Multiwavelength Characterization of Exoplanets and their Host Stars

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APAC Oct 15, 2021
Exoplanets and the Search for Life

- Exoplanet detection
- Demographics
- Characterization (compositions + atmospheres)
- Biosignatures

*Spacecraft not to scale*
Why Pandora?

Pandora is a SmallSat mission that fills a gap in NASA’s exoplanet roadmap.

Pandora’s goal is to disentangle star and planet signals in exoplanet transmission spectra to reliably determine exoplanet atmosphere compositions.

Exoplanet transmission spectroscopy is a proven technique used to probe the atmospheres of transiting exoplanets and reveal their compositions (Seager & Sasselov 2000)
Exoplanet Transmission Spectroscopy

A differential measurement that assumes the star’s spectrum is known and isn’t changing, and can simply be subtracted from the observed (=star+planet) spectra.
The Myth of a Perfect Star

In reality, most stars are active, with dark spots and bright faculae regions that evolve spatially and with time (stellar rotation).

These brightness variations can be imprinted in the observed spectrum and can contaminate the inferred planetary spectra.

See D. Apai’s description at https://distantearths.com/transit_lightsource_effect/
Spot-induced spectroscopic variations can mask or mimic planetary atmospheric features (like the presence and abundance of water!)
Exoplanet Transit Spectroscopy is a primary science case for JWST

30 transiting exoplanets in JWST GTO+ERS programs

Correcting for starspots is most important for smaller planets (smaller signals), and smaller stars (highly active), i.e. those that JWST will observe

38 added for JWST GO Cycle 1
Pandora is a SmallSat designed to observe transiting exoplanets and their host stars with long time-baseline, simultaneous visible photometry and infrared spectroscopy.

Goal:
Disentangle star and planet signals in transmission spectroscopy to reliably determine exoplanet atmosphere compositions.

Unique capabilities:
- **Long duration baseline** - observe 24 hours per transit [10 transits per planet]
- **Simultaneous visible photometry and NIR spectroscopy**
Objective I:

Determine the spot and faculae covering fractions of low-mass exoplanet host stars and the impact of these active regions on exoplanetary transmission spectra

Ia. What are typical spot coverages of low-mass exoplanet host stars, and how do they vary with time?

Ib. How do stellar properties (size, mass, temperature) correlate with contamination, and how does the impact of contamination change with planet properties (size/mass/bulk density, orbital distance)?

Objective II:

Identify exoplanets with hydrogen- or water-dominated atmospheres, and determine which planets are covered by clouds and hazes

IIa. How does the atmospheric composition of planets vary with size/mass/bulk density, orbital distance, and host star properties?

IIb. Which prior transmission spectroscopy observations yield the same atmospheric results after correcting for stellar contamination?
Pandora provides unique, continuous dual-band data to determine stellar photosphere properties and disentangle star and planetary signals in transmission spectroscopy.

Mission Overview

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Mid-2020s</th>
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<tbody>
<tr>
<td>Payload</td>
<td>Telescope (0.45m)</td>
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<tr>
<td>Channels</td>
<td>Visible photometry, IR spectroscopy</td>
</tr>
<tr>
<td>Orbit</td>
<td>Sun-sync LEO</td>
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<tr>
<td>Science Operations</td>
<td>1+ years</td>
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What do we measure?
- Time-varying star brightness (in visible band where stellar variability has high contrast)
- Time varying spectrum (in IR band where water is strong molecular absorber)

Star spot and faculae brightness contrasts (from visible) and covering fractions (from Vis+IR) as a function of time & stellar rotation

What do we learn?
- Stellar atmosphere contribution to planetary spectrum + deeper understanding of stellar heterogeneity
- Star-corrected planet spectrum revealing composition of intrinsic planetary atmospheres (water, hydrogen, clouds)

Why are the data unique?
- Pandora will produce the first long-duration dataset with simultaneous visible photometry and IR spectroscopy of exoplanets and their host stars.

Why Now?
- Pandora will inform JWST exoplanet transmission spectroscopy analyses, and operate concurrently with JWST.
Pandora’s Observing Strategy

Visible photometry captures stellar brightness over time.

Simultaneous IR spectroscopy captures variations in spectra over time.

The simultaneous visible photometry + spectroscopy provides constraints on star spot coverage, which is needed to disentangle the star and planet spectra, thereby enabling robust measurements of the planet’s true atmospheric makeup.
Target Selection Trade Study:
- developed instrument simulators
- science team applied independent star and exoplanet atmosphere joint retrieval models
- signal-to-noise input into requirements
- software developed for “year in the life” of operations

135 days of unscheduled time available for schedule margin and auxiliary (bonus) science
Lawrence Livermore National Lab is co-leading and managing the Pandora mission.

