The Exciting Opportunity of Subaru High-Contrast Observations for the Roman Coronagraphic Mission

M. Kuzuhara[1,2], S. Miyazaki[3], T. Mizuki[1,2], T. Uyama[4], N. Murakami[1,2], Y. Kawashima[5], K. Ohno[2]
J. Nishikawa[2,1,14], J. Livingston[1,2,14], T. Currie[6,8], O. Guyon[7,8], J. Lozi[8], M. Tamura[1,2], T. Brandt[11],
R. M. Anche[7], V. Bailey[9], G. Chauvin[10], J. Girard[11], T. Groff[15], J. Hom[7], H. Kawahara[3],
M. Millar-Blanchaer[12], J. Wang[13], S. G. Wolff[7]

1: Astrobiology Center, NINS, 2: NAOJ, 3: ISAS/JAXA, 4: CSUN, 5: Kyoto Univ., 6: UTSA, 7: Univ. Arizona, 8: Subaru Telescope,
9: MASA/JPL, 10: MPIA, 11: STScI, 12: UCSB, 13: Northwestern Univ. 14: SOKENDAI, 15: NASA/GSFC

Executive Summary

The coronagraphic imaging of the Roman Space Telescope marks the first space mission to combine adaptive optics with coronagraphs. It will observe bright nearby stars to assess high-contrast performance, initially targeting a 10^{-7} contrast. Afterward, it also explores deeper contrasts ($\lesssim 10^{-8}$) achievable in longer exposures. Demonstrating high-contrast techniques from space, such as "digging a dark hole," is crucial for future imaging of an Earth-like exoplanet. Detecting a $\sim 10^{-7}$ contrast companion in the optical would solidify the success of the mission and initiate a scientific study, but such targets are rare. Given the limited observing windows for the mission, locating as many suitable companions as possible across a broad sky coverage will boost the mission's outputs. Hence, we propose a high-contrast imaging survey to find self-luminous substellar companions (such as brown dwarfs and massive giant planets) ideal for the Coronagraph mission. First, we propose to observe 30–40 targets with SCExAO and CHARIS on the Subaru Telescope to discover several new companions, expanding Roman's target list. We will follow them up to confirm and characterize the discoveries using SCExAO/CHARIS. We also propose to observe them with Roman to obtain their photometry and low-resolution visual spectra, comparing them to CHARIS's near-infrared spectra. Finally, we propose to follow up the targets using the Subaru Telescope's REACH spectrographs, providing the high-resolution ($\mathcal{R} \sim 100{,}000$) spectra to significantly constrain their atmosphere properties. This Roman-Subaru synergy will provide photometry and spectroscopy ($\mathcal{R}$ =19–100,000) over 600–2400 nm, enabling detailed characterization of substellar atmospheres, including their dynamics, clouds, compositions, and structure.

Requirements for observations

- **Subaru instruments to be used:** SCExAO (Jovanovic et al. 2015), CHARIS (Groff et al. 2016), REACH (Kotani et al. 2020)
- **Required nominal and minimum (threshold) number of nights**: 22 (minimum) to 26 nights (nominal) in total (18–22 nights with SCExAO/CHARIS and 4 nights with REACH)
- **Required condition of nights (moon phase, airmass, seeing):** moon phase: any, airmass: < 2, seeing $< 1''$
- **Time criticality (year, season, date, time):** late 2026 with CHARIS (if a part of nights allocatable), between January and December of 2027 with CHARIS (18–22 nights), between January of 2028 and December of 2029 with REACH (4 nights)

1 Roman Coronagraph mission

Starlight suppression technologies are essential for detecting exoplanets and circumstellar objects around nearby stars. The Nancy Grace Roman Space Telescope ("Roman" hereafter) is equipped with a Coronagraph Instrument as a technology demonstrator, providing an unprecedented opportunity to demonstrate state-of-the-art starlight suppression technologies in space. This is a crucial step towards exploration of habitable exoplanets and search for biosignatures on them in 2040s.

