The Hubble Space Telescope PanCET Program: An Optical to Infrared Transmission Spectrum of the hot Jupiter KELT-7b

Dana R. Louie[1], Drake Deming[2], David Sing[3], Thomas Mikal-Evans[4], Munazza K. Alam[5], Nikolay Nikolov[6], Gregory W. Henry[7], and the PanCET Collaboration

[1]NASA Goddard Space Flight Center, [2]University of Maryland, [3]Johns Hopkins University, [4]Max Planck Institute for Astronomy, [5]Carnegie Earth & Planets Laboratory, [6]Space Telescope Science Institute, [7]Tennessee State University

Abstract: We present the first optical to infrared (0.3 - 5.0 micron) transmission spectrum of the ultra-hot Jupiter KELT-7b, which orbits a bright (V = 8.54) F-type star. With an equilibrium temperature of ~2048 K, the planet inhabits a parameter space where we can explore current exoplanet atmosphere theories regarding thermal dissociation, H- opacity, and aerosol formation. KELT-7b was observed in transit with the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) and Wide Field Camera 3 (WFC3) as part of the Panchromatic Comparative Exoplanet Treasury (PanCET) program. We derive transit depths across the STIS and WFC3 bandpasses, and present the HST STIS results for the first time. We combine our STIS and WFC3 transmission spectra with photometric data from TESS Sectors 19, 43, 44, and 45, as well as previously published Spitzer Infrared Array Camera (IRAC) data at 3.6 and 4.5 microns. We examine the atmospheric properties of KELT-7b using the isothermal equilibrium chemistry PLATON retrieval code with the *dynesty* nested sampling package, analyzing the full optical to infrared spectrum for the first time. We discuss the implications of our results within the context of current hot Jupiter formation and migration theories.

Observation Summary

- *HST PanCET program (PID: 14767):* 5 orbits/visit; 3 orbits out-of-transit (OOT) and 2 orbits mid-transit
  - STIS G430L grating (0.29 to 0.57 microns): 2 visits
  - STIS G750L grating (0.52 to 1.0 microns): 1 visit
  - WFC3 G141 grism (1.1 to 1.7 microns): 1 visit
- *Spitzer Archival Transit Depths (Garhart et al., 2020):*
  - IRAC 3.6 and 4.5 micron bandpasses
- *TESS Transit Depth:*
  - Analyzed PDCSAP Light Curves of 2-min cadence data from Sectors 19, 43, 44, 45 with EXOFASTv2

Hubble Analysis Features

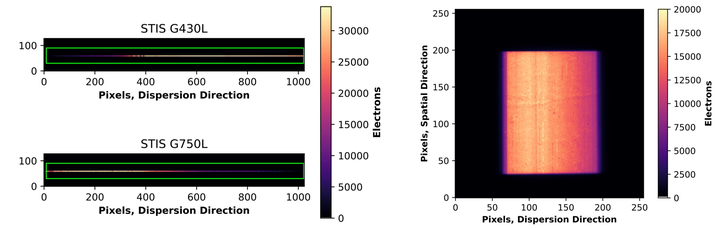

Figure 2. Example 2D images for STIS 1024x128 pixel subarray (left) and WFC3 256x256 subarray in spatial scan mode (right).

- *WFC3 analysis* followed Deming et al., 2013, with Wilkins et al., 2014, wavelength calibration; Highlights:
  - Downloaded 186 ima.fits files from the Mikulski Archive for Space Science (MAST)
  - *Difference reads* method→ 2D images (Fig 2)
  - Cosmic-ray corrections; flat-field calibrations
  - Sum spatial scan columns→ 1D spectra (Fig 3)
  - Eliminate first orbit data from analysis
- *STIS analysis* Highlights:
  - Downloaded 93 G430L and 120 G750L flt.fits files from MAST; files processed by calstis pipeline for bias & dark subtraction, flat-fielding, & linearity
  - Cosmic-ray corrections; wavelength calibration
  - Sum 2D image columns (Fig 2)→ 1D spectra (Fig 3)
  - G430L eliminate orbit 1; G750L eliminate orbit 2

