

A super-solar metallicity atmosphere for WASP-127b revealed by transmission spectroscopy from HST and Spitzer

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ABSTRACT

The chemical abundances of exoplanet atmospheres may provide valuable information about the bulk compositions, formation pathways, and evolutionary histories of planets. Exoplanets which have large, relatively cloud-free atmospheres, and which orbit bright stars provide the best opportunities for accurate abundance measurements. For this reason, we measured the transmission spectrum of the bright ($V \sim 10.2$), large ($1.37 R_J$), sub-Saturn mass ($0.19 M_J$) exoplanet WASP-127b across the near-UV to near-infrared wavelength range ($0.3\text{--}5 \mu\text{m}$), using the Hubble and Spitzer Space Telescopes. Our results show a feature-rich transmission spectrum, with absorption from Na, H₂O, and CO₂, as well as wavelength-dependent scattering from small-particle condensates, and a grey absorber which somewhat mutes the molecular absorption features. We ran two types of atmospheric retrieval models: one enforcing chemical equilibrium, and the other which fit the abundances freely. Our retrieved abundances at chemical equilibrium for Na, O and C are all super-solar, with abundances relative to solar values of 51^{+30}_{-29} , 23^{+15}_{-9} , and 33^{+43}_{-15} respectively. Despite giving conflicting C/O ratios, both retrievals gave super-solar CO₂ volume mixing ratios, which adds to the likelihood that WASP-127b’s bulk metallicity is super-solar, since CO₂ abundance is highly sensitive to atmospheric metallicity. In the future, spectroscopy with JWST will be able to constrain WASP-127b’s C/O ratio, and may reveal the formation history of this metal-enriched, highly observable exoplanet.

Key words: techniques: spectroscopic – planets and satellites: atmospheres – stars: individual: WASP-127

1 INTRODUCTION

WASP-127b is a sub-Saturn mass exoplanet discovered by the SuperWASP survey (Lam et al. 2017). It has the largest expected atmospheric scale height of any planet yet discovered, at ~ 2350 km. This, combined with the favorable brightness of its host star ($V \sim 10.2$, $J \sim 9.1$), means WASP-127b is a standout target for atmospheric characterization. With the Hubble (HST) and Spitzer Space Telescopes, it is possible to measure a transmission spectrum rivaling the quality of even the canonical planets HD 209458b and HD 189733b (Charbonneau et al. 2002; Sing et al. 2011; Pont et al. 2013; Deming et al. 2013). Importantly, with a mass of only $0.19 M_J$, WASP-127b is the most accessible planet in a sparsely populated regime at the low-mass end of gas-giant exoplanets. Evidence of sodium, lithium, potassium and haze have been reported by Palle et al. (2017) and Chen et al. (2018) using the ground-based NOT and GTC telescopes, respectively. They also report an intriguingly sharp rise in WASP-127b’s transmission spectrum shortwards of $0.4 \mu\text{m}$, which they attribute to a mystery UV absorber. Until now, there have been no observations of WASP-127b’s near-infrared transmission spectrum.

We carried out a joint HST and Spitzer programme to observe a broad optical-to-infrared transmission spectrum for WASP-127b. The combined wavelength coverage of the programme from 0.3 to $5 \mu\text{m}$ covers strong expected molecular absorption features from water and carbon-bearing species in the infrared, along with sodium and potassium absorption features, and Rayleigh scattering caused by high-altitude aerosols and H_2 in the optical region. Using HST transmission spectra and Spitzer/IRAC transit photometry, Sing et al. (2016) devised an effective metric for distinguishing between different atmosphere types, and classifying a planet as clear or cloudy. We aimed, with this study, to apply the same methodology to classify WASP-127b as cloudy or cloud-free, and measure the abundances of important gaseous species such as H_2O , Na and K. In the future, WASP-127b will likely become a focus of intensive James Webb Space Telescope (JWST) observations. The characterization described here will allow the community to optimize scientific objectives, instrument setup, and phase coverage for these future JWST observations.

In this work, we present new transit observations of WASP-127b from the Hubble Space Telescope and Spitzer Space Telescope. We describe the observations and data reductions in Section 2, discuss the transit light curve fitting in Section 3, present atmospheric retrievals in Section 4, and conclude with the results and discussion in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

The HST and Spitzer Space Telescope observations were made as part of a joint HST/Spitzer programme GO:14619 (PI: Spake). We observed five transits of WASP-127b using different instrument setups with HST and Spitzer, in order to build a transmission spectrum covering the 0.3 – $5 \mu\text{m}$ wavelength range. In addition, the Transiting Exoplanet Survey Satellite (TESS) observed 4 photometric transits of WASP-127b in Sector 9. A summary of the observations is given in Table 1.

Table 1. Summary of transit observations of WASP-127b.

Instrument	Start date (UTC)	Wavelength range (\AA)	Duration (hours)
HST/STIS+G430L	2018-06-23	2 900–5 700	6.8
HST/STIS+G750L	2018-02-18	5 240–10 270	6.8
HST/WFC3+G141	2018-04-09	11 000–17 000	6.8
Spitzer/IRAC Ch1	2017-04-02	31 750–39 250	9
Spitzer/IRAC Ch2	2017-04-06	39 850–50 050	9
TESS	2019-03-05	6 000–10 000	9
TESS	2019-03-09	6 000–10 000	9
TESS	2019-03-18	6 000–10 000	9
TESS	2019-03-22	6 000–10 000	9

2.1 TESS

TESS (Ricker et al. 2015) provides time-series photometry in a bandpass covering 0.6 – $1.0 \mu\text{m}$, and it observed four transits of WASP-127b in March 2019 (Sector 9) at 2-minute cadence. The high cadence and multiple, opportunistic transit observations meant we could use the TESS data to refine the transit ephemeris and physical parameters of the WASP-127 system. This was particularly useful since our HST observations do not cover much of the ingress or egress of WASP-127b’s transit. We used the TESS Presearch Data Conditioning (PDC) lightcurve of WASP-127b, which has been corrected for effects such as non-astrophysical variability and crowding (Jenkins et al. 2016). We removed all photometric points which were flagged with anomalies, and converted the Barycentric TESS Julian Dates ($BTJD$) to BJD_{TDB} by adding 2 457 000 days. For each of the four transits, we extracted the data in a 0.5 day window centered around the mid-transit time, and fit each transit event individually.

2.2 Spitzer/IRAC

We observed WASP-127b during two primary transits using the sub-array mode with Spitzer/IRAC channels 1 and 2, using 2 second integration times, for 9 hours each visit, with the duration set to include the 3.5 hour transit and a baseline equally as long to precisely measure the transit depth (plus some extra time as insurance). WASP-127’s expected flux is $75 \text{ mJy}/52 \text{ mJy}$ for $3.6/4.5 \mu\text{m}$, and our 2-second exposure time was short enough to stay well below saturation. The sub-array mode allowed for high cadence observations which aids in removing the detector intra-pixel sensitivity, and reduces data storage overheads. Each visit could only be done at a single wavelength requiring two transits to observe at 3.6 and $4.5 \mu\text{m}$, as cycling between the two channels greatly exacerbates the intra-pixel sensitivity noise. Each observation began with a recommended Pointing Calibration and Reference Sensor peak-up mode of 30 minutes, which locates the star into the sub-array pixel “sweet spot” and helps mitigate the intra-pixel sensitivity effects providing <100 parts per million (ppm) accuracies.

For both Spitzer channels, we followed the data reduction and photometry procedures of Evans et al. (2015). We reduced the Basic Calibrated Data (BCD) frames for each light curve using a publicly-available PYTHON pipeline¹, which does the following: first, it calculates the background

¹ from www.github.com/tomevans

level and locates the stellar centroid in each BCD frame. It estimates the background from the median pixel value of four 8×8 pixel subarrays at the corners of each frame, and then subtracts that value from each pixel in the array. It finds the centroid coordinates by taking the flux-weighted mean of a 7×7 pixel subarray centred on the star. The pipeline computes exposure mid-times in Barycentric Julian Date Coordinated Universal Time (BJD_{UTC}) using the BMJD_{OBS} and FRAMTIME header entries. It flags bad frames by identifying frames whose centroid coordinates or pixel counts deviate by 5σ from those of the 30 frames immediately preceding and following each frame. We removed bad frames from the analysis. We iterated this bad-frame identification twice, and discarded less than 5% of the frames.

The pipeline performed photometry on each remaining frame by summing the pixel counts within circular apertures of various sizes between 1.5 and 6 pixels, in increments of 0.5 pixels. Because the IRAC point spread function (PSF) is undersampled, we linearly interpolated the pixel array on to a 10×10 supersampled grid, which has previously been done by [Stevenson et al. \(2010\)](#), for example. We counted the interpolated subpixels towards the aperture sum if their centres fell within the aperture radius. Our selected photometric light curves are shown in Figures 1 and 3, and we discuss how the apertures were chosen in Section 3.2.

2.3 STIS

We observed two transits with HST’s Space Telescope Imaging Spectrograph (STIS), one each with the G430L and G750L gratings. We followed an observing strategy proven to produce high signal-to-noise spectra (e.g. [Brown et al. 2001](#), [Sing et al. 2011](#), [Huitson et al. 2012](#), [Nikolov et al. 2015](#)). The data were taken on 2018-06-23 and 2018-02-18, covering wavelengths of 2900–5700 and 5240–10270Å, respectively. Visits 1 and 2 both lasted 4.5 spacecraft orbits each. One HST orbit lasts ~ 96 minutes during which WASP-127b is visible for ~ 45 minutes, leaving ~ 45 minute gaps in the data as the spacecraft passes through the Earth’s shadow. WASP-127b has a long transit duration (~ 3.5 hours, compared to ~ 2 hours for a typical hot Jupiter, e.g. HD 209458b). We scheduled each visit such that 2 orbits fell fully inside a transit and 1.5 fell either side of it, in order to accurately measure the baseline stellar flux. We used integration times of 280 and 180 seconds, resulting in a total of 48 and 58 low-resolution spectra ($\Delta\lambda/\lambda = 500$) for the G430L and G750L visits respectively. We used $52'' \times 2''$ slits to minimise slit losses, and minimised the data-acquisition overheads by reading out a smaller portion of the CCD (128×128 pixels).

Our data reduction method for STIS follows previous works such as [Sing et al. \(2013\)](#), [Huitson et al. \(2013\)](#), and [Nikolov et al. \(2014, 2015\)](#). We used the most recent version of the CALSTIS automatic reduction pipeline ([Katsanis & McGrath 1998](#)) included in IRAF² ([Tody 1993](#)) to reduce the raw STIS data (which involves bias-, dark-, and flat-correction). Similarly to [Nikolov et al. \(2015\)](#), we corrected

the G750L spectra for fringing effects with the method described in [Goudfrooij & Christensen \(1998\)](#). Further, we used the method described in [Nikolov et al. \(2013\)](#) to correct the data for cosmic rays and bad pixels flagged by the CALSTIS pipeline. We then extracted 1D spectra from the reduced data frames using IRAF’s APALL. We used aperture widths ranging from 3.5 to 10.5 pixels, in 1-pixel steps, and found the aperture width for each visit that gave the lowest residual scatter in the white light curve (see Section 3.4.2). The selected aperture widths were 9.5 and 10.5 pixels for G430L and G750L, respectively. Finally, the wavelength solutions for each spectrum were obtained from the $x1d$ files from CALSTIS, and the spectra were then cross-correlated with the median of the out-of-transit spectra to place them on a common wavelength scale, which helps to account for sub-pixel shifts in the dispersal direction.

