2023 Sagan Summer Workshop

Characterizing Exoplanet Atmospheres: The Next Twenty Years

Group Projects Instructions

Workshop attendees are encouraged to participate in the group projects. These projects are intended for attendees to use what has been learned in the expert-led hands-on sessions during the week and apply them to solve given problems. There are four group projects in total. Please select *only* one to work on during the workshop.

Use this Google spreadsheet to sign up with teams to work on the projects together. Each tab is for one project. For remote attendees, please indicate your country (time zone) so you can coordinate how to work on the projects together.

Projects

[NOTE: the notebook links have been updated to their permanent archive location. In the notebooks change references from https://catcopy.ipac.caltech.edu/ssw to https://catcopy.ipac.caltech.ed/ssw2023]

1) Near-IR Transmission Spectrum of WASP-39b (Based on Sessions I & II)

This group project entails reducing and analyzing WASP-39b data from the JWST Transiting Exoplanet Community Early Release Science (JTEC ERS) program (#1366). **There are three possible datasets to choose from.** Download the dataset you wish to work with, in your preferred format (tar, zip or Google Drive).

NIRSpec/G395H NRS1 (2.9 - 3.7 microns)

- Stage 2 (699 Mb uncompressed; tar or zip)

NIRSpec/PRISM (0.6 - 5.2 microns)

- Stage 2 (8.9 Gb uncompressed – *not* recommended for Colab users; Google Drive)
- Stage 3 (259 Mb uncompressed; tar or zip)

NIRCam/F322W2 (2.5 - 4.0 microns)

- Stage 2 (1.1 Gb uncompressed; tar or zip)

Participants may already be familiar with the NIRSpec/G395H NRS2 dataset from tutorials earlier in the week. This is an opportunity for participants to apply lessons learned from the tutorials in generating a transmission spectrum with clear spectroscopic features.

Starting from the available FITS files (Stage 2), participants will use the **Eureka!** pipeline to generate a time-series of 1D spectra (Stage 3), followed by spectroscopic light curves (Stage

4). In order to produce a high-quality transmission spectrum, participants will need to optimize a myriad of parameters in these stages. Each group will work to answer the following questions:

- What aperture and background half-widths yield the "best" light curve(s)?
- What metric did you use to determine the "best" light curve(s)?
- Which sigma threshold parameters most impacted the quality of your data?
- How many spectroscopic channels did you use? What is a reasonable resolving power for your dataset?

Next, participants will fit the spectroscopic light curves using a combination of astrophysical and systematic models (Stage 5), use Bayesian techniques to estimate parameter uncertainties at each wavelength, and plot the resulting planet spectrum (Stage 6). Each group will work to answer the following questions:

- Under what conditions is it best to use fixed or free orbital parameters? Do both scenarios produce consistent results? If not, why?
- Under what conditions is it best to use fixed or free limb-darkening parameters? Do both scenarios produce consistent results? If not, why?
- Is your transmission spectrum (including uncertainties) consistent with published results? If not, why?
- What molecular features do you see in the spectrum?
- BONUS: Can you find an atmospheric forward model that provides a good fit to your data?

2) Mid-IR Phase Curve of WASP-43b (Based on Sessions I & II)

This group project entails reducing and analyzing WASP-43b data from the JWST Transiting Exoplanet Community Early Release Science (JTEC ERS) program (#1366). Here, MIRI/LRS obtained a full-orbit phase curve observation of the hot Jupiter WASP-43b. Participants may already be familiar with the MIRI/LRS dataset from fitting a secondary eclipse during tutorials earlier in the week. This is an opportunity for participants to apply lessons learned from the tutorials in fitting the full, white-light phase curve. Download the dataset below.

WASP43b_MIRI_PhaseCurve

- Stage 2 (6.2Gb uncompressed; Google Drive)

Starting from the available FITS files (Stage 2), participants will use the **Eureka!** pipeline to generate a time-series of 1D spectra (Stage 3), followed by a band-integrated (white) light curve (Stage 4). In order to produce a high-quality phase curve, participants will need to optimize a myriad of parameters in these stages. Each group will work to answer the following questions:

- What aperture and background half-widths yield the "best" light curve(s)?
- What metric did you use to determine the "best" light curve(s)?
- Which sigma threshold parameters most impacted the quality of your data?