The Roman Coronagraph Instrument uses a coronagraph (HCL or SPC) to passively filter out most of glare from bright stars. It also incorporates a wavefront control system with deformable mirrors to actively suppress starlight (a process known as "digging dark hole"). This suppression is further enhanced by post-processing techniques to minimize residual noise.

There are several observing modes available: only one "required" mode that is formally supported, and several other "best effort" modes (e.g., Bailey et al. 2023). Below is the observing modes that will potentially be relevant to this proposal (the first one is the "required"):

- Band 1 (575 nm, 10 % bandwidth) imaging with HLC, narrow field-of-view ($0\farcs14$–$0\farcs45$)
- Band 1 imaging with SPC, wide field-of-view ($0\farcs30$–$0\farcs95$)
- Band 3 (730 nm, 17 % bandwidth) spectroscopy ($\mathcal{R} \sim 50$) with SPC, narrow bowtie-shaped field-of-view ($0\farcs18$–$0\farcs55$)
- Band 4 (825 nm, 11 % bandwidth) imaging with SPC, wide field-of-view ($0\farcs45$–$1\farcs40$)

There is a top priority Level 1 (L1) requirement on the Band-1-HLC observing mode: demonstration of the capability to detect a point-like object with a contrast level of $\leq 10^{-7}$ with a signal-to-noise ratio of ≥ 5 at 6–9 λ/D (corresponding to $0\farcs3$–$0\farcs45$) from a $V \leq 5$ magnitude star. Beyond the L1 requirement performed with the Band-1-HLC mode, the "best-effort" goals are explored. For example, Roman plans to explore a performance even better at a contrast level of 10^{-8} to 10^{-9} at visual wavelengths, which is impractical from ground-based observations. In addition, spectroscopy with the Band-3 mode may be explored. Roman will offer exceptional opportunities to significantly advance scientific studies of circumstellar objects, including self-luminous exoplanets, detection of reflected light from mature planets identified by radial-velocity observations, exozodiacal dust, debris disks, and so on.

The Roman is scheduled for launch in October 2026 (no later than May 2027). After the launch and commissioning, 2200 hours (about 90 days) are allocated for the Coronagraph Instrument during the first 18 months of the mission as a technology demonstration phase. Observation planning during this phase is underway by the Community Participation Program (CPP). The allocated time is available to maximize not only technical but also scientific value of the Coronagraph Instrument beyond the L1 requirement.

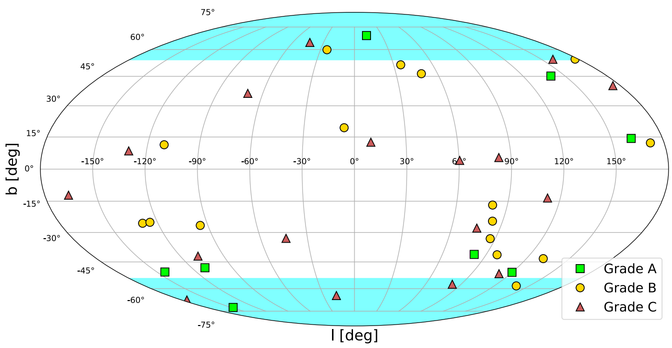

Figure 1: On-sky distribution of the reference star candidates in Ecliptic coordinates, epoch J2027. The cyan regions are the Roman's continuous viewing zone, and the candidates are ranked according to their qualities as reference stars (see inset).