2.4 WFC3

We observed one spectroscopic transit of WASP-127b using HST’s Wide Field Camera 3 (WFC3) instrument with the infrared G141 grism. The observations spanned the approximate wavelength range of 11000–17000Å, which covered a broad band of water absorption lines centred on 14000Å. We used HST’s spatial scan mode and a scan rate of 1 pixel per second for 15 observations of 120 seconds each, which spread WASP-127’s spectrum over 120 pixels. We used the SPARS10 sampling sequence with 14 non-destructive reads per exposure ($\text{NSAMP} = 14$). The maximum number of electron counts per pixel was 29000 - which is approximately 40% of the saturation limit of the detector. The raw frames were first reduced with the automatic CalWF3 pipeline. The 1-D spectra were then extracted following standard methods (e.g. [Evans et al. 2017](#)), i.e. by building up flux counts by summing the difference between successive non-destructive reads. First, we removed the background from each read difference by subtracting the median of a box of pixels uncontaminated by the spectrum. Then, we found the flux-weighted centre of each read-difference and set to zero all pixels more than 70 rows away from the centre in the cross-dispersion axis, which removes a majority of the cosmic rays. The remaining cosmic rays were flagged by finding 4σ outliers relative to the median along the dispersion direction. We replaced each flagged pixel with the median along the dispersion direction, re-scaled to the count rate of the cross-dispersion column. We then summed the corrected read differences to produce background- and cosmic-ray-corrected 2D images of the spatially scanned spectrum. We extracted 1D spectra from the corrected images by summing the flux in a rectangular aperture, centred on the flux-weighted centre of the scan. The aperture spanned the full dispersion axis and was 140 pixels wide in the spatial direction.

We found the wavelength solutions by cross-correlating the extracted spectra with an ATLAS model stellar spectrum ([Castelli & Kurucz 2004](#)) which most closely matches WASP-127 ($T_{\text{eff}} = 5500$ K, $\log g = 4.0$ cgs); modulated by the G141 grism throughput. Following standard methods ([Kreidberg et al. 2018](#)) we interpolated each spectrum onto the wavelength range of the first to account for shifts in the dispersion axis over time.

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

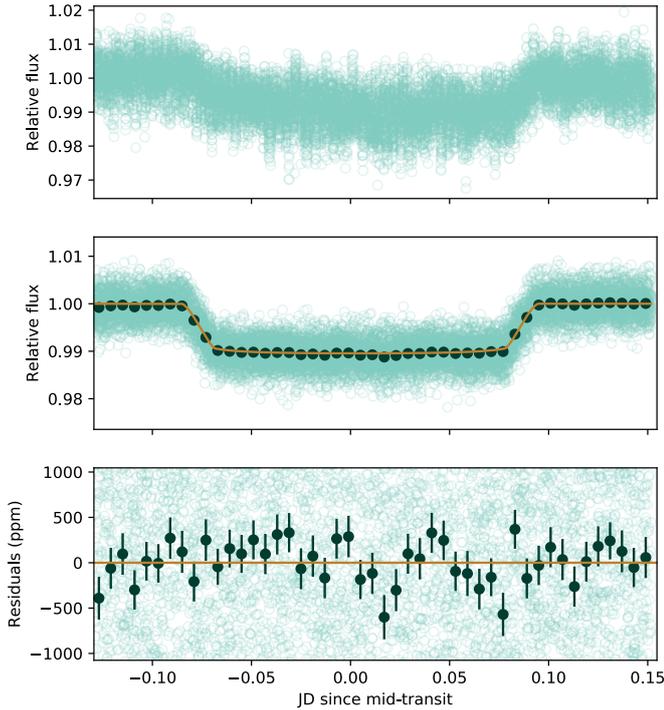


Figure 1. Light curve fit for WASP-127b using Spitzer/IRAC’s 3.6 μ m channel. Top panel: light green points are raw data. Middle panel: light green points are data divided by systematics model, dark green points are data in 9-minute bins for clarity, beige curve is the best-fit transit model. Bottom panel: Best-fit model residuals.

3 LIGHT CURVE FITTING

3.1 TESS

We fit each of the four the transit light curves separately, using the 4-parameter, non-linear, limb-darkened transit model of [Mandel & Agol \(2002\)](#), multiplied by a linear baseline time trend. We used the method of [Sing \(2010\)](#) to estimate the limb-darkening coefficients, using the ATLAS model stellar spectrum ([Castelli & Kurucz 2004](#)) which most closely matched WASP-127b ($T_{\text{eff}} = 5500$ K, $\log g = 4.0$ cgs). We found limb-darkening coefficients of $c_1 = 0.5802$, $c_2 = -0.1496$, $c_3 = 0.5504$, and $c_4 = -0.3115$.

For each of the 4 transits, we fit for six free parameters: the central transit time; planet-to-star radius ratio (R_p/R_*); two coefficients for the linear baseline; the cosine of the orbital inclination (i); and a/R_* (where a is the semi-major axis and R_* the stellar radius). We found weighted-average parameter values, including the radius ratio of $R_p/R_* = 0.10060 \pm 0.00038$; orbital inclination of $i=87.6 \pm 1.0$ degrees; and $a/R_* = 7.83 \pm 0.30$. The inclination and a/R_* were used as fixed values in the HST and Spitzer analyses. We found the four transit mid-times to be $2458548.120564 \pm 0.000357$, $2458552.297877 \pm 0.000349$, $2458560.654727 \pm 0.000351$, and $2458564.832716 \pm 0.000342$, in *BDJTB*D.

3.2 Spitzer

We used the same light curve fitting procedure for both Spitzer/IRAC channels. Spitzer photometry is prone to large intra-pixel systematics (e.g. [Deming et al. 2005](#)). To correct

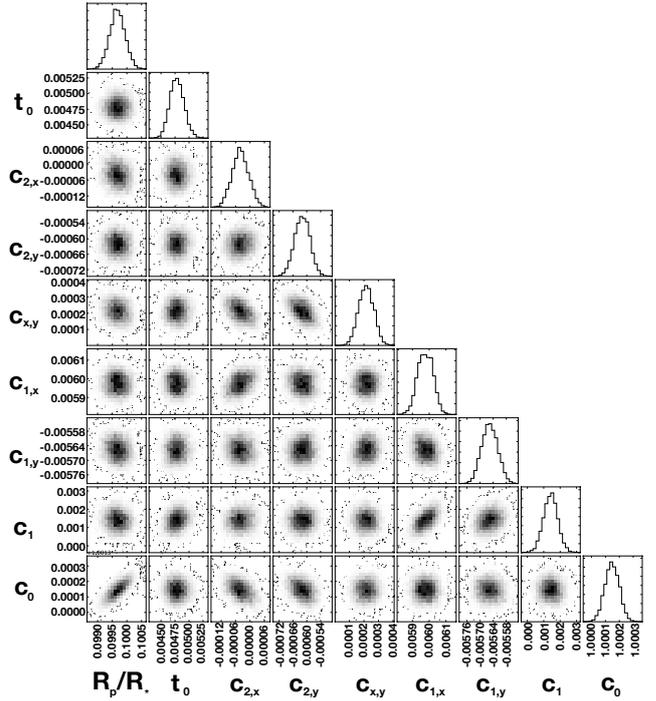


Figure 2. Posterior distributions for lightcurve MCMC fits for WASP-127b, using Spitzer/IRAC’s 3.6 μ m channel.

Parameter	Value
Transit depth (%)	$0.993^{+0.005}_{-0.005}$
Mid-time (JD)	$2457846.19996^{+0.00004}_{-0.00003}$
Period (day)	4.178^a
a/R_*	8.044^a
Inclination ($^\circ$)	88.7^a
Eccentricity	0^a
Arg. of Periastron	90^a
LD coefficients ($u_{1,2}$)	$0.0626^b, 0.1734^b$

Table 2. Results from light curve fit for WASP-127b using Spitzer/IRAC 3.6 μ m channel. ^a planet parameters fixed to values from ([Lam et al. 2017](#)). ^b Limb darkening parameters fixed from ATLAS models ([Castelli & Kurucz 2004](#)).

for this we fit for a two-dimensional quadratic trend in the photometry with the x and y position of WASP-127’s centroid (measured using the pipeline discussed in Section 2.2). The function has the form,

$$F = c_{2,x} \times x^2 + c_{2,y} \times y^2 + c_{1,x} \times x + c_{1,y} \times y + c_{x,y} \times xy, \quad (1)$$

and we fit for the following five free parameters: $c_{2,x}$, $c_{1,x}$, $c_{2,y}$, $c_{1,y}$ and $c_{x,y}$. We used the BATMAN Python package ([Kreidberg 2015](#)) to model the transit light curve signal, and fit for the planet-to-star radius ratio (R_p/R_*) and mid-transit time (t_0). We also fit for the gradient (c_1) and linear trend (c_0) in the baseline in the photometry. In total there were 9 free parameters in the light curve fit. We used the Markov chain Monte Carlo (MCMC) package emcee ([Foreman-Mackey et al. 2013](#)) to marginalise over the parameter space of the model likelihood distribution. We used 100 walkers and ran chains for 5000 steps, discarding the first 1000 as burn-in before combining the walker chains

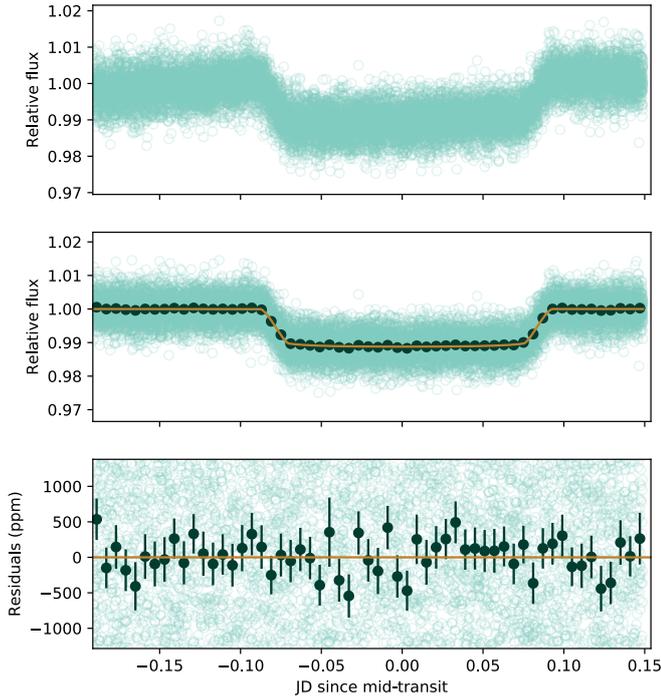


Figure 3. Light curve fit for WASP-127b using Spitzer/IRAC’s 4.5 μm channel. Top panel: light green points are raw data. Middle panel: light green points are data divided by systematics model, dark green points are data in 9-minute bins for clarity, beige curve is the best-fit transit model. Bottom panel: Best-fit model residuals.

