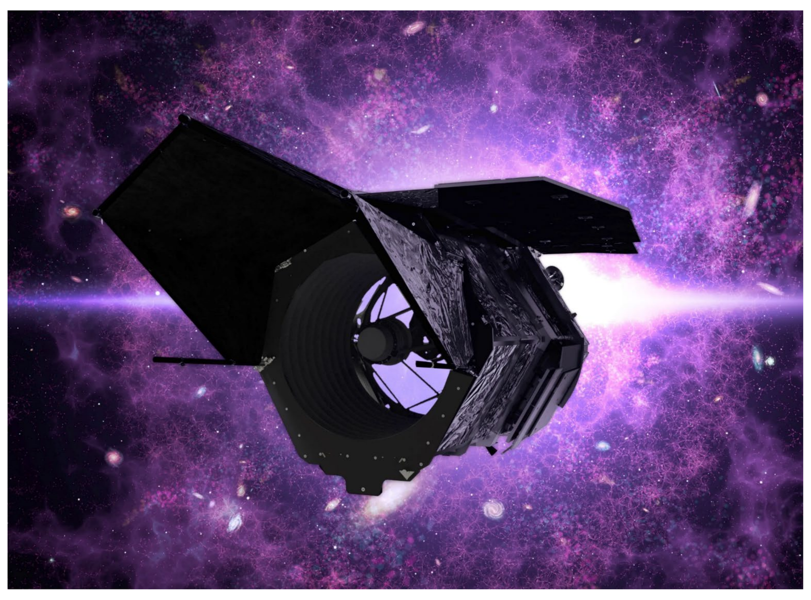


Image Credit: NASA's Goddard Space Flight Center

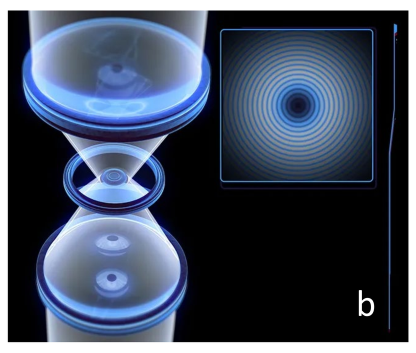
The telescope features two main instruments:

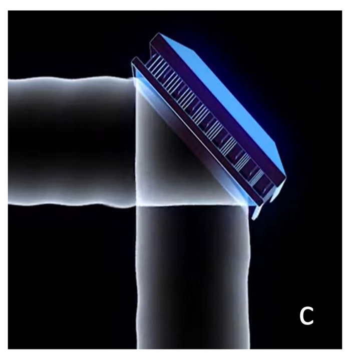
- The Wide-Field Instrument (field of view 100 times that of Hubble)
- **Coronagraph Instrument** (narrower field of view for high-resolution targets)

The Roman Coronagraph Instrument (RCI) Design

The Roman Coronagraph Instrument (RCI) is a technology demonstration that showcases novel starlight suppression that will improve capability over previous coronographs like those flown on Hubble and JWST by a factor of 100 to 1000. The novel technology inherent to the RCI is comprised of:

- **Ultra-precise wavefront sensing and control**
- **Large-format deformable mirrors**
- **High-contrast coronagraph masks**
- **Ultra-low noise photon counting Electron Multiplying Charge-Couple Device detectors**
- **Advanced algorithms for data post-processing**





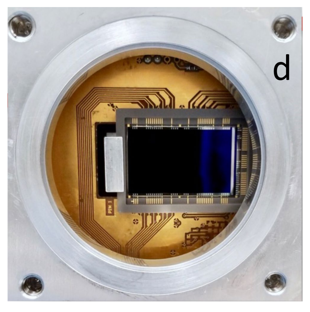


Figure 3. a) Coronagraph masks b) Effect of masking: blocked central star and deconstructive interference c) Deformable mirror d) EMCCD[2]

The RCI will serve as a crucial precursor for initiatives such as the Great Observatories Mission and Technology Maturation Program and the Habitable Worlds Observatory (HWO), which will eventually allow for the direct imaging of small, rocky planets.

RCI Capabilities

The Roman Coronagraph Instrument is designed to observe targets with an absolute visual magnitude ≤ 5 boasts a predicted visible-light **planet/star flux ratio detection limit of 10^{-8} or better** at angular separation of approximately 0.1 to 1 arcsecond. With three distinct observing modes—**Direct Imaging, Polarimetry, and Spectroscopy**.