2 Reference stars for wavefront sensing

The calibration of the Roman Coronagraph's optical system, which relies on light from reference stars, is crucial for achieving extremely high-contrast imaging of target stars. Reference stars are observed to model and correct wavefront errors caused by instrumental and telescope aberrations that evolve with time and temperature. This process of wavefront modeling ensures the precision of the observations and particularly crucial for "digging a dark hole". However, selecting suitable reference stars has stringent criteria that must be met to guarantee effective calibration. The main requirements (see Wolf et al. 2024 for detail) are:

- Singleness: For proper wavefront correction, the reference star must be a single star.
- Magnitude in the V-band: $V \leq 3$ mag is required for efficient dark-hole digging/maintenance times.
- Angular radius: $\theta_\star \leq 2$ mas (ideal) or $\theta_\star \leq 5$ mas (less optimal).
- Pitch angle[1] difference: The angular separation ($\Delta_{\rm pitch}$) between the target and reference stars in the pitch angle[2] ideally needs to be less than 5°.

These requirements have been derived from detailed numerical simulations of the Roman's high-contrast observation capabilities (Krist et al. 2023). Figure 1 shows the current on-sky distribution of reference star candidates. **The number of good candidates fully meeting these criteria for the time being is limited**—approximately only 10. Additionally, we must verify that these candidates exhibit minimal defects and assess their suitability for use as reference stars. The CPP team is now actively conducting precursor surveys, using high-contrast and interferometric observations with ground telescopes, to identify suitable reference stars that meet the stringent criteria (Wolff et al. 2024).

3 Motivations and plans

The primary goal of the Coronagraph mission is to demonstrate its capability of the contrast level better than 10^{-7}. Then, the detection of a companion satisfied this required level will be the most promising demonstration. In addition, the CPP plans to maximize the long term value of the mission by conducting the technology demonstration observations using scientifically interesting targets wherever possible. Self-luminous substellar companions (see Figure 2), which release their thermal energies by radiation, are promising targets. These sources are observable at moderate contrasts in the near-infrared ($\sim 10^{-5}$) and have predicted contrasts ($> 10^{-8}$–10^{-7}) in the optical, suitable for the early-phase observation in the Roman-Coronagraph mission. Figure 3 shows the flux ratios of a self-luminous companion relative to a star with an effective temperature ($T_{\rm eff}$) of 7500 K, a radius of 2.1 $R_\odot$, and an age of 300 Myr. It is notable that the flux emitted by a self-luminous object depends on its age. In Figure 3, Roman's B3 mode can detect a companion with a mass exceeding 28 times Jupiter's mass ($M_{\rm Jup}$) with a contrast limit of $> 10^{-8}$, while the Subaru can detect companions with masses greater than 12 $M_{\rm Jup}$ with a contrast limit of $> 10^{-6}$ in the H band. These multi-wavelength observations of those will serve

---

[1] `https://roman.gsfc.nasa.gov/science/field_slew_and_roll.html`

[2] $\Delta_{\rm pitch}$ must be small because changes in the Sun illumination angles with moving from reference and target stars will cause thermal variation and then degrading the dark hole. The exact threshold has not been quantified yet. See also `roman-pointing`.

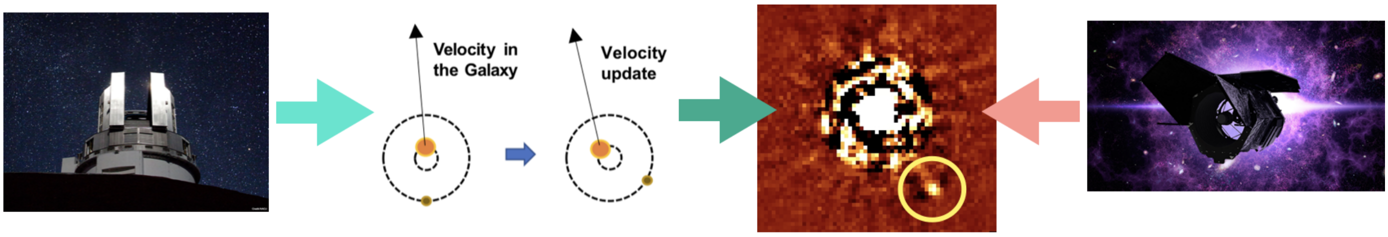

Figure 2: Concept illustration of our synergistic program. The Subaru Telescope will discover companions around accelerating stars, which will be followed up by Roman. The second-left panel illustrates the proper motion acceleration of a star gravitationally wobbled by its companion. Image credit: NAOJ (Subaru Telescope) and NASA GSFC/SVC (Roman Telescope).

as an excellent benchmark for the scientific studies of exoplanet atmospheres (see Section 6).