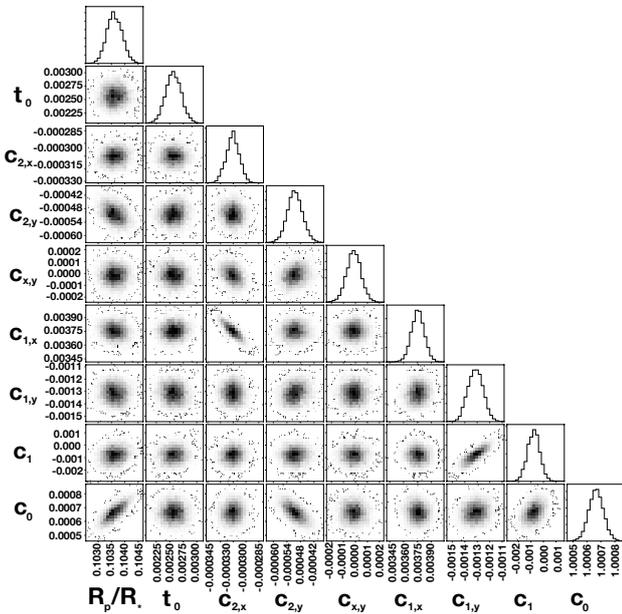


Figure 4. Posterior distributions for lightcurve MCMC fits for WASP-127b, using Spitzer/IRAC’s 4.5 μm channel.

Parameter	Value
Transit depth (%)	$1.073^{+0.006}_{-0.006}$
Mid-time (JD)	$2\,457\,850.37968^{+0.00001}_{-0.00001}$
Period (day)	4.178^a
a/R_*	8.044^a
Inclination ($^\circ$)	88.7^a
Eccentricity	0^a
Arg. of Periastron	90^a
LD coefficients ($u_{1,2}$)	$0.0639^b, 0.1374^b$

Table 3. Results from light curve fit for WASP-127b using Spitzer/IRAC 4.5 μm channel. ^a planet parameters fixed to values from (Lam et al. 2017). ^b Limb darkening parameters fixed from ATLAS models (Castelli & Kurucz 2004).

into a single chain. We followed this procedure for each of the photometric lightcurves that we produced, which used varying aperture sizes from a radius of 1.5 to 6 pixels, in increments of 0.5 pixels. Here we quote the results from the lightcurve which had the lowest model residuals after the fitting process. For the 3.6 μm channel the optimum aperture radius was 3.0 pixels, and for the 4.5 μm channel it was 2.5 pixels. Tables 2 and 3 show our best-fit transit depths and mid-transit times for each channel. Figures 1 and 3 show the light curves with their best-fit models and residuals, and Figures 2 and 2 show the posterior distributions of these fits.

Our results were consistent with those inferred by a more sophisticated treatment of Spitzer’s systematics. Deming et al. (2015) use a technique that involves modelling the light curves of individual pixels to correct for Spitzer’s intrapixel variations, called Pixel Level Decorrelation (PLD). The measured transit depths using both PLD and the light-curve fitting procedure described above are shown in Figure 21. For both channels they are consistent within 1σ .

3.3 Period and ephemeris fitting

WASP-127b has a long, ~ 3 hour transit, which, combined with the Earth occultations occurring in each HST orbit, meant we are unable to get continuous phase coverage of the target over the full transit. Because of the particular timings of our observations, we did not observe much of the ingress or the egress on any of the three HST transit observations. This made it difficult to fit for the transit mid-time. Indeed, when we did fit for the transit mid-time our best-fit solution for the WFC3 visit was earlier than expected by 6 minutes. Large inaccuracies in the mid-transit time can change the measured transit depth. However, the TESS and Spitzer observations have high cadence and full phase coverage, and so their mid-transit times may be more reliable. They can also be used to update the discovery-paper period and ephemeris so that the mid-transit times for the HST visits can be fixed to more reliable values. We fit the discovery paper reported values, all four TESS transit times and two spitzer transit times with a linear trend in time, fitting for the period and ephemeris (Figure 5). Our best fit period was 4.17807 ± 0.00013 days, and our best-fit ephemeris was $2457846.20526 \pm 0.00013$. The updated period and ephemeris were used to fix the mid-transit times for all three HST transit observations.

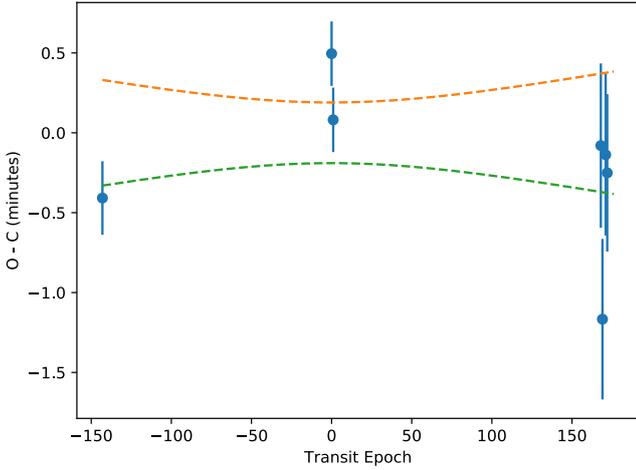


Figure 5. Timing offsets from the fitted mid-transit times for WASP-127b. Label discovery paper, TESS and Spitzer data. Transit epoch centred on Spitzer data.

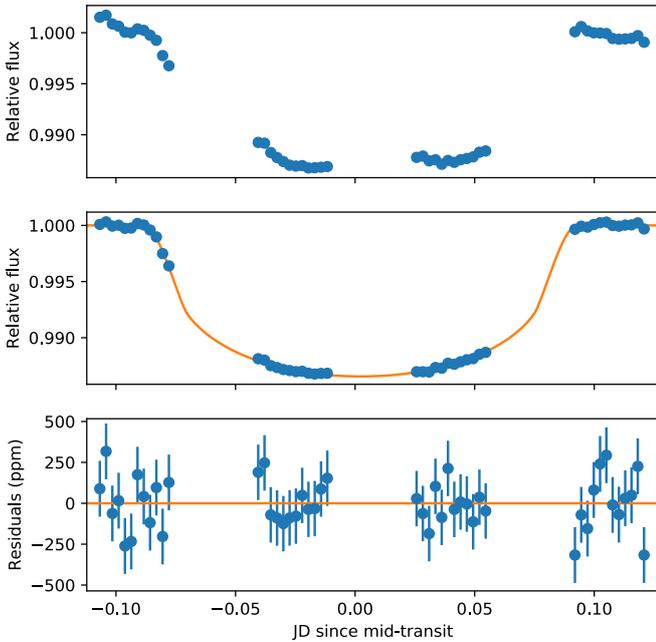


Figure 6. White light curve fit for WASP-127b using HST/STIS+G430L, covering the entire 2900–5700Å wavelength range. Top panel: raw flux before de-trending, divided by the median of the out-of-transit data. Middle panel: points are data divided by systematics model, curve is the best-fit transit model. Bottom panel: best-fit model residuals.

3.4 HST: STIS and WFC3

We followed the same light-curve fitting procedure for all three of the STIS and WFC3 visits, but here describe the process for one visit.

3.4.1 White light curve fit

For each visit (which comprises a set of time-series 1D spectra), we first created a white light curve by summing the counts of the 1D spectra across all wavelengths. The result-

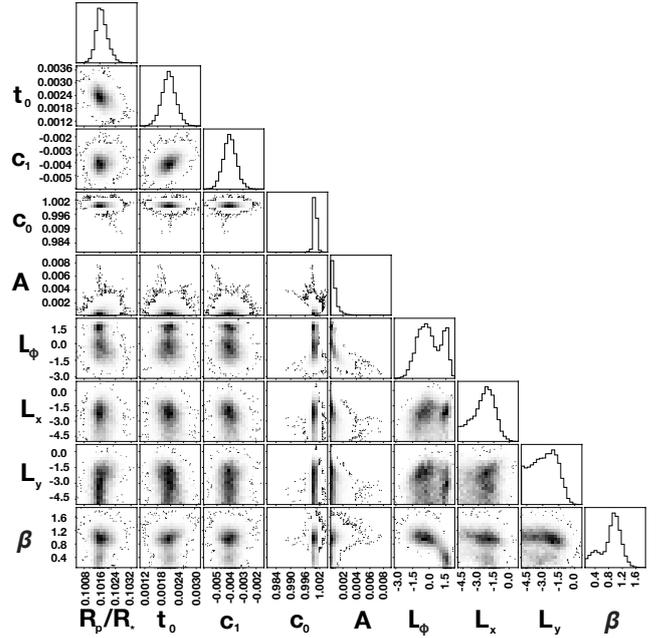


Figure 7. Posterior distributions for white lightcurve MCMC fit for WASP-127b, using HST/STIS+G430L.

Parameter	Value
Transit depth (%)	$1.034^{+0.006}_{-0.005}$
Mid-time (JD)	$2\,458\,293.2528^{+0.0005}_{-0.0005}$
Period (day)	4.178^a
a/R_*	8.044^a
Inclination ($^\circ$)	88.7^a
Eccentricity	0^a
Arg. of Periastron	90^a
LD coefficients (u_{1-4})	$0.5466^b, -0.3781^b, 1.2964^b, -0.5955^b$

Table 4. Results from white light curve fit for WASP-127b using HST/STIS+G430L. ^a planet parameters fixed to values from (Lam et al. 2017). ^b Limb darkening parameters fixed from ATLAS models (Castelli & Kurucz 2004).

ing time-series flux measurements show the transit signal modulated by systematic trends which correlate with HST phase, and the changing position of the spectrum on the detector. Such trends are commonly reported in STIS and WFC3 time-series data (e.g. Brown et al. 2001, Deming et al. 2013; Wakeford et al. 2016). Since we do not know the functional form of the systematic trends, Gibson et al. (2012) suggest treating the lightcurve as a Gaussian Process (GP). Therefore, we follow the implementation of GPs for the HST lightcurves pioneered by Evans et al. (2013, 2018), except we use the Python library for GP regression, George (Ambikasaran et al. 2015) rather than a custom code. Similarly to Evans et al. (2013, 2018), we used a squared-exponential kernel for the GP covariance matrix. We used three GP input variables - the HST orbital phase (ϕ), the position of the spectrum in the spatial direction on the detector (x), and the position in the dispersion direction (y). This gave four free GP parameters: the covariance amplitude (A), and a correlation length scale for each of the four input variables: L_ϕ , L_x , and L_y for HST phase, x , and y respectively. We used BATMAN to model the transit light curve signal, and fit for