RCI utilizes four bandpass filters in visible wavelength ranges. Bands 2 and 3 are used for spectroscopy, allowing CGI to capture spectra of orbiting planets by dispersing the light from the planet's location through a prism, with signal from the reference star subtracted during post-processing to generate flux ratios (Fp/Fs) for analysis.

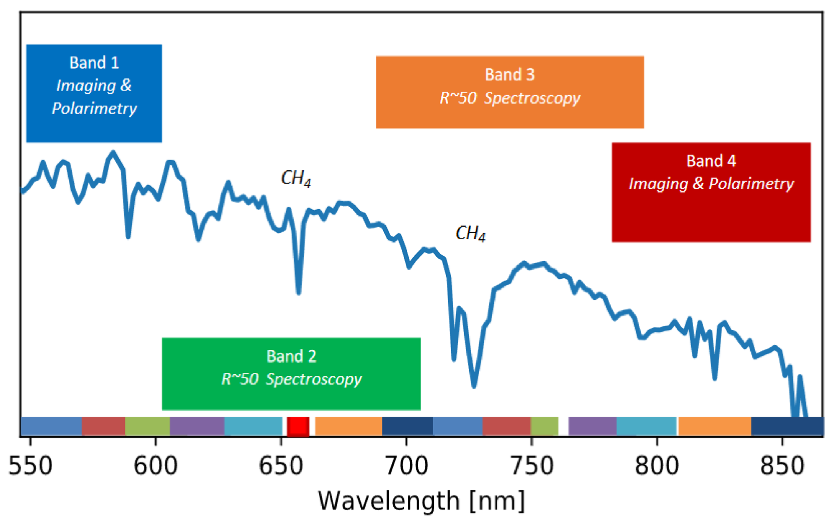


Figure 4. Roman Space Telescope observing bands compared to an atmospheric spetctrum[2].

Goal: RCI Exoplanet Target Planning

Our research will support the investigation of self-luminous young jovians in emitted light and cool jovians in reflected light, to be imaged by the Roman Space Telescope. Target selection is crucial due to limited observing time, but interpreting atmospheric spectra poses challenges as it's an inverse problem that can lead to degenerate solutions. To aid in target selection and data interpretation, we'll utilize the following tools:

1. PICASO: This Python Planetary Intensity Code for Atmospheric Scattering Observations[3] simulates the 1D structure of exoplanetary atmospheres, including temperature-pressure profiles and chemical composition. It incorporates a high-fidelity radiative transfer model to generate high-resolution, phase-dependent spectra.
2. rfast: This inverse modeling tool, designed to support future missions like HabEx and LUVOIR, helps explore the information encoded within exoplanetary spectra. It identifies regions of parameter space consistent with observed spectra, facilitating data interpretation.

Goal: Incorporating Hazes

Clouds and hazes can obscure spectral signatures, mask surface features, and significantly impact temperature and climate, thus posing challenges to accurately characterizing planetary atmospheres. Laboratory experiments have highlighted the connection between haze properties and the thermochemical environments in which they form[4], making them of particular interest.

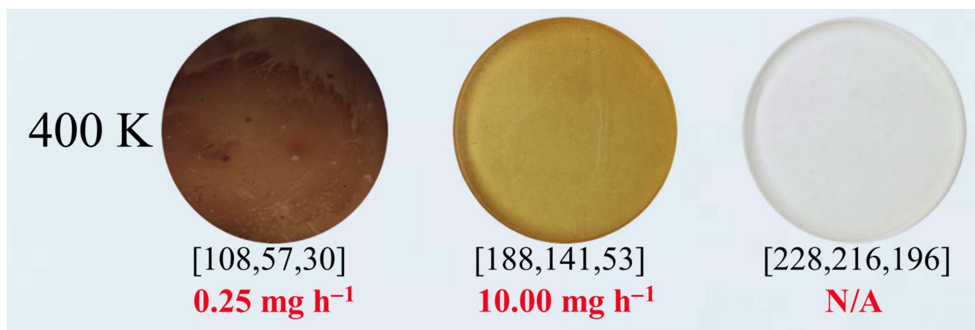


Figure 5. Hazes produced in a laboratory at conditions relevant to potential target atmospheres for the RCI from He et al. (2018)[4]. The metallicities from left to right are 100 X, 1,000 X and 10,000 X leading to differing formation rates shown at bottom in red.

