SSC24-WP1-17

Commissioning Plans for the Pandora SmallSat: a mission to quantify stellar contamination of exoplanet transmission spectra

Lindsey Wiser
Arizona State University, School of Earth and Space Exploration
781 Terrace Mall, Tempe, AZ 85287; +1 (510) 333-3038
lindsey.wiser@asu.edu

Jessie Dotson, Tom Greene
NASA Ames Research Center
Moffett Field, CA 94035

Tom Barclay, Knicole Colon, Christina Hedges, Ben Hord, Aishwarya Iyer, Elisa Quintana
NASA Goddard Spaceflight Center
8800 Greenbelt Road, Greenbelt, MD 20771

Rae Holcomb
University of California, Irvine
4129 Frederick Reines Hall, Irvine, CA 92697-4575

Trevor Foote
Cornell University
404 Space Sciences Building, Ithaca, NY 14853

Jordan Karburn
Lawrence Livermore National Laboratory
7000 East Ave, Livermore, CA 94550

ABSTRACT

Pandora is a SmallSat mission designed to observe exoplanet atmospheres and stellar activity. Funded by the NASA Science Mission Directorate (SMD) Astrophysics Division through the Pioneers program, Pandora is a collaboration between NASA centers Goddard and Ames, the Lawrence Livermore National Laboratory, the University of Arizona, and other scientific institutions. Pandora will survey at least 20 transiting exoplanets during one year of science operations, obtaining a long baseline of simultaneous visible-light photometric and near-IR spectroscopic observations. These observations will be used to quantify and correct for stellar contamination of exoplanet transmission spectra due to spots and faculae on host stars. Pandora will subsequently identify exoplanets with hydrogen or water-dominated atmospheres.

In this paper, we share a preliminary plan for commissioning Pandora during its first month of operation after launch, anticipated for 2025. Broadly, commissioning includes bus and payload checkouts, followed by instrumentation checks, which include telescope pointing and tasks for non-pointed and pointed calibration. This paper focuses primarily on commissioning Pandora's instrumentation, including visible-light photometry and near-IR spectroscopy capabilities. We outline each commissioning task, our timeline, and our workflow for planning and managing an adaptable commissioning plan. This paper informs on Pandora's plans and provides an example of telescope commissioning for future missions.

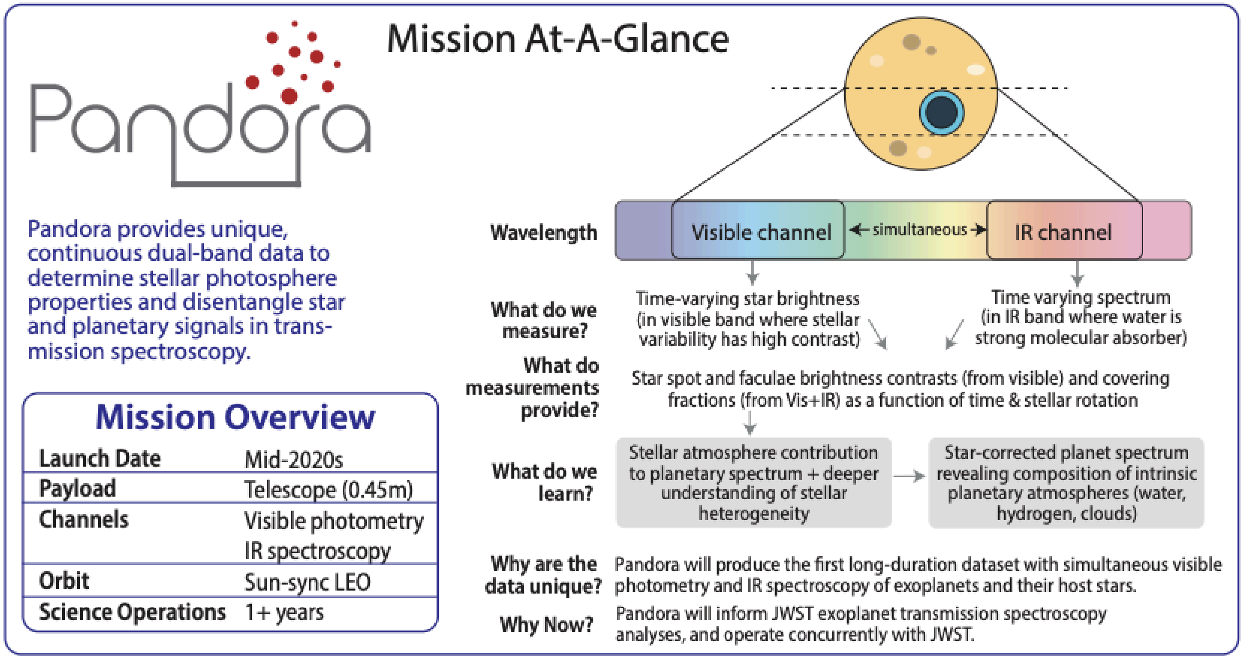

Figure 1: Pandora mission at-a-glance, as shown in reference 2.