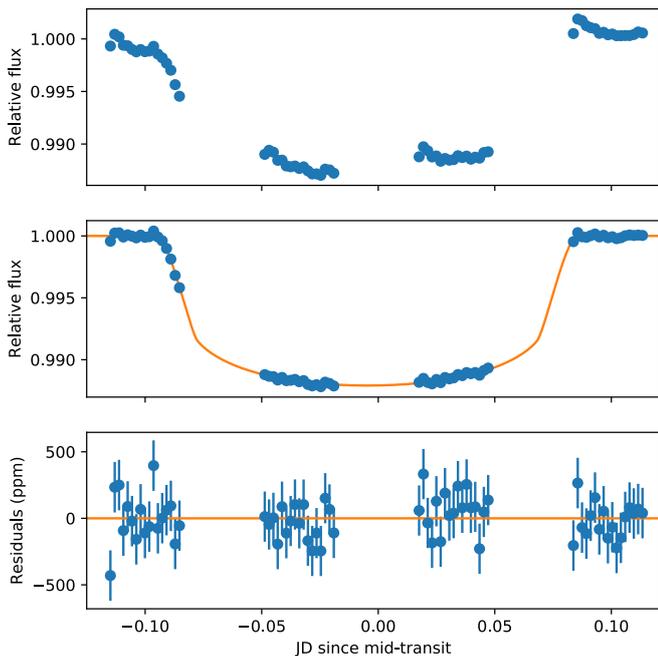


Figure 8. White light curve fit for WASP-127b using HST/STIS+G750L, covering the entire 5240–10270Å wavelength range. Top panel: raw flux before de-trending, divided by the median of the out-of-transit data. Middle panel: points are data divided by systematics model, curve is the best-fit transit model. Bottom panel: best-fit model residuals.

the planet-to-star radius ratio (R_p/R_*), fixing the remaining orbital parameters to the values given in Table 5. To model the stellar limb darkening we fitted a four-parameter non-linear limb darkening law (Claret 2000) to the ATLAS stellar model (Castelli & Kurucz 2004) which most closely matches WASP-127 ($T_{\text{eff}} = 5500$ K, $\log g = 4.0$ cgs). We also fit for the gradient (c_1) and y-intercept (c_0) of a linear trend in the out-of-transit baseline. Therefore, for the white light curve, we fit for 7 free parameters overall: R_p/R_* , c_1 , c_0 , A , L_ϕ , L_x , and L_y . We used the Markov chain Monte Carlo (MCMC) package emcee (Foreman-Mackey et al. 2013) to marginalise over the parameter space of the model likelihood distribution. We used 80 walkers and ran chains for 500 steps, discarding the first 100 as burn-in before combining the walker chains into a single chain. The best-fit results for the transit depths [$(R_p/R_*)^2$] are given in Tables 4, 5 and 6 for the G430L, G750L and G141 visits respectively. Similarly, Figures 6, 8 and 10 show the best-fit white light curves and their residuals for each visit. Figures 7, 9, and 11 show corner plots of the MCMC chains, which illustrate the posterior distributions for each of the fits. The posterior distributions appear well sampled, and there are no problematic correlations between R_p/R_* and the other fitted parameters.

3.4.2 Spectroscopic light curve fit

We used the same spectroscopic light curve fitting procedure for each of the three HST visits. First, we binned each individual spectrum into spectroscopic channels (the wavelength ranges are given in Tables 7, 8 and 9), to make the spectroscopic light curves. We then employed a “common-

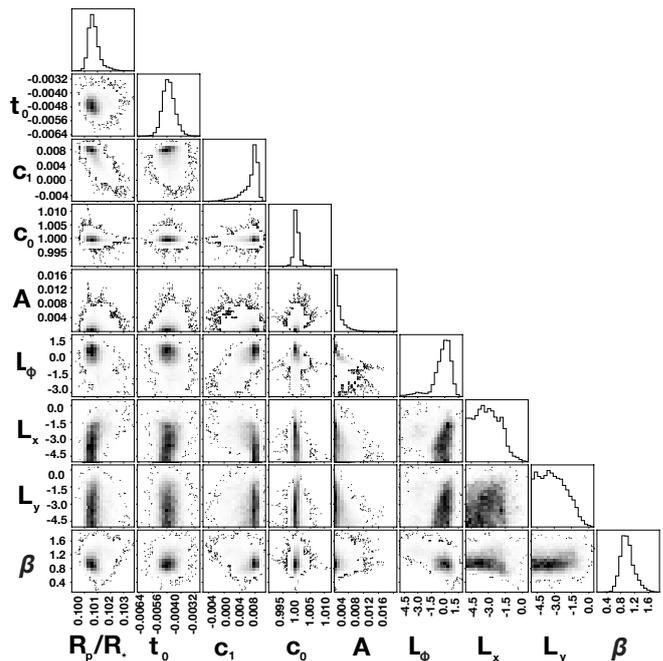


Figure 9. Posterior distributions for white lightcurve MCMC fit for WASP-127b, using HST/STIS+G750L.

Parameter	Value
Transit depth (%)	$1.013^{+0.009}_{-0.006}$
Mid-time (JD)	$2458167.9226^{+0.0008}_{-0.0027}$
Period (day)	4.178^a
a/R_*	8.044^a
Inclination (°)	88.7^a
Eccentricity	0^a
Arg. of Periastron	90^a
LD coefficients (u_{1-4})	$0.7017^b, -0.5462^b, 1.1008^b, -0.5233^b$

Table 5. Results from white light curve fit for WASP-127b using HST/STIS+G750L. ^a planet parameters fixed to values from (Lam et al. 2017). ^b Limb darkening parameters fixed from ATLAS models (Castelli & Kurucz 2004).

mode” correction to remove wavelength-independent systematic trends in the data (e.g. Evans et al. 2018). The process entails finding the systematic trends common to all wavelengths by dividing the white light curve by its best-fit transit model, and then subtracting the result from each spectroscopic lightcurve before the fitting procedure. Similarly to the white light curve fits, we fixed t_0 to the expected values found from our updated period and ephemeris, and fixed the orbital parameters to those derived from Lam et al. (2017), and wavelength-dependent limb darkening coefficients from the same ATLAS model which best describes WASP-127. Similarly to the white light curve fit, we treat each spectroscopic light curve as a Gaussian Process, using a squared-exponential kernel, and the same three GP input variables: (ϕ), (x), and (y). Therefore, for each spectroscopic channel the fitted parameters were R_p/R_* , c_1 , c_0 , A , L_ϕ , L_x , and L_y . We used the Markov chain Monte Carlo (MCMC) package emcee (Foreman-Mackey et al. 2013) to marginalise over the parameter space of the model likelihood distribution. We used 80 walkers and ran chains for 500 steps, dis-

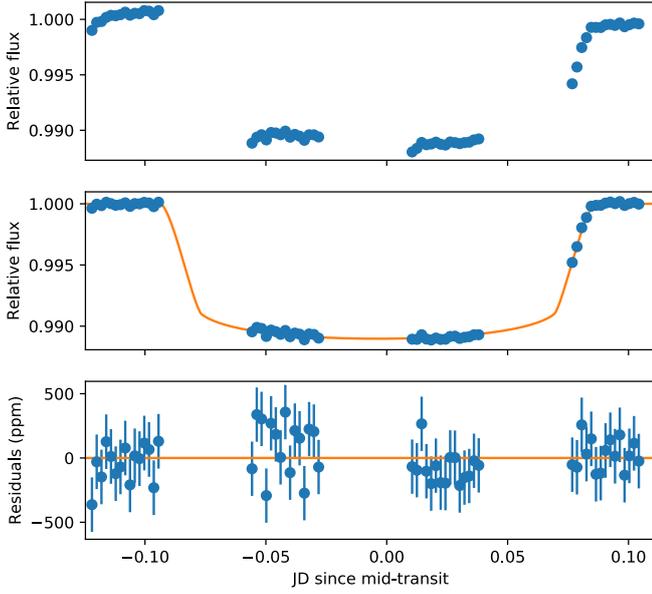


Figure 10. White light curve fit for WASP-127b using HST/WFC3+G141, covering the entire 11 000 – 17 000Å wavelength range. Top panel: raw flux before de-trending, divided by the median of the out-of-transit data. Middle panel: points are data divided by systematics model, curve is the best-fit transit model. Bottom panel: best-fit model residuals.

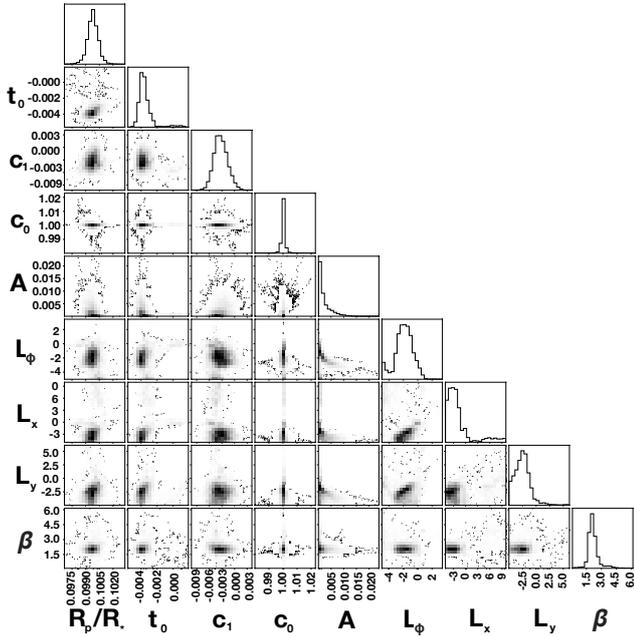


Figure 11. Posterior distributions for white lightcurve MCMC fit for WASP-127b, using HST/WFC3+G141.

carding the first 100 as burn-in before combining the walker chains into a single chain. The best-fit transit depths are given in Tables 7, 8 and 9 for the G430L, G750L and G141 visits respectively. The best fit spectroscopic lightcurves and their residuals are shown in Figures 12, 14 and 16. Example posterior distributions for individual spectroscopic light curves are shown in Figures 13, 15 and 17. The posterior dis-

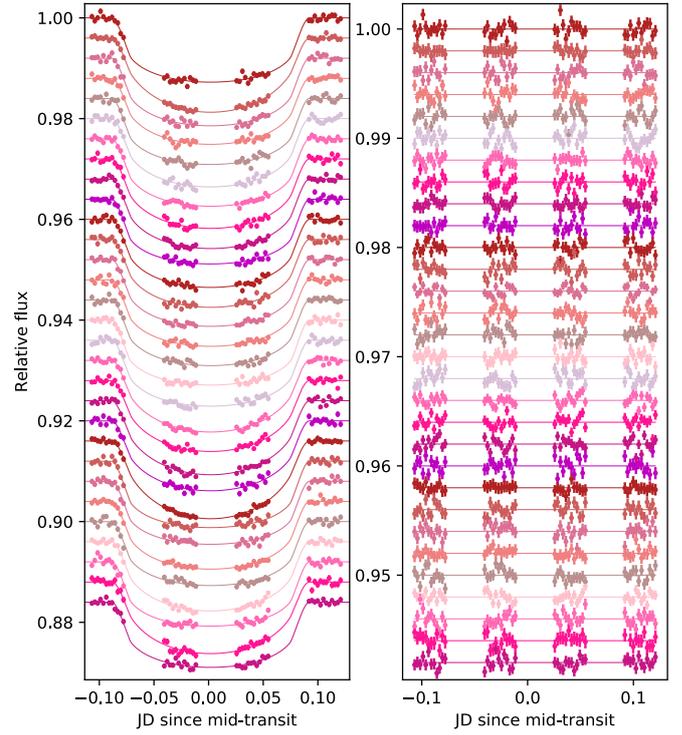


Figure 12. Spectroscopic light curves for WASP-127b using HST/STIS+G430L, covering the 2 900–5 700Å wavelength range. (a) Points are light curves divided by systematics models, curves are best-fit transit models. (b) Best-fit model residuals. Arbitrary vertical offsets applied for clarity.