Next, participants will fit the phase curve using a combination of astrophysical and systematic models (Stage 5) and use Bayesian techniques to estimate parameter uncertainties. Each group will work to answer the following questions:

- Is it better to fit the ramp at the beginning of the phase curve or trim the data?
- Should you fit for the time of secondary eclipse?
- In units of degrees, what is your measured hotspot offset? Is it an eastward or westward offset?
- What are your maximum and minimum planet flux values? What is your measured heat redistribution [(F_{max} - F_{min}) / F_{Max}]?
- Are your measured transit and eclipse depths (including uncertainties) consistent with published results? If not, why?
- BONUS: Generate and fit spectroscopic phase curves. Is there a wavelength dependence to the hotspot offset or heat redistribution?

3) Grid Search: Fitting models to Data (Based on Session III)

SSW2023_Group_Project_Fitting_Models_to_Data.ipynb
https://catcopy.ipac.caltech.edu/ssw2023/hands-on/SSW2023_Group_Project_Fitting_Models_to_Data.ipynb
Note: This notebook includes the data download step.

During the hands-on session you learned how to compute grid models including radiative-convective climate modeling and cloud modeling. That will enable you to create a grid of models for any kind of planet. However, in order to compare grids to data you must also understand how to use basic grid fitting tools that yield a best fit model. For the group project, we take this more quantitative approach to grid fitting by compute the single best fit model, which has the least chi squared. In this notebook, we show how to use the PICASO-formatted grid models to interpret data. We continue focusing on the ERS WASP-39b result. For the hands on session, we started by using the results of the JWST Transiting Exoplanet Community Early Release Science Team's first look analysis of WASP-39 b, which used the NIRSpec Prism data. However, as part of that team, there were four other analyses using four instruments. One benefit of JWST is its broad wavelength coverage. This often means you will be stringing together multiple instruments as part of a single planet analysis. Therefore, in this group project we will focus on this. We will take these grid fitting tools in order to analyze the reduced spectra from:

1. NIRISS SOSS spectrum (Feinstein et al. 2023)
2. NIRSpec G395H spectrum (Alderson et al. 2023)
3. NIRSpec Prism spectrum (Rustamkulov et al. 2023)
4. NIRCam f322w2 spectrum (Ahrer et al. 2023)

As part of the group project your goal is to determine:

1. What are the best fit cloud-free parameters (M/H, C/O, internal heat, heat redistribution) for each of the four instruments? Are they similar or different?

2. Are there cases where different data reductions result in different best fit cloud-free parameters?
3. Does including clouds affect the best fit model?
4. How does the best fit cloudy model change for each instrument? Are some instruments more affected by clouds than others?
5. Are there cases where different data reductions result in different best fit cloudy parameters?
6. Do any best fit parameters seem meaningfully constrained by the datasets? Are any physical parameters better constrained than others (e.g., does M/H seem better fit than C/O or internal temperature)?

Ultimately, we hope you will gain intuition for how to use grid models to analyze data. Combined with the hands-on session lesson, this will give you all the pieces needed to start interpreting spectroscopic data with forward models!

4) Emission spectrum retrieval of the hot Jupiter WASP-77 Ab (Based on Session IV)

SSW2023_Group_Project_Retrieval.ipynb
https://catcopy.ipac.caltech.edu/ssw2023/hands-on/SSW2023_Group_Project_Retrieval.ipynb

In this group exercise you will run a retrieval on the atmospheric properties of WASP-77 Ab, which is a hot Jupiter (Teq$\sim$1700 K) in orbit around a sun-like star. WASP-77 Ab's atmosphere has been found to be depleted in metals when compared to solar, both based on high-resolution ground based data (Line et al. 2021) and JWST observations. Here you will try to reproduce this result, using the JWST data of August et al. (2023). Like in the transmission spectrum retrieval example of the hands-on session, we will be using NIRSpec G395H data here.

Each group will carry out the following analysis and answer the subsequent questions:

- Implement an "on-off analysis" that turns the effect of a given molecular absorber off. Which molecules are likely contributing to the spectrum?
- Look at the inferred values for metallicity ([Fe/H]) and the carbon-to-oxygen number ratio (C/O) in the atmosphere. How do these values compare to the values reported in August et al. (2023)? Study what happens to the spectrum if the metallicity is changed to 0.1 x solar ([Fe/H] = -1), solar ([Fe/H]=0), and 10 x solar ([Fe/H]=1). Why do you think the retrieval found the reported metallicity?
- Carry out an "on-off analysis" at [Fe/H]=1 to see where CO_2 dominates the spectrum.
- Compare the retrieved P-T profile with the one reported in August et al. (2023), also turn on the contribution function. How does the P-T profile compare to August et al. at locations where the contribution is high?