INTRODUCTION TO PANDORA

The Pandora SmallSat, anticipated to launch in 2025, is one of the first NASA missions from the Pioneers Program ($20M cost cap).[1] Pandora will observe at least 20 stars and their planets to build our understanding of other worlds.[2] To date, over 5,600 exoplanet discoveries have been confirmed, and over the past few decades, exoplanet science has progressed beyond planet discovery into the characterization of planet atmospheres with both space-based (e.g., Spitzer, Hubble, Webb) and ground-based observatories (e.g., Gemini). Transmission spectroscopy is one of the most common methods used to characterize exoplanet atmospheres – as a planet passes in front of its host star from our perspective, some stellar light is blocked, and some passes through the planet's atmosphere. By measuring the relative dip in flux from the host star at different wavelength bins, we can extrapolate what molecules may be present in the atmosphere.[3] One challenge, however, is that this method depends on an accurate understanding of the host star's spectrum. Studies have shown that stellar activity, i.e., relatively dim or bright regions on the star itself, can be misinterpreted as features of the planet's atmosphere.[e.g., 4-7]

Pandora's primary goal is to disentangle stellar and exoplanet signals in transmission spectra to determine exoplanet atmosphere compositions reliably. This goal is broken down into two objectives: (1) Determine the spot and faculae covering fractions of low-mass exoplanet host stars and the impact of these active regions on exoplanetary transmission spectra, and (2) Identify exoplanets with hydrogen- or water-dominated atmospheres, and determine which planets are covered by clouds and hazes.[2]

To achieve these objectives, Pandora will observe a population of stars and their transiting planets over one year of science operations. For each star-planet system, Pandora will observe at least 120 hours, including at least ten transits per planet. Observations will include simultaneous visible photometry (0.4-0.65 um) and near-infrared spectroscopy (1.0-1.6 um, spectral resolution ≥30) (see Figure 1). Photometry will measure stellar brightness over time, while spectroscopy will measure spectral variability with time in a wavelength regime particularly sensitive to spectral features of atmospheric hydrogen and water. Pandora's science will complement other observatories in two key ways: First, the simultaneous observations enable real-time measurements of the impacts of stellar activity on transit spectra. Second, Pandora can provide long-duration baseline observations that more subscribed telescopes cannot.

Pandora is a collaboration between NASA Goddard Spaceflight Center, NASA Ames Research Center, Lawrence Livermore National Laboratory, the University of Arizona, and other institutions. Pandora