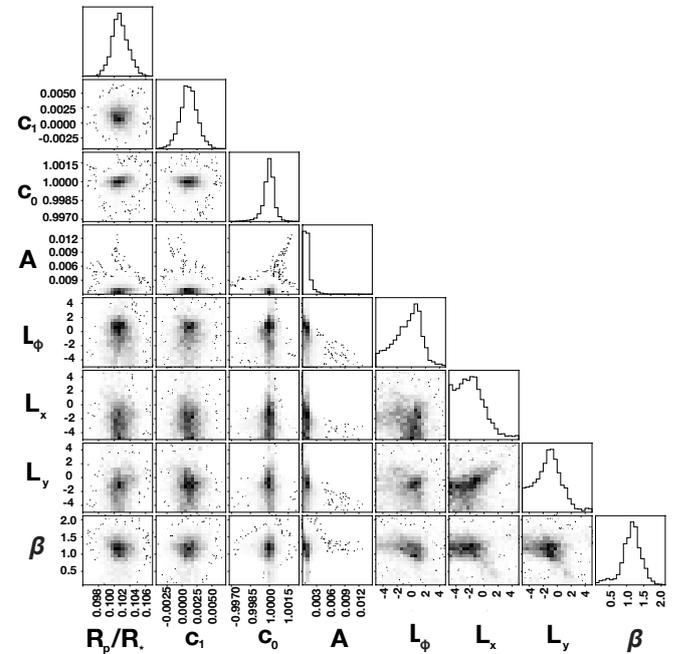


Figure 13. Typical posterior distributions for spectroscopic lightcurve MCMC fits for WASP-127b, using HST/STIS+G430L.

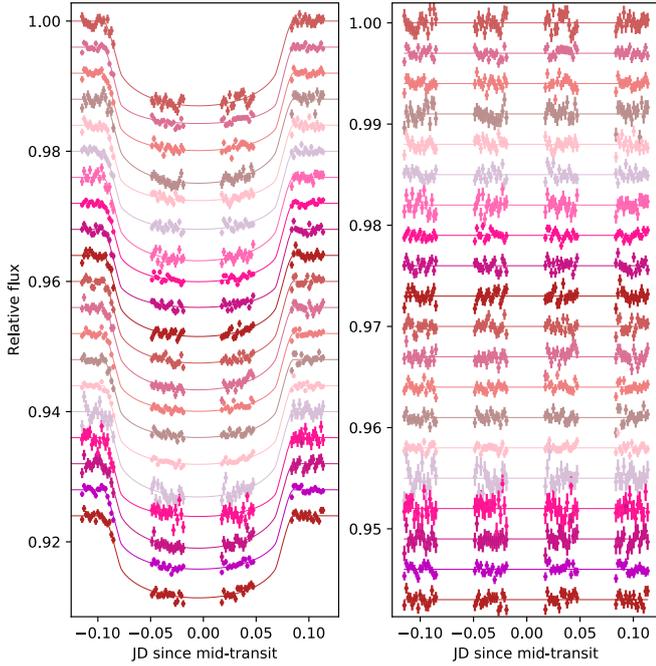


Figure 14. Spectroscopic light curves for WASP-127b using HST/STIS+G750L, covering the 5 240–10 270Å wavelength range. (a) Points are light curves divided by systematics models, curves are best-fit transit models. (b) Best-fit model residuals. Arbitrary vertical offsets applied for clarity.

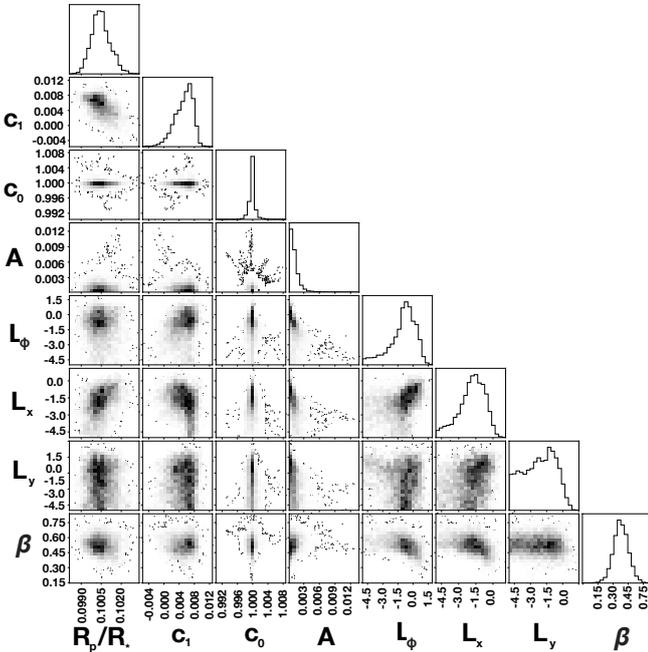


Figure 15. Typical posterior distributions for spectroscopic lightcurve MCMC fits for WASP-127b, using HST/STIS+G750L.

Parameter	Value
Transit depth (%)	$0.996^{+0.011}_{-0.011}$
Mid-time (JD)	$2\,458\,218.0484^{+0.0017}_{-0.0015}$
Period (day)	4.178^a
a/R_*	8.044^a
Inclination (°)	88.7^a
Eccentricity	0^a
Arg. of Periastron	90^a
LD coefficients (u_{1-4})	$0.5944^b, 0.0707^b, -0.1204^b, 0.0202^b$

Table 6. Results from white light curve fit for WASP-127b using HST/WFC3+G141. ^a planet parameters fixed to values from (Lam et al. 2017). ^b Limb darkening parameters fixed from ATLAS models (Castelli & Kurucz 2004).

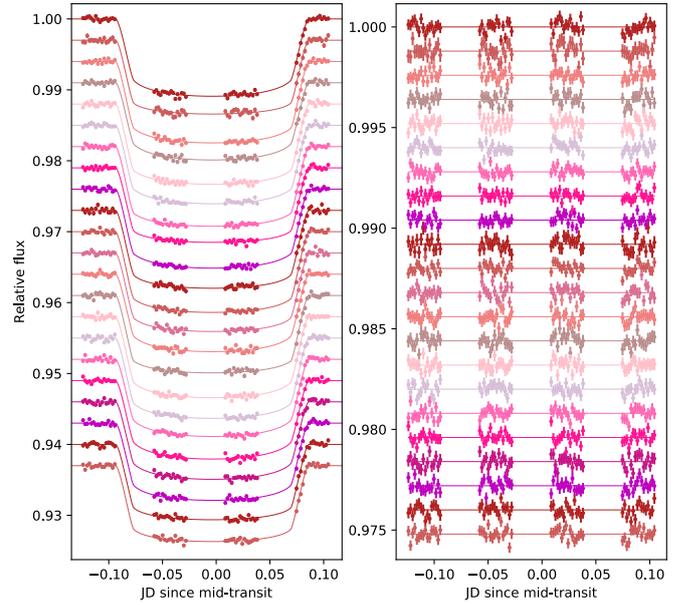


Figure 16. Spectroscopic light curves for WASP-127b using HST/WFC3+G141, covering the 11 000–17 000Å wavelength range. (a) Points are light curves divided by systematics models, curves are best-fit transit models. (b) Best-fit model residuals. Arbitrary vertical offsets applied for clarity.

tributions appear well sampled, and there are no problematic correlations between R_p/R_* and the other fitted parameters. We also ran the spectroscopic analysis for WFC3 G141 following the instrument systematic marginalization method outlined in Wakeford et al. (2016) and found the transmission spectral shape to be robust across the two systematic treatments with the absolute values of the measured depths within $1\text{-}\sigma$ of each other. Similarly, we ran the spectroscopic analysis for both STIS visits following the marginalisation method outlined in Nikolov et al. (2014), and found that the transit depths agreed within $1\text{-}\sigma$.

4 ATMO RETRIEVAL

For the combined STIS, WFC3 and Spitzer spectrum of WASP-127b, we performed an atmospheric retrieval analysis using a one-dimensional radiative transfer code for planetary atmospheres, ATMO (Amundsen et al. 2014; Tremblin et al. 2015, 2016, 2017; Goyal et al. 2018; Mikal-Evans et al.

Bin start (Å)	Bin end (Å)	Transit depth (%)	u_1	u_2	u_3	u_4
2898	3700	1.036 ^{+0.014} _{-0.015}	0.5188	-0.8368	2.0778	-0.815
3700	4041	1.024 ^{+0.019} _{-0.016}	0.7102	-1.1242	2.1235	-0.7717
4041	4261	1.013 ^{+0.015} _{-0.013}	0.5224	-0.6401	1.7752	-0.738
4261	4426	1.048 ^{+0.018} _{-0.021}	0.6179	-0.7511	1.7207	-0.6878
4426	4536	1.024 ^{+0.019} _{-0.014}	0.4502	-0.2005	1.2133	-0.5686
4536	4646	1.005 ^{+0.014} _{-0.012}	0.4359	-0.1007	1.0827	-0.531
4646	4756	1.023 ^{+0.011} _{-0.011}	0.4582	-0.146	1.1212	-0.5536
4756	4921	1.028 ^{+0.014} _{-0.013}	0.4853	-0.143	1.0708	-0.5453
4921	5030	1.027 ^{+0.014} _{-0.015}	0.519	-0.2152	1.0986	-0.5414
5030	5140	1.050 ^{+0.037} _{-0.044}	0.5397	-0.2945	1.1957	-0.5839
5140	5250	1.025 ^{+0.009} _{-0.012}	0.6078	-0.465	1.3201	-0.616
5250	5360	1.007 ^{+0.016} _{-0.017}	0.5829	-0.3203	1.1244	-0.5466
5360	5469	1.034 ^{+0.016} _{-0.015}	0.575	-0.2891	1.0862	-0.5385
5469	5579	1.035 ^{+0.016} _{-0.018}	0.5927	-0.3243	1.1044	-0.5449
5579	5688	1.028 ^{+0.012} _{-0.012}	0.6041	-0.3355	1.09	-0.5378

Table 7. Results from spectroscopic light curve fits for WASP-127b, using HST/STIS+G430L. Fixed, four-parameter limb darkening law coefficients denoted by u_i