However, **the number of known self-luminous substellar companions that are observable with Roman is extremely small** due to the strong requirements for the targets in the Roman-Coronagraph imaging. The targets need to be bright in V band and close to reference stars (see above); few known samples meet these requirements. Furthermore, **the targets for Coronagraph imaging depends on the unfixed schedule of the entire Roman mission including the projects relevant to the Wide Field Imager, requiring more suitable targets across a broader sky coverage.**

The survey for self-luminous companions is currently ongoing with SCExAO and CHARIS on the Subaru Telescope (PI: T. Currie; El Morsy et al. 2024b) **until 2026A**. CHARIS is a near-infrared (JHK) integral field unit ($\mathcal{R} = 19$ or 80) and available with the extreme adaptive optics SCExAO. The ongoing survey is already focused on identifying potential targets for Roman, while also expanding the sample of lower-mass planets.

As the Roman mission approaches, the technical specifications and observational strategies continue to evolve. In particular, the science samples will not be finalized while the vetting of the reference stars for "digging dark hole" is in progress, necessitating additional targeted surveys that can further enhance the mission's scientific yield. Therefore, we propose a complementary survey with SCExAO/CHARIS that builds upon the foundation established by the ongoing one. Our proposed observations will expand the target pool by specifically focusing on stars located near high-grade dark-hole references that meet the Roman's evolving technical requirements. It also prioritizes companions that are more compatible with Roman's capabilities, even if they have higher masses. Using estimation procedures as shown in Figure 3, we predict potential companion candidates detectable with both Subaru and Roman. Thus, our complementary survey will further enhance the mission's flexibility by identifying additional companions that align with Roman's technical capabilities. **This expanded target pool will be particularly valuable given the scheduling constraints and sky-coverage requirements that will ultimately shape Roman's observing program**.

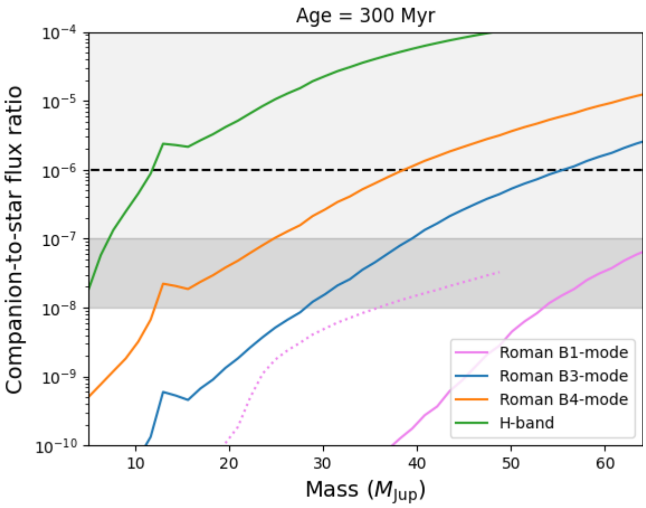

Figure 3: An example of expected flux ratios for a substellar companion relative to its host star. For an assumed age of 300 Myr, each curve illustrates the expected flux ratio for a companion of a given mass (x-axis), with different colors representing various bands (see legend). Dashed curves correspond to cloudy atmospheres, while solid curves represent clear atmospheres. The contrast limit for the proposed Roman observations is indicated by the darker gray area (which corresponds to the contrast level achievable in the early phase of the mission), with the lighter gray region being more accessible. A dashed horizontal line represents the contrast limit of the Subaru Telescope. Flux ratios were computed using the `species` package (Stolker et al. 2020), along with theoretical models from Phillips et al. 2020, Morley et al. 2024, and Allard et al. 2014.