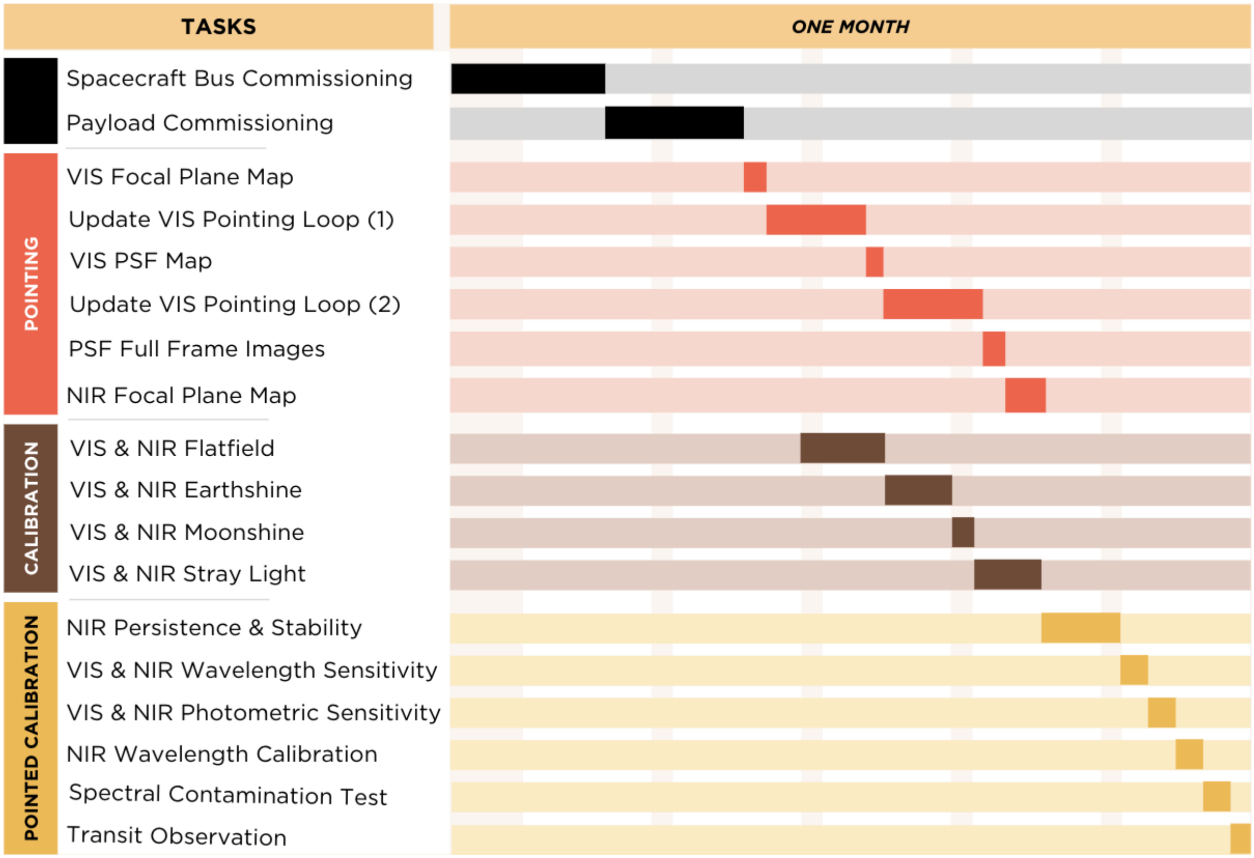

Figure 2: Overview of commissioning timeline and tasks. Time blocks are estimations based on data volume and downlink time, which is Pandora's primary time constraint.

has emphasized engaging early-career personnel to train the next generation of mission leaders.

COMMISSIONING ACTIVITIES

Commissioning will occur during the first month after launch and include checks of the spacecraft bus, payload, and science instrumentation. In this paper, we outline the commissioning plans for Pandora, focusing on the science instrumentation. The overarching goals of instrument commissioning are to check telescope performance against our predictive models and to test the edge cases of possible observation scenarios. Figure 2 outlines our broad commission tasks.

Before instrument commissioning, spacecraft bus and payload commissioning must be completed. The bus checkout is expected to take about three days and involves, among other tasks, deploying the solar array, establishing and verifying communication paths, and verifying guidance, navigation, and control. The payload check is planned for five days and includes checking power to the payload, verifying subsystem operation, and testing image acquisition, staging, and download. Ultimately, these commissioning steps ensure essential spacecraft operations and coarse telescope pointing.

The first set of instrument commissioning tasks is intended to refine our telescope pointing:

- *Visual Detector (VIS) Focal Plane Map* – Observe multiple stars in the same VIS field-of-view (FOV) to determine the mapping between the sky and the VIS detector.
- *Update VIS Pointing Loop* – Update the VIS pointing control parameters. Then, observe multiple stars over ~1 spacecraft orbit to quantify pointing performance. We will repeat this task twice (see Figure 2).
- *VIS PSF Map & PSF Full-Frame Images* – Acquire data to measure the VIS array's Point Spread Function (PSF) as a function of location on the array and source temperature. For an initial look, we will observe two stars of different temperatures at

multiple locations across the array. We will then take full-frame VIS images to test our PSF model further.

- *Near Infrared Detector (NIR) Focal Plane Map* – Observe a star at multiple positions across the NIR array to determine the mapping between the sky and the detector.

The second set of instrument commissioning tasks is for initial calibration. These tasks do not require fine pointing, so they can be done while pointing tasks are still being completed.