Bin start (Å)	Bin end (Å)	Transit depth (%)	u_1	u_2	u_3	u_4
5500	5600	1.066 ^{+0.024} _{-0.023}	0.5963	-0.3281	1.1005	-0.5429
5600	5700	1.018 ^{+0.011} _{-0.011}	0.6029	-0.3282	1.0782	-0.5331
5700	5800	0.995 ^{+0.020} _{-0.017}	0.5987	-0.2994	1.0337	-0.5182
5800	5878	1.026 ^{+0.014} _{-0.017}	0.593	-0.2704	0.9903	-0.5042
5878	5913	1.004 ^{+0.013} _{-0.012}	0.6326	-0.3954	1.1143	-0.5468
5913	6070	1.023 ^{+0.027} _{-0.021}	0.6126	-0.3129	1.0114	-0.5113
6070	6200	1.020 ^{+0.022} _{-0.026}	0.6537	-0.4235	1.0947	-0.5342
6200	6300	1.010 ^{+0.020} _{-0.019}	0.6632	-0.4382	1.094	-0.5331
6300	6450	1.047 ^{+0.022} _{-0.023}	0.6696	-0.455	1.0978	-0.5349
6450	6600	0.997 ^{+0.016} _{-0.012}	0.6986	-0.4715	1.0601	-0.5246
6600	6800	1.014 ^{+0.014} _{-0.014}	0.6883	-0.5005	1.1059	-0.5346
6800	7000	1.036 ^{+0.015} _{-0.016}	0.7015	-0.5355	1.1128	-0.5306
7000	7200	1.022 ^{+0.018} _{-0.020}	0.732	-0.6214	1.1791	-0.551
7200	7450	1.025 ^{+0.018} _{-0.017}	0.7449	-0.658	1.1933	-0.5537
7450	7645	1.005 ^{+0.023} _{-0.018}	0.7339	-0.6262	1.1383	-0.5317
7645	7720	1.009 ^{+0.013} _{-0.014}	0.7356	-0.6251	1.115	-0.5196
7720	8100	1.028 ^{+0.020} _{-0.016}	0.749	-0.6699	1.1521	-0.5322
8100	8485	1.003 ^{+0.017} _{-0.016}	0.7713	-0.7465	1.2143	-0.555
8485	8985	1.051 ^{+0.018} _{-0.020}	0.7557	-0.7033	1.1225	-0.5143
8985	10240	0.986 ^{+0.026} _{-0.018}	0.7199	-0.6086	0.9678	-0.4452

Table 8. Results from spectroscopic light curve fits for WASP-127b, using HST/STIS+G750L. Fixed, four-parameter limb darkening law coefficients denoted by u_i

2019). Previous retrieval results using ATMO can be found in Wakeford et al. (2017), Evans et al. (2017), and Mikal-Evans et al. (2019). ATMO solves the radiative transfer equation for a given set of opacities, pressure-temperature (P-T) profile, and chemical abundances. The code can also solve for the P-T profile that satisfies hydrostatic equilibrium and conservation of energy, but we do not use this function for the initial analysis presented here. ATMO includes a relatively simple treatment of clouds and hazes, and the following description is based on a that from Goyal et al. (2018): ATMO does not consider the type or distribution of condensate particles. Instead, the scattering (‘haze’) effects on the transmission spectrum are parameterised as follows. Scattering by small particles is implemented as enhanced Rayleigh scattering, presented as

$$\sigma(\lambda) = \alpha_{\text{haze}} \sigma_0(\lambda), \quad (2)$$

where $\sigma(\lambda)$ is the total scattering cross-section of the material, α_{haze} is an empirical enhancement factor, and $\sigma_0(\lambda)$ is the scattering due to all other gases at a particular wave-

length (ATMO considers multigas scattering). The strength of grey scattering (‘cloud’) caused by large-particled clouds is represented by

$$\kappa(\lambda)_c = \kappa(\lambda) + \alpha_{\text{cloud}} \kappa_{\text{H}_2}, \quad (3)$$

where $\kappa(\lambda)_c$ is the total scattering opacity, $\kappa(\lambda)$ is the scattering opacity due to nominal Rayleigh scattering, α_{cloud} is an empirical factor governing the strength of the grey scattering, and κ_{H_2} is the scattering opacity due to H_2 at 3500Å. We performed two retrievals, one in chemical equilibrium with the elemental abundances free to vary and a free chemistry model where the molecular abundances were freely fit. A differential-evolution MCMC was used to marginalize the posterior distribution (Eastman et al. 2013), and for each retrieval we ran 18 chains each for 30 000 steps and discarded the burn-in before combining them into a single chain.

For the model assuming chemical equilibrium, the elemental abundances for each model were freely fit and calculated in equilibrium on the fly. Five elements were selected to vary independently, as they are major species

Bin start (Å)	Bin end (Å)	Transit depth (%)	u_1	u_2	u_3	u_4
11225	11409	1.042 ^{+0.009} _{-0.009}	0.6515	-0.4064	0.6627	-0.3206
11409	11594	1.046 ^{+0.007} _{-0.007}	0.6312	-0.3375	0.5764	-0.2851
11594	11779	0.995 ^{+0.008} _{-0.007}	0.6281	-0.3166	0.544	-0.2745
11779	11963	1.010 ^{+0.007} _{-0.008}	0.6205	-0.287	0.5009	-0.2564
11963	12148	0.993 ^{+0.009} _{-0.009}	0.6093	-0.2483	0.4502	-0.2362
12148	12333	1.001 ^{+0.008} _{-0.009}	0.5884	-0.162	0.3459	-0.1968
12333	12517	1.054 ^{+0.009} _{-0.010}	0.5787	-0.1206	0.2867	-0.1716
12517	12702	0.991 ^{+0.008} _{-0.008}	0.5727	-0.0874	0.2388	-0.1533
12702	12887	0.975 ^{+0.012} _{-0.011}	0.5709	-0.0386	0.1613	-0.1299
12887	13071	0.992 ^{+0.008} _{-0.007}	0.554	0.006	0.1075	-0.0997
13071	13256	0.967 ^{+0.013} _{-0.012}	0.5476	0.0484	0.0384	-0.0685
13256	13441	0.997 ^{+0.009} _{-0.009}	0.5386	0.1046	-0.0462	-0.0321
13441	13625	1.031 ^{+0.009} _{-0.010}	0.5338	0.1452	-0.1094	-0.0057
13625	13810	1.046 ^{+0.010} _{-0.011}	0.5332	0.1813	-0.1788	0.0266
13810	13995	1.028 ^{+0.009} _{-0.012}	0.5265	0.2444	-0.2789	0.0708
13995	14179	1.053 ^{+0.007} _{-0.006}	0.5238	0.2836	-0.3521	0.1059
14179	14364	1.016 ^{+0.008} _{-0.008}	0.5301	0.2999	-0.4012	0.1308
14364	14549	0.986 ^{+0.009} _{-0.009}	0.5418	0.3015	-0.431	0.1464
14549	14733	0.983 ^{+0.009} _{-0.009}	0.5518	0.3122	-0.4668	0.1632
14733	14918	1.051 ^{+0.011} _{-0.011}	0.567	0.29	-0.4699	0.1709
14918	15102	1.052 ^{+0.008} _{-0.008}	0.5795	0.2891	-0.5072	0.1952
15102	15287	1.012 ^{+0.010} _{-0.010}	0.5983	0.31	-0.585	0.2369
15287	15472	1.001 ^{+0.010} _{-0.011}	0.631	0.2627	-0.5741	0.2409
15472	15656	0.999 ^{+0.010} _{-0.009}	0.6489	0.2307	-0.5607	0.2408
15656	15841	0.993 ^{+0.008} _{-0.008}	0.6836	0.13	-0.4668	0.2097
15841	16026	1.000 ^{+0.012} _{-0.011}	0.7076	0.0634	-0.4054	0.19
16026	16210	0.991 ^{+0.010} _{-0.009}	0.7347	0.0371	-0.4274	0.21
16210	16395	1.001 ^{+0.009} _{-0.010}	0.7468	0.0085	-0.4018	0.2017

Table 9. Results from spectroscopic light curve fits for WASP-127b, using HST/WFC3+G141. Fixed, four-parameter limb darkening law coefficients denoted by u_i

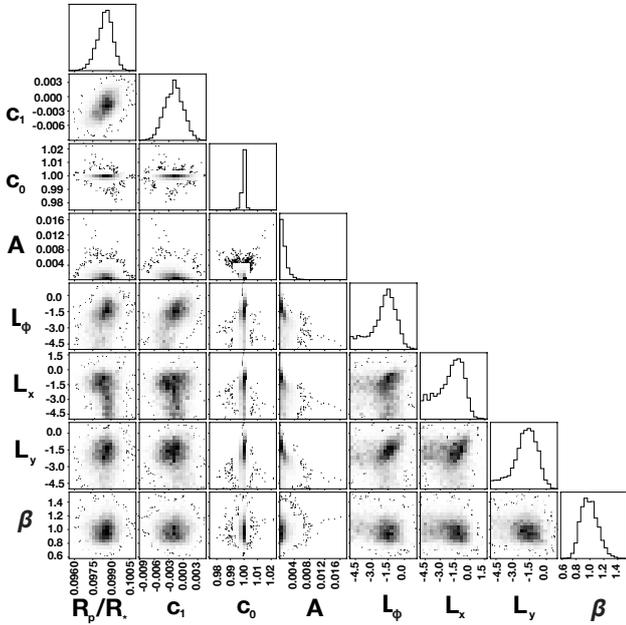


Figure 17. Typical posterior distributions for spectroscopic lightcurve MCMC fits for WASP-127b, using HST/WFC3+G141.

which are also likely to be sensitive to spectral features in the data, while the rest were varied by a trace metallicity parameter ($[Z_{\text{trace}}/Z_{\odot}]$). By varying the carbon, oxygen, sodium and potassium elemental abundances ($[C/C_{\odot}]$,

$[O/O_{\odot}]$, $[Na/Na_{\odot}]$, $[K/K_{\odot}]$, $[Li/Li_{\odot}]$) separately we allow for non-solar compositions but with chemical equilibrium imposed such that each model fit has a chemically-plausible mix of elements given the retrieved temperatures, pressures and underlying elemental abundances. Importantly, by varying both O and C separately (rather than a single C/O value) we alleviate an important modeling assumption which can affect the retrieved C/O value (see ?). For the spectral synthesis, we included the spectroscopically active molecules of H_2 , He, H_2O , CO_2 , CO, CH_4 , NH_3 , H_2S , HCN, C_2H_2 , Na, K, TiO, VO, FeH, and Fe. The temperature was assumed to be isothermal, fit with one parameter, and we also included a grey cloud parameterized by a uniform opacity and a cloud top pressure level, as well as a scattering wavelength-dependent haze opacity. Rainout of condensate species was also included. The results are shown in Figs. 18 and 19 with the results also given in Table 10 including the best-fitting model parameters and 1σ uncertainties (which correspond to the range of parameters which contain 68% of the MCMC samples). Good fits to the data were obtained, with the minimum χ^2 of 55.2 found for 54 degrees of freedom.