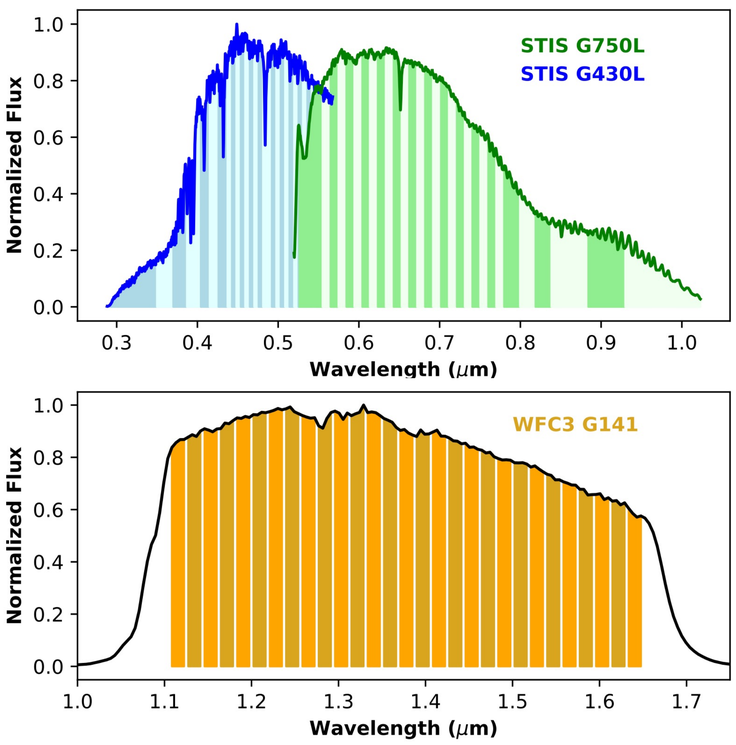

Figure 3. Example 1D spectra for STIS (top) and WFC3 (bottom). Alternating light and dark bands show adopted wavelength bins.

Background & Comparison to Other Ultra-Hot Jupiters

Parameter	Units	Value
R_{star}	Radius ($R_\odot$)	$1.732^{+0.043}_{-0.045}$
M_{star}	Mass ($M_\odot$)	$1.535^{+0.066}_{-0.054}$
log g_{star}	Surface Gravity (cgs)	4.149 ± 0.019
$T_{star,\,eff}$	Effective Temperature (K)	6789^{+50}_{-49}
R_{pl}	Radius (R_{Jup})	$1.533^{+0.046}_{-0.047}$
M_{pl}	Mass (M_{Jup})	1.28 ± 0.18
ρ_{pl}	Density (g cm^{-3})	$0.442^{+0.079}_{-0.068}$
$T_{pl,\,eq}$	Equilibrium Temperature (K)	2048 ± 27
T_o	Mid-Transit Time (BJD$_{TDB}$)	$2456355.229809 \pm 0.000198$
P	Period (days)	2.7347749 ± 0.0000039

Table 1. KELT-7b Parameters from Bieryla et al. (2015) Discovery paper

- KELT-7b spin-orbit alignment:
  - Rossiter-McLaughlin estimate $\lambda = 9.7^o \pm 5.2^o$
  - Doppler tomography: $\lambda = 2.7^o \pm 0.6^o$ (Zhou et al., 2016)
  - Implies migration via disk-planet interaction

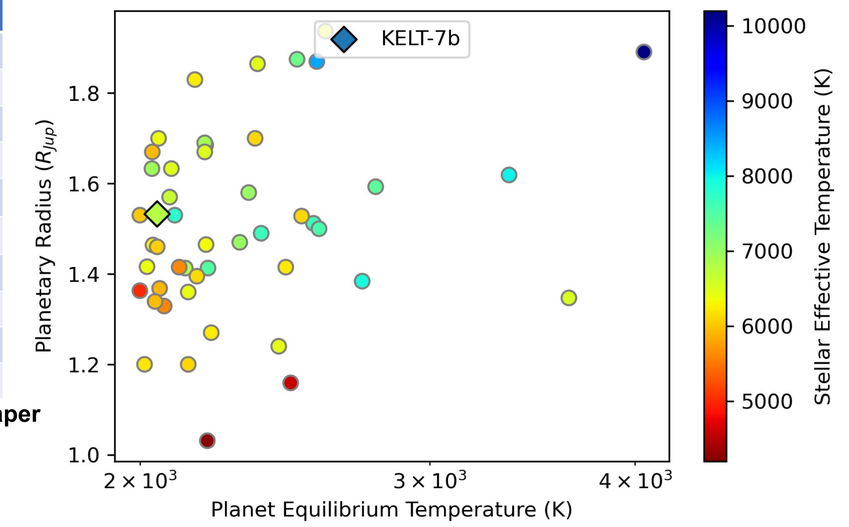

Figure 1. Confirmed Jupiter-sized planets ($R_{pl} > 1R_{jup}$) on short period orbits (P < 3 days), with high equilibrium temperatures (T_{eq} > 2000K). Data from Exoplanet Archive, accessed 4/27/2022.

Preliminary Results

Qualitatively examining our composite transmission spectrum (Fig 4), we note higher transit depths—and thus higher opacities—coincident with the well-known 1.4 μm H_2O-band, as well as near the KI resonance doublet at 0.77 μm and the NaI resonance doublet at 0.59 μm (Seager & Sasselov, 2000). At blue-optical wavelengths, the downward slope from ~0.3 μm to 0.4 μm is consistent with Rayleigh scattering as well as opacity from atomic metals and ions (Lothringer et al., 2020).

We applied the open source PLATON retrieval code to our transmission spectrum, but the best fit models fail to capture the rich variation in transit depths. Rather, the models flatten the spectrum by imposing some combination of high-altitude clouds and metallicity.