While PICASO currently incorporates cloud modeling, we are working on integrating hazes into the code. This involves prescribing mode particle sizes and aerosol mass densities to determine haze number densities to include in the radiative transfer calculations.

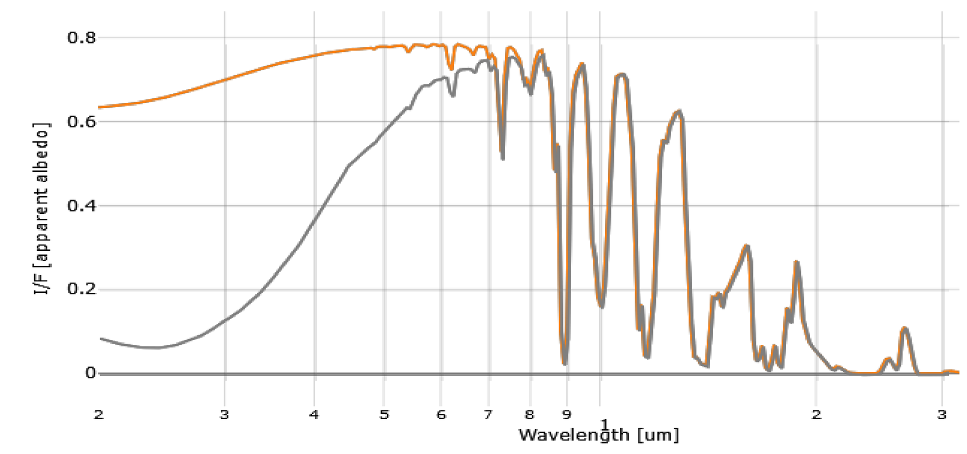


Figure 6. Jupiter in reflected light as modeled by the Planetary Spectrum Generator[5] to simulate viewing with the Hubble Space Telescope (orange). The addition of haze (grey) based on Titan tholins produces broad absorption features at shorter wavelengths.

Synopsis: The Nancy Grace Roman Space Telescope Coronagraph Instrument promises unprecedented capabilities in direct imaging. We will use the PICASO climate modeling and radiative transfer code to create model grids of cool and warm jovian planets, facilitating the selection of promising targets with a higher likelihood of yielding discernible atmospheric properties from their spectra. By incorporating hazes into the PICASO model, we will better understand their potential impact on observations with the Roman Telescope.

Contact

Zarah Brown
University of Arizona
Lunar and Planetary Laboratory
zarahbrown@arizona.edu

zarahbrown.com

hablabnet.wordpress.com

References

1. C. Marois, B. Macintosh, T. Barman, B. Zuckerman, I. Song, J. Patience, D. LaFreniere, and R. Doyon. *Direct Imaging of Multiple Planets Orbiting the Star HR 8799*. Science 322, 1348-1352 (2008). DOI:10.1126/science.1166585.
2. Roman/CGI Science and Engineering Project Teams, Jet Propulsion Laboratory, California Institute of Technology. *Roman Coronagraph Instrument Reference Information.* February 2021. https://roman.gsfc.nasa.gov/science/RRI/Roman-CGI-Reference-Info-Feb2021.pdf
3. N.E. Batalha, M.S. Marley, N.K. Lewis, J. Fortney. *Exoplanet Reflected-light Spectroscopy with PICASO*. The Astrophysical Journal 878, 70 (2019). DOI:10.3847/1538-4357/ab1b51. https://github.com/natashabatalha/picaso
4. C. He, S.M Horst, N.K. Lewis, X. Yu, J.I. Moses, E.M. Kepmton, P. McGuiggan, C.V. Morley, J.A. Valenti, V. Vuiton. *Laboratory Simulations of Haze Formation in the Atmospheres of Super-Earths and Mini-Neptunes: Particle Color and Size Distribution.* The Astrophysical Journal Letters 856, L3 (2018). DOI:10.3847/2041-8213/aab42b.
5. G.L. Villanueva, M.D. Smith, S. Protopapa, S. Faggi, A.M. Mandell. *Planetary Spectrum Generator: An accurate online radiative transfer suite for atmospheres, comets, small bodies and exoplanets*. Journal of Quantitative Spectroscopy and Radiative Transfer 217, 86-104 (2018). DOI:10.1016/j.jqsrt.2018.05.023. https://psg.gsfc.nasa.gov/