In the free-chemistry model, we assumed that the volume mixing ratio (VMR) for each species was constant with pressure, and each molecule VMR was independently fit. We varied the H_2O , CO_2 , CO, CH_4 , Na and K abundances. Li was not fit nor was TiO, VO, FeH, HCN, Fe, FeH, and C_2H_2 as no signs of them were observed in the data. The uniform cloud and scattering scheme was the same as the equilibrium model. The results are shown in Figs. 18, 20 with the results also given in Table 11. The free-retrieval also resulted in a

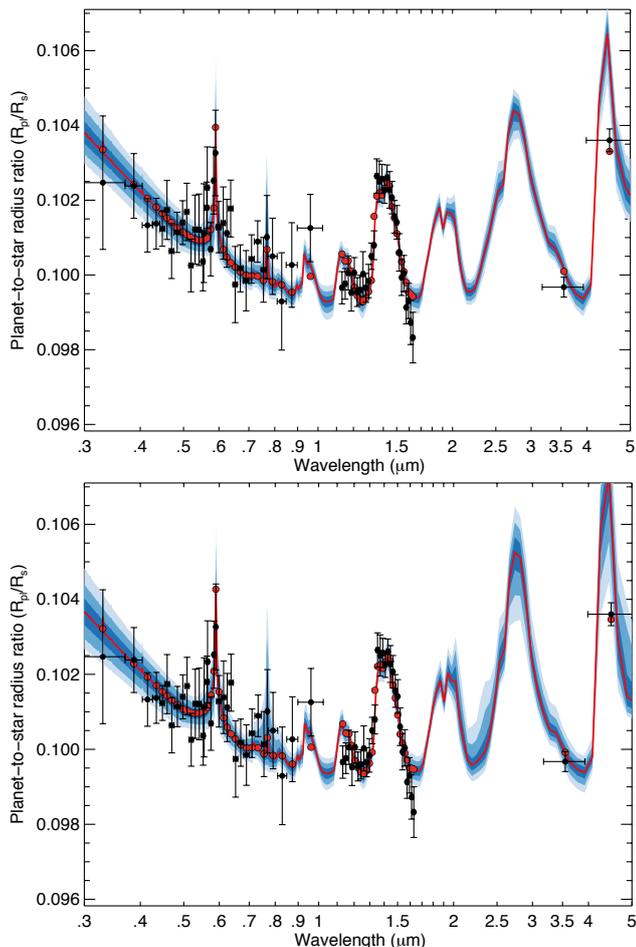


Figure 18. Atmospheric modeling retrieval results assuming chemical equilibrium (top) and free chemistry (bottom). Shown are data (black data points) along with (red line) the median spectrum of the posterior distribution and the band-integrated values (red circles). The 1, 2, and 3- σ model distributions are also shown (dark blue, blue, light blue respectively).

good fit, with a minimum χ^2 of 50.7 found for 54 degrees of freedom.

5 RESULTS AND DISCUSSION

The transmission spectrum of WASP-127b shows strong absorption from both atomic and molecular species with evidence of wavelength-dependent scattering in the optical; absorption by sodium and potentially potassium; a grey absorber in the infrared which mutes the absorption features; a strong water absorption; and a strong feature at $4.5\mu\text{m}$ which is evidence of CO_2 (see Figure 21). We do not see the sharp rise blueward of 5600\AA that [Chen et al. \(2018\)](#) report from the ground-based NOT data. Instead, we find a shallower slope, presumably caused by scattering off some kind of condensate/haze material made from small ($< 1\mu\text{m}$) particles, which slopes down into the near-infrared. The HST spectrum also contains no evidence for Li, which was also previously reported to be present from ground-based spectroscopy. We note that ground-based optical transmission spectra frequently suffer from differential atmospheric ex-

tingtion problems at $< 0.4\mu\text{m}$. The retrievals find H_2O , Na, and CO_2 are well constrained by the data, while Li is not detected nor is K or CH_4 definitively found.

Both our free and equilibrium retrievals favour super-solar abundances and strong absorption by CO_2 . The $4.5\mu\text{m}$ absorption feature in the transmission spectrum is unusually strong, and to the best of our knowledge, no broadband transmission spectrum to date has shown such a strong feature in this wavelength band (e.g. [Sing et al. 2016](#)). Both retrievals fit this strong feature with CO_2 , which is an indication of high metallicities as there is a well-studied sensitivity of CO_2 to metallicity (e.g. [Lodders & Fegley 2002](#), [Fortney 2005](#), [Fortney et al. 2008](#), [Burrows et al. 2008](#), [Line et al. 2010](#), [Moses et al. 2011](#), [Heng & Lyons 2016](#), [Goyal et al. 2018](#)). The free-chemistry model gives a VMR abundance of $-3.71^{+0.77}_{-0.87}$ which is similar to the VMR from the best-fit equilibrium chemistry model of -3.67. These values correspond to super solar metallicities, with the chemical equilibrium retrievals finding O and C are 23 and 33 \times solar respectively, with both values well-constrained with 1- σ uncertainties of ~ 0.25 dex (see 10). Na is also well-constrained, with the chemical equilibrium retrievals finding 51 \times solar values. Note that the parent star WASP-127A has a slightly sub-solar metallicity of $[\text{Fe}/\text{H}] = -0.18 \pm 0.0$, ([Lam et al. 2017](#)). The H_2O and Na abundances in the free-chemistry retrievals also give similar super-solar abundances. With Na, H_2O and CO_2 all showing signatures of super-solar metallicities, WASP-127b is currently one of the few such cases where the abundances of multiple species can be constrained within the planet’s atmosphere.

To highlight the evidence for CO_2 in the transmission spectrum, in Figure 21 we show two ATMO model atmospheres: our best-fit model from the free-chemistry retrieval; and a model with all of the same parameters as the best fit, except the CO_2 abundance, which is set to zero. The strong absorption feature centred on the $4.5\mu\text{m}$ Spitzer channel disappears in the latter model. With only Spitzer photometry, however, the contribution of CO to the $4.5\mu\text{m}$ point complicates the interpretation of the C/O ratio. Theoretical models have found that CO should be the dominant carbon-bearing molecule for hydrogen-dominated atmospheres above 1000K (e.g. [Lodders & Fegley 2002](#); [Heng & Lyons 2016](#)), and CO has been detected at high resolution in hot Jupiter atmospheres (e.g. [Snellen et al. 2010](#)). In our equilibrium chemistry retrieval, CO is about 10 \times more abundant than CO_2 . However, at $4.5\mu\text{m}$ the CO_2 opacity is much stronger and dominates over the CO contribution even though CO has much higher VMR concentrations. In the free-chemistry retrieval, the CO VMR is not constrained by the data, only an upper-limit to the CO is found as very high values affect the mean molecular weight, and the data is consistent with no CO contribution. The lack of a CO feature in the WFC3 data further pushes the free-chemistry retrieval to prefer CO_2 over CO. With CO constrained through chemistry in one retrieval and unconstrained in the free case, the C/O ratios obtained are vastly different. In the chemical-equilibrium case, a super-solar C/O is found (see Fig. 19) while in the free-case a sub-solar C/O ratio is found (Fig. 20). This finding highlights the extreme sensitivity and degeneracies of measuring the C/O ratio with a free-chemistry retrieval model, as all major molecular species have to be well constrained by the data. For a hot Jupiter such as WASP-127b, we consider

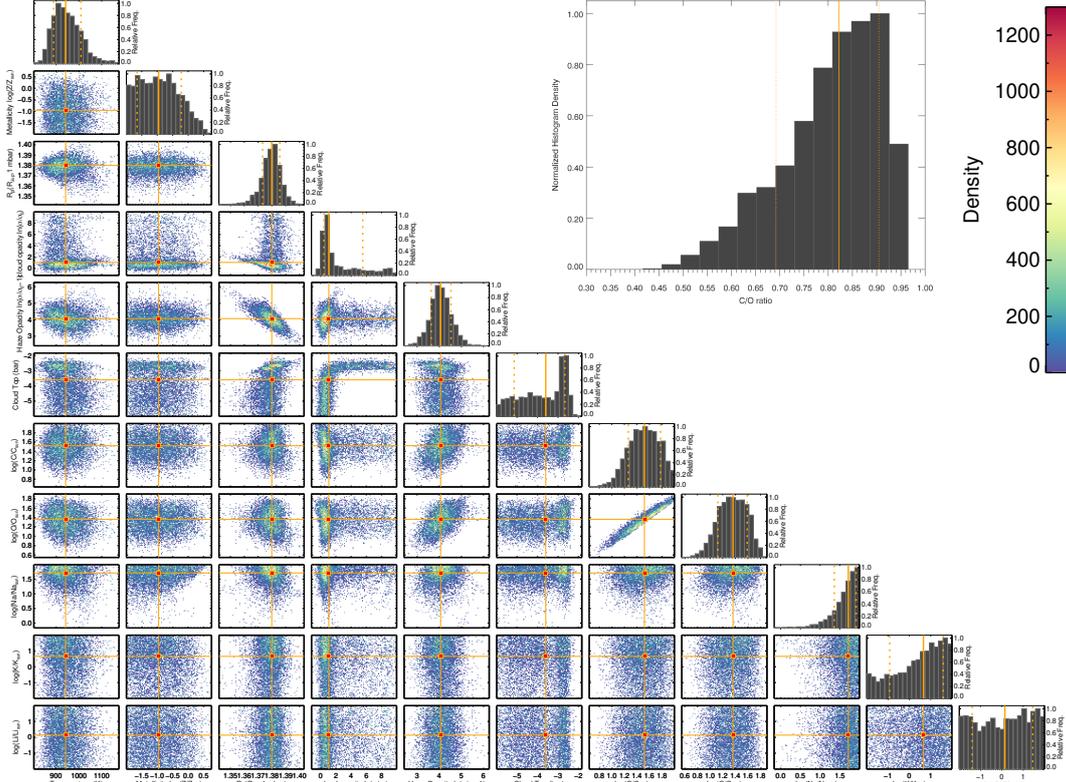


Figure 19. Posterior distributions for atmospheric retrieval fit for WASP-127b assuming chemical equilibrium. Colours represent density of MCMC samples; solid orange lines show median values; dashed orange lines contain 68% of samples. The posterior distribution of the C/O ratio is also shown.

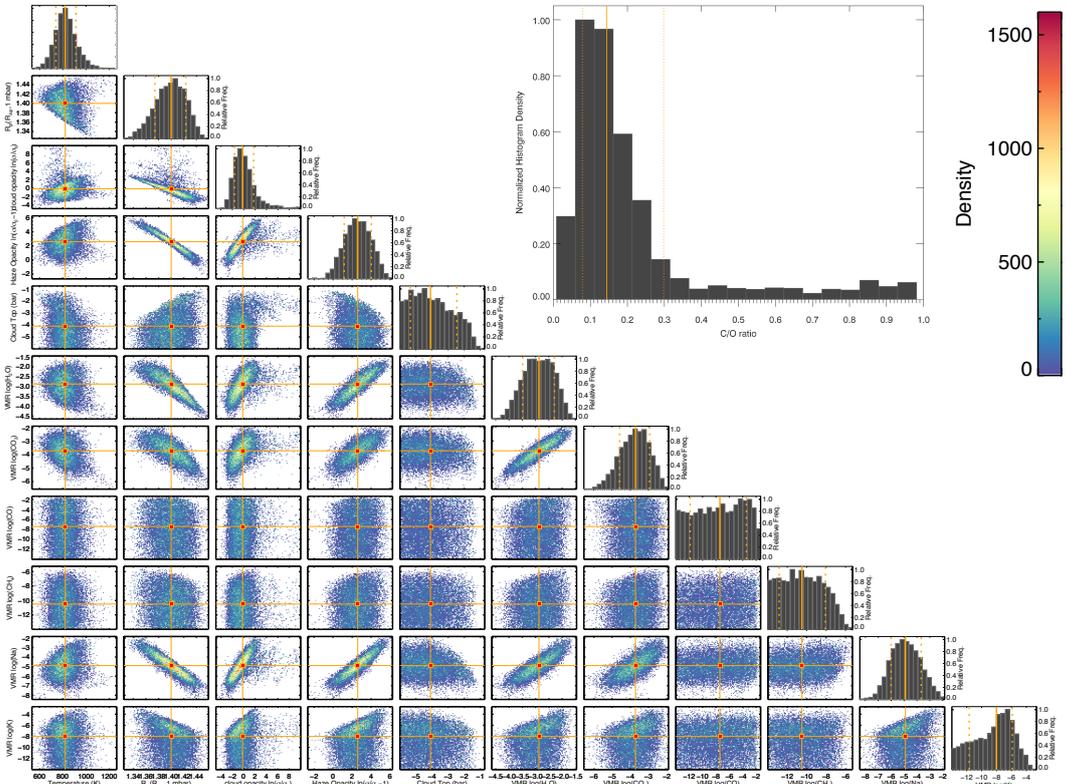


Figure 20. Similar as Fig. 19 but for freely fit chemistry.