Our median retrieved metallicity for the fiducial model is 30.2 x solar, with the 68% credible region spanning from 3.24 to 302 x solar. This result agrees well with the Thorngren & Fortney (2019) estimates of KELT-7b metallicity. In addition, our findings that KELT-7b has a supersolar metallicity and subsolar C/O ratio are in agreement with Madhusudhan et al. (2014)'s predictions of disk-driven migration.

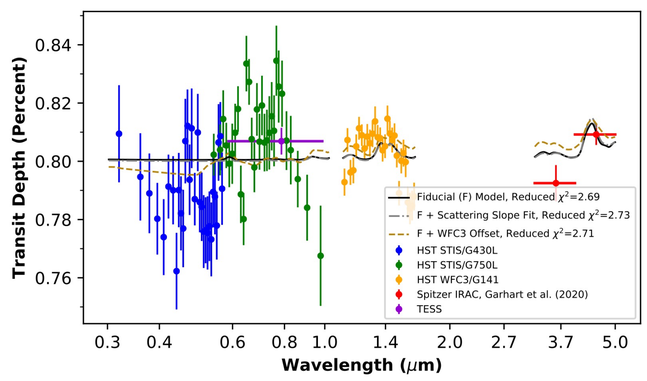

Figure 4. Transmission Spectrum overplotted with fiducial model, as well as fiducial model with fits for either scattering slope or WFC3 offset. In each case, PLATON retrieves a subsolar C/O ratio, supersolar metallicity, cloudy atmosphere. Reduced chi-squared $\chi^2_\nu > 1$ indicates the fit has not fully captured the data. However, the fit allowing WFC3 offset allows the model to capture some variation in the optical regime.

Parameter	Symbol	Distribution	Range/Width	Default Value
Planet Radius	R_{pl}	Uniform	$1.3–1.58R_{Jup}$	$1.44R_{Jup}$
Limb Temperature	T	Uniform	1023 – 3068K	2045K
Carbon-to-Oxygen Ratio	C/O	Uniform	0.05 – 2.0	0.53
Metallicity	Z	Log-uniform	0.1 - $1000Z_\odot$	$1Z_\odot$
Planet Mass	M_{pl}	Gaussian	$0.29M_{Jup}$	$1.48M_{Jup}$
Stellar Radius	R_*	Gaussian	$0.022R_\odot$	$1.775R_\odot$
Cloudtop Pressure	P_{cloud}	Log-uniform	10^{-1} – 10^6 Pa	10^4 Pa

Table 2. Prior Parameter Distribution for Fiducial Model

***PLATON* Retrievals:**
- Open source
- Isothermal, equilibrium chemistry
- *Dynesty* nested sampling package
- Updated K and Na line profiles
- Incorporates H$^-$ opacity

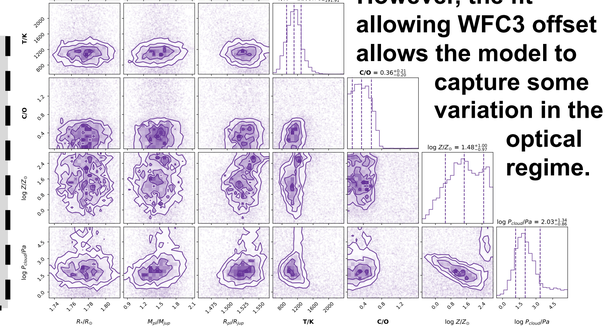

Figure 5. Fiducial model PLATON retrieval results.

Next Steps

- Analyze STIS G430L visit k8 complicated systematics
  - Apply jitter decorrelation (e.g., Sing et al., 2019)
- Enhanced retrieval analysis, considering:
  - Free chemistry retrievals (Welbanks et al., 2019)
  - Inhomogeneous clouds (Line & Parmentier, 2016)
  - Instrumental offsets: both STIS gratings, WFC3
- Examine implications of refined results within context of planet formation/migration theories

References:

Bieryla et al., 2015, AJ, 150
Deming et al., 2013, ApJ, 774
Eastman et al., 2019, arXiv:1907.09480
Garhart et al., 2020, AJ, 159
Line & Parmentier, 2016, ApJ, 820
Lothringer et al., 2020, ApJL, 898
Madhusudhan et al., 2014, ApJL, 794
Magic et al., 2015, A&A, 573
Mandel & Agol, 2002, ApJ, 580
Seager & Sasselov, 2000, ApJ, 537
Sing et al., 2019, AJ, 158
Thorngren & Fortney, 2019, ApJL, 874
Wakeford et al., 2020, AJ, 159
Welbanks et al., 2019, ApJL, 887
Wilkins et al., 2014, ApJ, 783
Zhang et al., 2019, PASP, 131
Zhang et al., 2020, ApJ, 899
Zhou et al., 2016, MNRAS, 460

Contact:
dana.r.louie@nasa.gov
www.linkedin.com/in/danalouie