**CHEOPS geometric albedo of the hot Jupiter HD 209458 b**

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**ABSTRACT**

We report the detection of the secondary eclipse of the hot Jupiter HD 209458 b in optical/visible light using the CHEOPS space telescope. Our measurement of 20.4$^{+1.3}_{-1.2}$% per million translates into a geometric albedo of $A_g = 0.096 \pm 0.016$. The previously estimated dayside temperature of about 1500 K implies that our geometric albedo measurement consists predominantly of reflected starlight and is largely uncontaminated by thermal emission. This makes the present result one of the most robust measurements of $A_g$ for any exoplanet. Our calculations of the bandpass-integrated geometric albedo demonstrate that the measured value of $A_g$ is consistent with a cloud-free atmosphere, where starlight is reflected via Rayleigh scattering by hydrogen molecules, and the water and sodium abundances are consistent with stellar metallicity. We predict that the bandpass-integrated TESS geometric albedo is too faint to detect and that a phase curve of HD 209458 b observed by CHEOPS would have a distinct shape associated with Rayleigh scattering if the atmosphere is indeed cloud free.

**Key words.** techniques: photometric – planetary systems – planets and satellites: atmospheres – planets and satellites: individual: HD 209458 b

1. **Introduction**

The albedo of an exoplanet determines how much starlight enters its atmosphere and hence its global energy budget. Measurements of the secondary eclipse (occultation) depth of a transiting exoplanet directly yield the albedo at full phase (Seager 2010), which is known as the geometric albedo (Russell 1916), if only reflected starlight is measured (Heng & Demory 2013) or if thermal emission is accounted for using complementary infrared data (Wong et al. 2020, 2021). Such measurements have been made using the Kepler (Heng & Demory 2013; Angerhausen et al. 2015; Esteves et al. 2015), TESS (Wong et al. 2020, 2021), Hubble (Swain et al. 2009; Beatty et al. 2017; Evans et al. 2013), and CHEOPS (Lendl et al. 2020; Hooton et al. 2022) space telescopes. The most convincing measurement of the geometric albedo of an exoplanet is that of the hot Jupiter Kepler-7b using four years of Kepler data (Kipping & Bakos 2011; Demory et al. 2011, 2013; Angerhausen et al. 2015), although its exact value has been debated in the literature (Esteves et al. 2015; Heng et al. 2021).

HD 209458 b has been observed with the *Spitzer* 4.5 μm phase curve reveals a dayside brightness temperature of about 1500 K (Zellem et al. 2014; Evans et al. 2015). Its optical/visible transmission spectrum measured by the STIS instrument on board the *Hubble* Space Telescope (HST), indicates a spectral slope at wavelengths ≤600 nm due to Rayleigh scattering (Lecavelier Des Etangs et al. 2008; Sing et al. 2016). Its dayside emission spectrum suggests a water abundance consistent with stellar metallicity and a cloud-free atmosphere at the wavelengths probed by HST-WFC3 (Line et al. 2016). Observations of Fe and Mg (Cubillos et al. 2020) might suggest clouds along the terminator (Gao et al. 2020), which would contradict observations of HST-WFC3 versus J bands in transmission that indicate a cloud-free terminator (Stevenson 2016). A potential source of opacity in a cloud-free atmosphere is neutral sodium through its strong resonance lines, whose line wings dominate over a very broad spectral range (Sudarsky et al. 2000). Na has been observed in transmission (Charbonneau et al. 2002; Sing et al. 2008; Snellen et al. 2008; Jensen et al. 2011), although these results have recently been suggested to be
analysis artefacts (Casasayas-Barris et al. 2020, 2021). Na and/or TiO in the atmosphere are found to explain the broadband transmission spectrum of the planet best (Santos et al. 2020). Na has never been observed in emission for HD 209458 b (D.K. Sing, 2021, priv. comm.). Other elements of interest are atomic hydrogen, oxygen, and carbon, which have been reported in the extended escaping atmosphere of the planet (Vidal-Madjar et al. 2003, 2004).

Previous efforts to detect the optical/visible occultation of HD 209458 b using the MOST space telescope yielded upper limits ($\sigma$) in the MOST bandpass, Rowe et al. 2006, 2008). In this Letter, we report a robust $>6\sigma$ detection of the occultation depth of HD 209458 b using the CHEOPS space telescope (Benz et al. 2021) and demonstrate that the corresponding geometric albedo is consistent with a cloud-free atmosphere of a chemical abundance similar to that of the star.

2. Methods

2.1. Observations and data processing

We observed ten occultations of HD 209458 b between July and September 2021 (CHEOPS programme CH_PR100016; see observation log in Table 1). Each visit lasted for about 11 h, corresponding to seven CHEOPS orbits with an efficiency (fraction of time on target) of $\sim$70%. To save bandwidth, groups of three 11.5 s exposures of a circular subarray with a radius of 100 pixels were co-added prior to downlink, resulting in a cadence of 34.5 s.