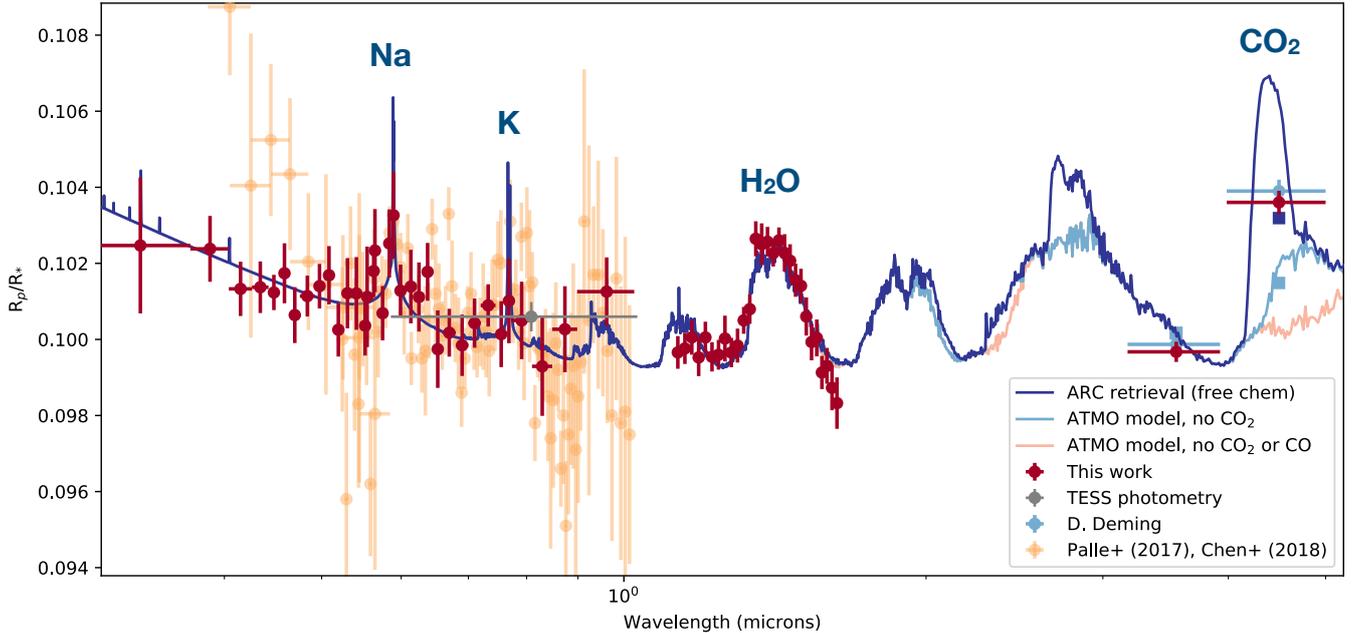


Figure 21. Transmission spectrum for WASP-127b. Red data points are from this work, blue data points are from an independent analysis of the Spitzer light curves from D. Deming. Yellow points are previously published data from Palle et al. (2017) and Chen et al (2018) using ground-based telescopes. Dark blue line is are our best-fit retrieval models using ARC and MPFIT, light blue line is same model with CO_2 abundance set to zero. Square points show models binned to the resolution of the Spitzer data.

a scenario with all of the carbon found in CO_2 and little to none in CO to be thermochemically implausible, as no obvious non-equilibrium mechanism would deplete CO by many orders of magnitude while enhancing CO_2 . This situation is unlike CH_4 , where dynamical mixing and vertical quenching can dramatically enhance CH_4 (e.g. Cooper & Showman 2006; Moses et al. 2011; Tsai et al. 2017; Drummond et al. 2018a,b). With only one photometric data point at $4.5\mu\text{m}$, it is currently impossible to fully disentangle the contribution of both CO and CO_2 in a model-independent way. Further transmission spectroscopy observations of WASP-127b at high resolution with the James Webb Space Telescope will clarify which is the dominant carbon-bearing molecule in WASP-127b’s atmosphere, and allow stronger constraints to be placed on its carbon-to-oxygen ratio.

To place the broader abundance measurements in a wider context, we plot the measured atmospheric metallicity from the equilibrium chemistry retrieval against other exoplanet measurements and the solar system giant planets. Figure 22 shows the measured metallicity of the solar system giant planets via their abundance of CH_4 (Wong et al. 2004; Fletcher et al. 2011; Karkoschka & Tomasko 2011; Sromovsky et al. 2011), and exoplanets via predominantly their H_2O abundance (Kreidberg et al. 2014, 2015; Brogi et al. 2017; Bruno et al. 2019; Wakeford et al. 2018; Chachan et al. 2019; Wakeford et al. 2017; Morley et al. 2017; Benneke et al. 2019). The trend of increased atmospheric metallicity with decreasing mass seen for the solar system giant planets is thought to be indicative of core accretion formation. The measurements of WASP-127b place it in the middle of the exoplanet distribution and along the trend shown by the solar system giants. However, for the current exoplanet population, all of which are orbiting much closer to their stars

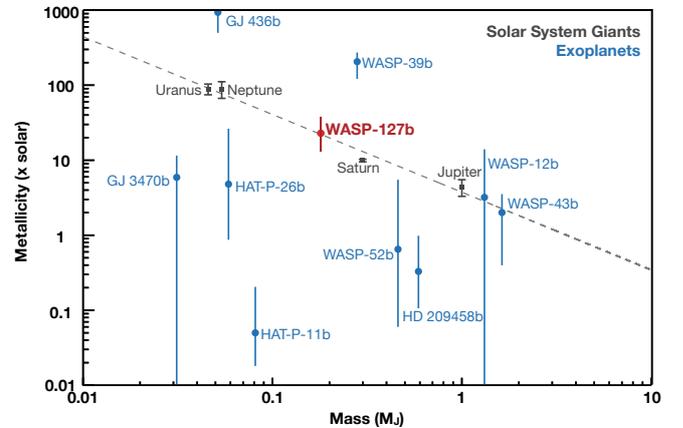


Figure 22. Mass against atmospheric metallicity for the solar system giant planets (grey squares) and measured exoplanets (blue and red dots). The trend seen in the solar system giants is taken to indicate formation via core accretion. Our measurement of WASP-127b’s atmospheric metallicity using the equilibrium chemistry oxygen abundance as proxy (red dot) fits squarely on this trend line. However, including the other measured exoplanets there is no clear trend seen throughout the measured exoplanet population.

than their solar system mass counterparts, there is no significant trend in the data.

Overall, we have observed evidence of strong absorption features from several atomic and molecular species, which means that the level of clouds and potential hazes in WASP-127b is not so strong as to prevent the determination of its atmospheric composition. We find the atmosphere has a super-solar metallicity which is traced by

Parameter	Value
χ^2_{min}	55.2
N_{free}	11
N_{data}	65
T_{eff} (K)	941^{+67}_{-52}
$R_{P,1bar}$ (R_J)	$1.3799^{+0.0058}_{-0.0067}$
Cloud ^a	$1.06^{+4.47}_{-0.65}$
Cloud Top (bar)	$-3.60^{+0.93}_{-0.34}$
Haze ^a	$4.06^{+0.43}_{-0.43}$
$\log_{10}(Z_{trace}/Z_{\odot})^b$	$-2.2^{+1.69}_{-1.60}$
$\log_{10}(O/O_{\odot})$	$1.36^{+0.22}_{-0.24}$
$\log_{10}(C/C_{\odot})$	$1.52^{+0.26}_{-0.26}$
$\log_{10}(Na/Na_{\odot})$	$1.71^{+0.20}_{-0.36}$
$\log_{10}(K/K_{\odot})$	$0.66^{+0.93}_{-1.58}$
$\log_{10}(Li/Li_{\odot})$	$0.14^{+1.31}_{-1.52}$

Table 10. Equilibrium chemistry retrieval results fitting to WASP-127b’s transmission spectrum. ^aThe cloud and haze strengths are defined in Section 4. ^b $\log_{10}(Z_{trace}/Z_{\odot})$ is not the overall bulk metallicity but contains the abundances for trace species not otherwise fit (i.e. all except H, He, O, C, Na, K and Li).

Parameter	Value
χ^2_{min}	50.7
N_{free}	11
N_{data}	65
T_{eff} (K)	820^{+91}_{-80}
$R_{P,1bar}$ (R_J)	$1.3999166^{+0.02}_{-0.03}$
Cloud ^a	$1.06^{+1.94}_{-0.18}$
Cloud Top (bar)	$-3.60^{+1.64}_{-1.43}$
Haze ^a	$+2.59^{+1.42}_{-1.25}$
VMR $\log_{10}(H_2O)$	$-2.87^{+0.58}_{-0.61}$
VMR $\log_{10}(CO_2)$	$-3.71^{+0.77}_{-0.87}$
VMR $\log_{10}(CO)$	$-7.41^{+3.96}_{-2.43}$
VMR $\log_{10}(CH_4)$	$-10.50^{+1.22}_{-2.33}$
VMR $\log_{10}(Na)$	$-4.89^{+1.11}_{-1.11}$
VMR $\log_{10}(K)$	$-8.01^{+2.12}_{-3.66}$

Table 11. Free-chemistry retrieval results fitting to WASP-127b’s transmission spectrum. VMR refers to the volume mixing ratio.

several species (H_2O , Na, and CO_2). Assuming chemical-equilibrium, these three species have an average metallicity of $33\pm 10\times$ solar. While there has been considerable spread in retrieved metallicities of exoplanets to date, WASP-127b is in good agreement with the mass-metallicity trend of the solar system (see Fig. 22). This evidence, combined with a long transit duration, means that WASP-127b is the ideal benchmark exoplanet for measuring chemical abundances of exoplanet atmospheres and should be one of the prime targets for James Webb Space Telescope. In particular, the hint of a large absorption feature around $4.5\mu m$ is strong evidence that future observations of WASP-127b with JWST will be able to measure the abundances of carbon-bearing species in its atmosphere.

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