- *VIS & NIR Flatfield* – Observe an extended bright source to simultaneously illuminate large portions of the VIS and NIR arrays. We may illuminate sub-portions of the arrays over multiple observations.
- *VIS & NIR Earthshine* – Observe multiple point sources near Earth's keep-out angle to measure background flux due to the Earth's light. Determine if this background flux is dependent on spacecraft orientation.
- *VIS & NIR Moonshine* – Repeat VIS & NIR Earthshine, replacing Earth with the Moon.
- *VIS & NIR Stray Light* – Observe multiple point sources while a very bright source is just out of, then just on the edge of, the VIS and NIR FOVs. Repeat for multiple separation angles between the nominal targets and the bright source, and for multiple rotation orientations.

Finally, we plan for a set of calibration tasks that require fine-pointing. These will occur once the pointing and coarse calibration tasks are complete.

- *NIR Persistence & Stability* – Observe a bright source for varied durations. After this observation, rapidly repoint the observatory to position the boresight on a nearby blank part of the sky. Continue to read out the detector after repointing to quantify persistence.
- *VIS & NIR Wavelength Sensitivity* – Observe multiple stars with well-understood spectra across Pandora's wavelength range to estimate the VIS and NIR instruments' sensitivity as a function of wavelength.
- *VIS & NIR Photometric Sensitivity* – Observe multiple photometric standard stars to determine the photometric sensitivity of the VIS and NIR instruments.
- *NIR Wavelength Calibration* – Observe the spectrum of a well-understood post-AGB star for wavelength calibration of the Pandora NIR prism spectra.
- *NIR Spectral Contamination Testing* – Take multiple observations of a target star with nearby sources of spectral contamination to test our ability to mitigate this contamination. Adjust the spacecraft roll angle to observe the target with (1) no spectral contamination, (2) mild spectral contamination that the science team has deemed manageable, and (3) significant spectral contamination that is unacceptable for science.
- *Transit Observation* – Observe the transit of a well-studied exoplanet. Include significant pre- and post-transit observations to approximate a nominal Pandora transit observation. The chosen exoplanet should be known to have a featureless spectrum.

COMMISSIONING TOOLS

Pandora's instrument commissioning needs to be adaptable. As a Pioneers SmallSat, Pandora will launch on rideshare, so our team has limited influence over the launch window. Therefore, we must be able to determine what targets we can observe for our commissioning tasks with potentially little turnaround time. Additionally, as each commissioning task is completed, we expect to update our predictive performance models and potentially adjust upcoming commissioning observations in light of new information. We are developing a suite of tools to facilitate dynamic planning and real-time adjustment to upcoming commissioning tasks.

GitHub Project & Repository

We plan to use a GitHub Project to document an overview of our commissioning activities and to track progress during commissioning.[8] This Project allows us to create a list of tasks, including descriptions, dates, assignees, status (i.e., "planning," "ready to observe," "in progress," "done"), and any other flags we may need. The Project is also linked to a GitHub Repository, where we will store other necessary commissioning files.

For each commissioning activity, the GitHub Project includes a task with a generalized description. This description is intentionally non-specific, so it remains accurate as specifics are iterated. Instead, the linked Repository will include files with specific observation parameters, including Task Notebooks, Simulated Task Products, and Science Operations Center (SOC) Reference Files.

PandoraSim & Pandora Scheduler

Independent from commissioning planning, a Python package for simulating Pandora observations, PandoraSim, is being developed. From input observation parameters, PandoraSim outputs simulated files mirroring those we expect to receive from the