LLNL is responsible for the design and development of the payload Pandora leverages technology investments from LLNL, including “CODA” telescope.
Pandora Instrument
Overview

Pandora’s single instrument: an all aluminum 0.45m relayed Cassegrain telescope “CODA”

LLNL’s CODA Program Goal: Produce an inexpensive telescope that could be produced in large quantities for ESPA Grande class missions with minimal NRE

Features
— Fabricated from readily available 6061 Aluminum
— Bulk materials allow for multiple sets of mirror to be produced quickly
— Flexible relay design allows for wide variety of detectors to be hosted
— Utilizes existing state of the art processes and coatings for optical elements

Optical relay assembly contains dispersion prism and dichroic, separates visible and NIR channels

• Visible Detector: Fairchild CIS2521
• NIR Detector: Teledyne H2RG
Leveraging Investments from Government and Commercial Entities

Pandora has partnered with LLNL, and thereby benefits from investments made by other gov agency programs.

Pandora acquired donated JWST NIRCAM flight qualified spare (2.5 micron) detectors and SIDECAR.

Pandora has partnered with commercial entities for spacecraft bus.

Importance of Small, Innovative Missions

- **Expand** science programs to take advantage of small satellite rapid innovation to achieve breakthrough science.
- **Enable** fast access to space with focused science measurements to fill a critical gap between large flight projects.
- **Leverage** technology investments to further improve potential of science instruments.
- **Partner** with commercial entities to acquire new capabilities of small satellite platforms.

Writing Successful Proposals: OBSERVATIONS FROM NASA

Dr. Thomas H. Zurbuchen
Associate Administrator
Science Mission Directorate
Shown above are mission leadership and science team members. Early Career Team Members in over half of science team roles (12 EC doctorates, 2 grad students in shadow position); Engineering (LLNL) includes 7 EC and summer interns. Mentoring model matches experienced team member with EC.
The Pandora Team is Diverse

Best practices already established:
- Team Code of Conduct
- Publication Plan
- Communications (internal/external)

underrepresented minorities in leadership positions (PI, PS, Lead Detector Scientist)
Pandora Mission Timeline

Why now?

- Bounty of targets are being identified by TESS
- Pandora will be pathfinder for JWST, identifying benchmark targets & which are obscured by clouds
- Pandora will operate simultaneously with HST and JWST (Pandora provides complementary stellar characterization with long baseline)
Pandora addresses NASA’s Key Goals and fills a gap in the ExEP’s strategy plan

**NASA’s Astrophysics Themes**

| **2010 NRC Decadal Survey:** Science Frontier Discovery Area “Identification and characterization of nearby habitable exoplanets” |
| **2014 NASA Science Plan:** goal to “Discover and study planets around other stars and explore whether they could harbor life” |
| **2018 NASA Strategic Plan:** goal of “Searching for Life Elsewhere” by “Improving techniques and ideas for discovering and characterizing habitable and/or inhabited environments on these planets, coupled with an understanding of the potential false positives for habitability or life, will enable prioritization of exoplanets for targeted follow-up observations” |

**Exoplanet Exploration Program Office Science Gap List:** (#SCI- 03) Spectral signature retrieval, “Early spectral detections have not withstood reanalysis”; “Systematic instrumental and stellar effects limit the ability to extract reliable spectra”; **Capabilities needed:** Ability to reliably extract physical parameters; calibration and mitigation studies like “studies on contamination of stellar photospheric heterogeneities as limitation to extraction of transiting planet spectra”

**Exoplanet Science Strategy Plan from the National Academies:** “An understanding of exoplanets is inextricably linked to an understanding of the stars they orbit. Moreover, the ability to detect planets and the precision with which researchers can determine their properties is often limited by knowledge of the star.” “Heterogeneities on stellar photospheres are ubiquitous. At optical and infrared wavelengths, such regions of various temperatures, and thus differing local emission spectra, will corrupt the wavelength-dependent transit measurements of any planet”, “These concerns also directly impact plans to search at infrared wavelengths for atmospheric biosignature gases in the atmospheres of HZ planets”

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The Effect of Stellar Contamination on Space-based Transmission Spectroscopy is the topic of Study Analysis Group (SAG) 21 of NASA’s Exoplanet Exploration Program Analysis Group (ExoPAG).

**Co-Chairs:** Drs. Néstor Espinoza (STScI) and Benjamin Rackham (MIT)
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<th>Date</th>
<th>Events</th>
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| Feb 1, 2021  | • Pioneers Selection  
• Pandora one of four selected projects  
• Funding for 6mo “Initial Formulation Phase” |
| Feb 1 - now  | • Performed 8 trade studies  
• Developed L1-L2 Requirements  
• Write-up Concept Study Report (CSR) and Project Plan |
| Aug 2, 2021  | • Submit Concept Study Report |
| Sept 7-8, 2021 | • Gate Review: Systems Requirements Review & Site Visit (at LLNL) |
| NET Sept 30, 2021 | • Gate Review Decision  
• No downselects of 4 Pioneers, but final approvals will be given |
Pioneers fleet!