We will perform follow-up observations of SCExAO/CHARIS for discovered companions, which will reveal its orbital motion and higher-resolution ($\mathcal{R} \approx 80$) spectrum to better constrain atmosphere parameters of those. We plan to propose the discovered companions as the targets for the technician demonstration of the Roman-Coronagraph mission. Furthermore, we propose to conduct additional follow-up observations using the high-resolution ($\mathcal{R} \sim 100,000$) near-infrared (1–1.7 μm) spectrograph REACH. The REACH data will be analyzed in conjunction with observations from Roman and Subaru/CHARIS, enabling us to cover the visual-to-infrared wavelengths (0.6–2.4 μm) with both low ($\mathcal{R} < 50$) and high resolutions. The combined use of these three instruments will significantly expand the parameter space for companion characterization (see Section 6).

4 Target selections

We select targets for this program from the Hipparcos-Gaia Catalog of Accelerations (HGCA; Brandt et al. 2021), which lists nearby stars with accelerating proper motions determined by combining high-precision astrometric data from Hipparcos and Gaia with the long time baseline (∼25 yr) between these two missions (see Figure 2). This approach enables us to efficiently identify promising host stars of substellar companions, significantly improving detection yield compared to conventional blind surveys. Indeed, high-contrast imaging surveys using HGCA have expanded the sample size of substellar companions so far (e.g., Currie et al. 2021; Kuzuhara et al. 2022; Currie et al. 2023; Franson et al. 2023). Furthermore, the combination of HGCA with high-contrast imaging and/or radial velocity measurements determines a detected companion's dynamical mass, which is model-independent and robust compared with conventional mass estimations. Follow-up spectroscopic observations characterized atmospheric dynamics and chemical compositions of the discovered companions (e.g., Zhang et al. 2024; El Morsy et al. 2024a).

Our selected targets will exhibit significant accelerations, most likely caused by orbiting companions. **The discovery rate of a substellar companion was 16% in our pilot survey (El Morsy et al. 2024b), which employed this target-selection technique**. Based on this empirical success rate, we predicted the detection yield from our target selections (see Section 5). We plan our target selections as follows. First, we prioritize targets that best meet the requirements of the Roman mission. All stellar targets in this survey are brighter than 6.5 mag in the V band, over which a Roman-Coronagraph performance can rapidly degrade. Additionally, we restrict $\Delta_{\rm pitch}$ between the targets and the reference stars[3] (graded as "A" or "B"; see Figure 1) to within 5°. The (minimum) masses of candidate companions are inferred using HGCA. Based on the inferred masses, we will confirm whether they are detectable with both Roman and Subaru following the scheme outlined in Figure 3.

The sample of reference stars will be expanded through our precursor observations to validate their suitability. We will use the updated reference-star list to refine our target selection. By the end of 2026, the upcoming Gaia Data Release (DR4) is expected to provide proper motion measurements that are 5–10 times more precise than current values (Gaia Collaboration et al. 2023), which can improve our target list. Based on the procedures described above, we made a tentative target list, which contains at least 30 targets that match our plan. Our tentative calculations of $\Delta_{\rm pitch}$ will be realized based on the Roman's exact schedule once it is fixed. Considering the potential updates mentioned above, we anticipate that this number will increase to 40. Thus, we propose observations of 30–40 targets.

5 Detection yield and requested nights

The number of detected companions suitable for the Coronagraph mission from our new survey is predicted as follows. We propose observing 30–40 targets in the new SCExAO/CHARIS survey. Given the empirical detection rate of 16% from our pilot survey, we expect to detect 5 (6) substellar companions from 30 (40) targets. Also, we predict that half of the detected companions will be located within Roman's field of view for the Band-1-HLC (the fiducial mode) and Band-3 modes (see Section 1). This prediction is based on the fact that half of the substellar companions discovered by recent extreme high-contrast imaging are found at projected separations smaller than $0\farcs5$. The remaining discovered companions ($r > 0\farcs5$) can be observed using the Band-1-SPC and Band-4 modes.