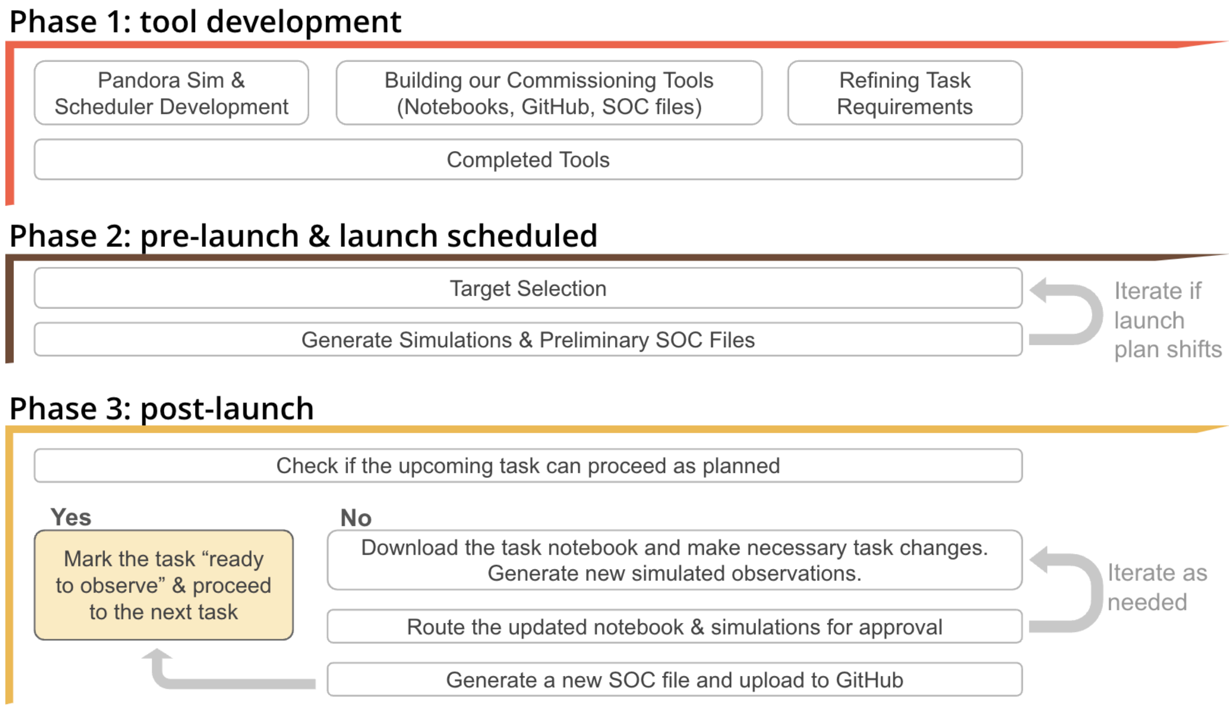

Figure 3: A summary of Pandora's instrument commissioning planning workflow.

telescope. Additionally, PandoraSim includes functions for visualizing VIS and NIR images, target positions on the detectors, integration schemes, and more.

Also in development independent of commissioning is the Pandora Scheduler.[9] The primary goal for the Scheduler is to produce an efficient observation calendar based on the observability of targets and the timing of planet transits. However, during commissioning, the order of tasks is mostly pre-determined, and the target(s) we observe for each task are relatively flexible. Therefore, we are adapting the Scheduler to tell us which targets are observable at the time we plan to conduct a given commissioning task. We will then filter observable targets based on each task's target criteria to select task targets.

Task Notebooks & Simulated Products

Jupyter Notebooks that utilize PandoraSim will be our tools for simulating each commissioning observation and generating Simulated Products, i.e., simulated observation output files from the telescope. These "Task Notebooks" will be used to check observation parameters, generate an "expected" output to compare to actual observations, and generate SOC Reference Files. Task Notebooks and Simulated Products will be stored in the GitHub Repository connected to the GitHub Project.

SOC Reference Files

Science Operations Center (SOC) Reference Files contain all the observation parameters required for scheduling a Pandora observation. They will follow a standard format that the Pandora Scheduler can read. We plan to generate SOC Reference Files within the Task Notebooks and store them in the GitHub Repository associated with our GitHub Project.

Task Result Summaries

Lastly, we plan to summarize the results from each commissioning task in short documents. While the content will vary significantly, we will have a generalized format so that Task Result Summaries are easily parsable. These Summaries will be shared on the GitHub Repository and viewable by the mission team for general updates and to inform future commissioning tasks that depend on previous results.

COMMISSIONING PLANNING WORKFLOW

We have broken our instrument commissioning planning process into three phases. For a summary, see Figure 3.

Phase one is tool development. We are currently in this phase as we continue to develop and finalize the tools described in the previous section.

Phase two will begin once we have a scheduled launch. At that point, we will have an initial prediction for our spacecraft position with time, and we can begin target selection using the Pandora Scheduler. Using Task Notebooks, we will create preliminary observation Simulated Products and SOC Reference Files. As the launch plan is refined and potentially shifts, we will iterate on target selections. Simulated Products and SOC Reference files will be labeled with appropriate version numbers to track changes.

Phase three begins at launch and enables real-time updates to the instrument commissioning plan. Initially, all instrument commissioning tasks will be set to the status "planning" on the GitHub Project. We will check each upcoming task to see if it can proceed as planned, which may partially involve reviewing previous Task Result Summaries. If the task can proceed as planned, its status will be updated to "ready to observe," and the most recent SOC Reference File will be forwarded to the SOC.