In addition, single-exposure circular imagettes with a radius of 30 pixels were downloaded. We analysed the subarrays using photometry from the Data Reduction Pipeline (DRP; Hoyer et al. 2020) and the point-spread function photometry package PIPE developed specifically for CHEOPS (Brandeker et al., in prep.; see also descriptions in Szabo et al. 2021 and Morris et al. 2021) as well as imagette photometry with PIPE. We found that the results were consistent with a $\sim$100 ppm in standard deviation over 1 min bins (for this $G = 7.5$ mag star), but the imagette photometry resulted in a scatter lower by 10% in the measured occultation depths. This is likely due to the faster cadence of the imagettes, which allows detrending with a higher time-resolution.

We thus here focus on the analysis of the imagette photometry.

The light curves were analysed using the pycheops software, a Python module specifically developed to analyse light curves from CHEOPS (Maxted et al. 2021). Data points marked as poor by PIPE (due to e.g. strong cosmic rays or contamination from a satellite passing through the field of view; this affects 527 out of 25866, i.e., $\approx0.2\%$ of the data points) were masked from the analysis. We also removed data with a background higher than 300 e$^-$ pix$^{-1}$ (an additional 652 out of 25866, i.e., $\approx2.5\%$) because they are empirically difficult to reduce adequately, possibly due to non-linear sensitivity linked to charged-transfer inefficiency. The poor data points were flagged at the data reduction stage, uninformed by the extracted light curve. The end result are therefore not biased by the filtering. Each visit was analysed individually, for which we fixed the transit depth and used informative priors based on their literature values given to the transit width, impact parameter, and transit central time (Table A.1). The orbit was assumed to be circular (Deming et al. 2005; Crossfield et al. 2012), such that the occultation time is shifted by half an orbit compared to the transit, corrected for light-travel time. The occultation depth was generally given a broad uniform prior (1–200 ppm), with the exception for visit 5, where the Monte Carlo Markov chain (MCMC) analysis did not converge (using $10^3$–$10^4$ steps and 128–512 walkers).

Instead, the occultation depth for visit 5 was derived with an unconstraining improper prior $U(-\infty, \infty)$, resulting in a negative occultation depth (Table 2). It is statistically expected for single visits that a negative occultation depth may be derived because the signal-to-noise ratio per visit is low. An initial fit of individual visits was made using the least-square minimisation Python package lmfit, which includes roll angle and $(x, y)$-position decorrelation (selected so that it results in a Bayes factor $< 1$). The residuals were then fitted by a Gaussian process (GP), which give strong priors on the GP (based on a preliminary fit in which only GP parameters were free) and the planetary parameters (from the lmfit analysis) for the subsequent fit. In the end, all of these visits were analysed simultaneously using the MCMC scheme with the MultiVisit method within pycheops, in which the priors were inferred from the fit to the individual visits. To search for remaining correlations in the residuals, we used the Shapiro-Wilk test (Shapiro & Wilk 1965). The resulting $p$-value of 0.72 indicates that the residuals are indistinguishable from white noise.

To convert the measured occultation depth into a geometric albedo, we first estimated the contribution from thermal emission by extrapolating the daytime temperature as found by Spitzer 4.5 μm occultation measurements (Zellem et al. 2014) to the CHEOPS bandpass assuming an irradiated model.

Table 1. Logs of CHEOPS observations.

| Visit # | Start date (2021) | End date (2021) | File key | Num. of subarrays | Num. of imagettes |
|---------|------------------|----------------|----------|-------------------|------------------|
| 1       | 2021-07-27 11:09:49 | 2021-07-27 22:09:36 | PR100016_TG013701 | 830 | 2490 |
| 2       | 2021-08-03 12:11:49 | 2021-08-03 23:21:58 | PR100016_TG013702 | 861 | 2583 |
| 3       | 2021-08-06 23:50:49 | 2021-08-07 11:59:10 | PR100016_TG013703 | 911 | 2733 |
| 4       | 2021-08-10 12:25:49 | 2021-08-10 23:35:58 | PR100016_TG013704 | 877 | 2631 |
| 5       | 2021-08-21 03:09:49 | 2021-08-21 14:11:55 | PR100016_TG013705 | 901 | 2703 |
| 6       | 2021-08-31 17:06:49 | 2021-09-01 04:07:45 | PR100016_TG013706 | 884 | 2652 |
| 7       | 2021-09-04 04:34:49 | 2021-09-04 15:44:58 | PR100016_TG013707 | 876 | 2628 |
| 8       | 2021-09-11 05:45:48 | 2021-09-11 17:06:55 | PR100016_TG013708 | 886 | 2658 |
| 9       | 2021-09-18 07:03:59 | 2021-09-18 18:06:40 | PR100016_TG013709 | 840 | 2520 |
| 10      | 2021-09-21 20:58:49 | 2021-09-22 07:47:39 | PR100016_TG013710 | 756 | 2268 |