Each target requires 3 hours of observation, including overheads, resulting in a total of 3 × 30 (40) hours to observe all targets. Assuming a 70% weather success rate, we estimate that approximately 130 (170) hours will be needed, equivalent to 13 (17) nights (assuming 1 night = 10 hours).

We request 5 nights to confirm the discovered companions through second-epoch imaging and higher-resolution spectroscopy with CHARIS. To obtain the REACH spectrum for each target, we require 5 hours per target, including overheads. Accordingly, a total of 5 × 6 hours is needed, which corresponds to 4 nights, considering the weather success rate. Consequently, our proposed program could provide 5 (6) targets suitable for detailed characterization with the Roman and Subaru Telescopes from a total of 22 (26) nights of observations. **Those near-infrared observations with narrow field-of-view can be performed in bright nights.**

6 Science cases and impact

We have the following strategy to study self-luminous companions via the Roman-Subaru synergy. A photometric measurement at 575 nm is obtained by following-up a sample revealed by Subaru using the Roman Coronagraph. The comparison of the photometry with the infrared spectrum from CHARIS ($\mathcal{R} \sim 20$ and 80) makes it possible to perform the first atmosphere characterization with the Roman data. **Even if Roman does not detect the target, comparing the upper limit with the Subaru data can still contribute to characterization, strengthening the publication.** For example,

---

[3] Because $\Delta_{\rm pitch}$ cannot be validly calculated until fixing the schedule of the Roman Coronagraph mission, we approximated $\Delta_{\rm pitch}$ calculations with one based on ecliptic longitude. A true $\Delta_{\rm pitch}$ is smaller than the approximation, so we expect that the $\Delta_{\rm pitch}$ values of the tentative targets nearly fulfill the requirement.

a photometry upper-limit constrains a cloud property because the brightness of a companion depends on the property of clouds in the atmosphere (see Figure 3 and 4). The detection of a self-luminous companion with Roman improves the orbital analysis. After Band-1 imaging, the follow-up observations with the other modes of Roman is possible. The Band-3 mode enables us to obtain a low-resolution spectrum at wavelengths between 670 and 790 nm. If a companion is exterior to $\sim0.5''$, we image it using the Band-1-HLC and Band-4 mode, providing photometric measurements compared with the Subaru data.

One of the major challenges in characterizing exoplanets is the presence of clouds in their atmospheres, which makes it crucial to first constrain their properties and understand their formation processes. **The optical spectrum of a self-luminous companion is particularly sensitive to cloud properties such as particle size and composition**. As shown in Figure 4, clouds with a size of 0.1 μm (blue line) produce a steeper spectral slope in the optical than those with a size of 0.05 μm (orange line). However, the optical spectral slope is also influenced by the thermal structure, whose theoretical prediction involves some uncertainty (compare the blue and green lines in Figure 4).

A high-resolution spectroscopy with REACH helps us mitigate the uncertainties. By measuring the strength ratios of multiple absorption lines, which are sensitive to temperature (see the inset of Figure 4), we can robustly constrain the thermal structure. In addition, high-resolution spectra provide valuable constraints on chemical composition and surface gravity (e.g., Kawashima et al. 2024), all of which are essential for a comprehensive understanding of planetary atmospheres—yet difficult to obtain with low-resolution spectroscopy. Thus, the data from our Roman-Subaru synergistic program, which allows for precise constraints on the thermal structure, is essential for maximizing the scientific return of Roman's observations.