If the upcoming task cannot proceed as planned, we will revisit the Task Notebook to make necessary changes and generate new Simulated Products. These will be routed for appropriate approval. Once approved, a new SOC Reference File will be generated, and the most recent SOC Reference File and Simulated Products will be uploaded to the GitHub Repository. The task status can then be marked "ready to observe."

A task scheduled for observation will have the status "in progress." Once data is received from the telescope and the necessary analysis has been done to inform future commissioning tasks, including uploading a Task Result Summary to GitHub, the task status will be labeled "complete."

CONCLUSIONS

Pandora is an exciting new mission designed to disentangle stellar and exoplanet signals to improve our understanding of exoplanet atmospheres. In this conference paper, we present an overview of our instrument commissioning plans to provide a mission update and an example workflow for the instrument commissioning of a SmallSat telescope. The tools and processes we are developing for Pandora are intended to facilitate a commissioning plan that is adaptable to in-the-moment changes, particularly to target selection. The tools we plan to use for commissioning will also be valuable during science operations, particularly PandoraSim and the Scheduler, so commissioning planning provides an opportunity to stress test these tools before conducting our core science. In the coming months, we plan to have a completed suite of commissioning tools, as outlined here, and initial target selections leading up to a 2025 launch date.

Acknowledgments

Lindsey Wiser thanks the Pandora team and the student shadow program for supporting this work.

Pandora is supported by NASA's Astrophysics Pioneers Program.

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

References

1. NASA, Astrophysics Pioneers, accessed June 2024. https://science.nasa.gov/astrophysics/programs/astrophysics-pioneers/
2. Quintana, E. V., Colòn, K. D., Mosby, G., Schlieder, J. E., Supsinskas, P., Karburn, J., Dotson, J. L., Greene, T. P., Hedges, C., Apai, D., Barclay, T., Christiansen, J. L., Espinoza, N., Mullally, S. E., Gilbert, E. A., Hoffman, K., Kostov, V. B., Lewis, N. K., Foote, T. O., Mason, J., Youngblood, A., Morris, B. M., Newton, E. R., Pepper, J., Rackham, B. V., Rowe, J. F., Stevenson, K., "The Pandora SmallSat: Multiwavelength Characterization of Exoplanets and their Host Stars," Proceedings of the Small Satellite Conference on Science/Mission Payloads SSC21-VI-02, Logan, UT, 2021.
3. Madhusudhan, N., "Exoplanetary Atmospheres: Key Insights, Challenges, and Prospects," Annual Review of Astronomy and Astrophysics, vol. 57, p.617-663, August 2019.
4. Iyer, A. R., Line, M. R., "The Influence of Stellar Contamination on the Interpretation of Near-infrared Transmission Spectra of Sub-Neptune Worlds around M-dwarfs," The Astrophysical Journal, Volume 889, Issue 2, id.78, February 2020.

5. Dittmann, J. A., Close, L. M., Green, E. M., Fenwick, M., “A Tentative Detection of a Starspot During Consecutive Transits of an Extrasolar Planet from the Ground: No Evidence of a Double Transiting Planet System Around TrES-1,” The Astrophysical Journal, Volume 701, Issue 1, pp. 756-763, August 2009.

6. Rackham, B. V., Apai, D., Giampapa, M. S., “The Transit Light Source Effect: False Spectral Features and Incorrect Densities for M-dwarf Transiting Planets,” The Astrophysical Journal, Volume 853, Issue 2, article id. 122, February 2018.

7. Wakeford, H. R., Lewis, N. K., Fowler, J., Bruno, G., Wilson, T. J., Moran, S. E., Valenti, J., Batalha, N. E., Filippazzo, J., Bourrier, V., Hörst, S. M., Lederer, S. M., de Wit, J., “Disentangling the Planet from the Star in Late-Type M Dwarfs: A Case Study of TRAPPIST-1g,” The Astronomical Journal, Volume 157, Issue 1, article id. 11, January 2019.

8. GitHub Docs, About Projects, accessed June 2024. https://docs.github.com/en/issues/planning-and-tracking-with-projects/learning-about-projects/about-projects

9. Foote, T. O., Barclay, T., Hedges, C. L., Lewis, N. K., Quintana, E. V., Rackham, B. V., “Schedule optimization for transiting exoplanet observations with National Aeronautics and Space Administration's Pandora SmallSat mission,” Journal of Astronomical Telescopes, Instruments, and Systems, Volume 9, id. 047001, October 2023.