If possible, we propose photometric monitoring for a couple of targets using the Roman Coronagraph. This observation allows us to determine the rotation period ($P_{\rm rot}$) of a companion, whose projected rotation velocities ($v\sin i$) can be measured with REACH. Thus, the inclination (i) of the companion's spin axis is measurable ($v\sin i = 2\pi R/P_{\rm rot}\sin i$, where R is a companion's radius). Because the orbital inclination of the companion is then known, the companion's 3D obliquity can be determined. This kind of a characterization has been unrealistic except for special cases (which are mostly substellar companions having extremely-wide separations from their host stars; e.g., Poon et al. 2024). The Roman mission may be able to constrain the obliquity of a substellar companion with a semi-major axis of ∼5–100 au.

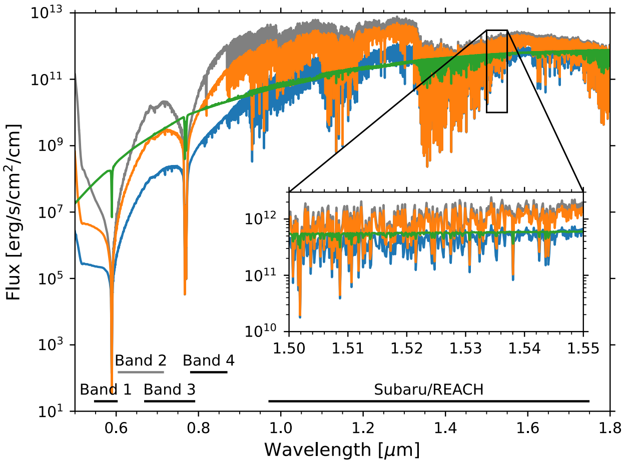

Figure 4: Spectrum models for a self-luminous companion with a $T_{\rm eff}$ of 1400 K and gravity of $\log g = 4.5$ simulated by an open-source code PICASO (Batalha et al. 2019). Four example cases are shown: clear atmosphere (gray), atmosphere with 0.1 μm-size clouds (blue line), atmosphere with 0.05 μm-size clouds (orange line), atmosphere with 0.1 μm-size clouds and smaller temperature gradient than the theoretical expectation by Sonora Bobcat (Marley et al. 2021) (green line). The inset figure highlights a wealth of molecular lines observable by high-resolution spectroscopy with REACH.

The small sample size will not enable population-level findings. However, **those samples will be important benchmark objects because high-contrast observations at visual wavelengths have not revealed the atmospheres of substellar companions located within $1\farcs0$ of their parent stars. Roman enables those characterizations for the first time, which can be combined with the data from the Subaru Telescope to validate and enhance the characterizations as described above**. We hope these efforts will ultimately lead to even more exciting discoveries with space telescopes expected in the 2040s (i.e., HWO).

References

Allard et al. 2014 Proc. of the IAU Symposium, 299, 271–272; **Bailey et al. 2023** Proc. of the SPIE, 12680 126800T; **Batalha et al. 2019** ApJ, 878, 70; **Brandt et al. 2021** ApJS 254, 42; **Currie et al. 2020** ApJL, 904, 25; **Currie et al. 2023** Science, 380, 198–203; **El Morsy et al. 2024a** ApJ, 981, 20; **El Morsy et al. 2024b**: arXiv:2409.06773; **Franson et al. 2023** ApJL 950, 19; **Gaia Collaboration et al. 2023** A&A, 674, A1; **Groff et al. 2016** Proc. of the SPIE, 9908, 99080O; **Jovanovic et al. 2015** PASP, 127, 890; **Kawashima et al. 2024**: arXiv:2410.11561; **Krist et al. 2023** JATIS, 9, 045002; **Kuzuhara et al. 2022** ApJL, 934, 18; **Kotani et al. 2020** Proc. of the SPIE, 11448, 1144878; **Marley et al. 2021** ApJ, 920, 85; **Morley et al. 2024** ApJ, 975, 59; **Phillips et al. 2020** A&A, 637, A38; **Poon et al. 2024** AJ, 168, 270; **Stolker et al. 2020**; A& A, 635, A182; **Wolff et al. 2024** Proc. of the SPIE, 13092, 1309255; **Zhang et al. 2024** AJ, 168, 131