Notes. Time notation follows the ISO-8601 convention. The File Key aids the retrieval of data from the CHEOPS archive.

https://github.com/alphapsa/PIPE

1 https://github.com/alphapsa/PIPE

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The monochromatic geometric albedo associated with Rayleigh scattering is (Heng et al. 2021)
\[
A_{g,\lambda} = \frac{\omega}{16} + \frac{\epsilon^2}{2} + \frac{\epsilon^4}{6} + \frac{\epsilon^6}{24},
\]
where \(\omega\) is the single-scattering albedo, \(\epsilon = (1 - \gamma)/(1 + \gamma)\) is the bimhemispherical reflectance (Hapke 1981), and \(\gamma = \sqrt{1 - \omega}\). In the preceding expression, the first term accounts for single scattering of starlight, while the other terms account for multiple scattering. The single-scattering albedo is given by the ratio of cross sections,
\[
\omega = \frac{0.9\sigma_{H_2}}{0.9\sigma_{H_2} + \sigma_{abs}},
\]
where the Rayleigh scattering cross section due to molecular hydrogen is (Cox 2000)
\[
\sigma_{H_2} = \frac{24\pi^3}{n_{ref}^4 \lambda^4} \left( \frac{k^2 - 1}{k^2 + 2} \right)^2,
\]
\(n_{ref} = 2.68678 \times 10^{19} \text{ cm}^{-3}\), \(\lambda\) is the wavelength, and the refractive index is
\[
k = 1.358 \times 10^{-4} \left[ 1 + 0.00752 \left( \frac{\lambda}{1 \mu\text{m}} \right)^{-2} \right] + 1.
\]
Commensurate with the limited amount of information that is measured, the absorption cross section is assumed to depend only on \(H_2O\) and \(Na\),
\[
\sigma_{abs} = X_{H_2O} \sigma_{H_2O} + X_{Na} \sigma_{Na},
\]
where the mixing ratios of \(H_2O\) and \(Na\) are denoted by \(X_{H_2O}\) and \(X_{Na}\), respectively. Other absorbers such as \(CH_4\) or \(CO\) are not sufficiently abundant to produce significant opacities in the considered bandpass.

The cross section of \(H_2O\) (\(\sigma_{H_2O}\)) was computed using input from the ExoMo1 spectroscopic line-list database (Polyansky et al. 2018) and using the open-source HELIOS-K opacity calculator\(^2\) (Grimm & Heng 2015; Grimm et al. 2021). It is publicly available in the Swiss-based DACE opacity database\(^3\) (Grimm et al. 2021).

The cross section of \(Na\) (\(\sigma_{Na}\)) was computed using Kurucz line-list data (Kurucz & Bell 1995). We accounted for the natural line width, thermal broadening, and pressure broadening using the tabulated van der Waals broadening coefficients from the line list. The latter ones were scaled from collisions with atomic hydrogen to those of collisions with molecular hydrogen by using the Unsöld approximation (Unsöld 1955). The strong resonance lines of \(Na\) are known to deviate from the usual Voigt profiles. Their strongly non-Lorentzian far-wing line profiles originating from collisions with \(H_2\) were calculated based on Allard et al. (2019).

To compute these cross sections, we assumed a temperature of 1500 K. This is consistent with the brightness temperature measured by Spitzer (Zelllem et al. 2014; Evans et al. 2015). We also assumed a pressure of 0.1 bar (Line et al. 2016).

We computed \(X_{H_2O}\) using previously benchmarked formulae (Heng & Tsai 2016), assuming the chemical abundance of the Sun (Lodders 2003) scaled to that of the star (close to the solar value at \([Fe/H]=0.04 \pm 0.01\); Sousa et al. 2021). This yielded the input elemental abundances of carbon, oxygen, and nitrogen: \(C/H = 2.69 \times 10^{-4}\), \(O/H = 5.37 \times 10^{-4}\), and \(N/H = 7.41 \times 10^{-5}\). These elemental abundances correspond to \(C/O = 0.50\) and \(N/O = 0.14\). With these inputs, the volume mixing ratio of \(H_2O\) is \(X_{H_2O} = 5.36 \times 10^{-4}\).

Formally, \(A_{g,\lambda}\) is defined at a single wavelength. In practice, the occultation depth is measured across a range of optical/visible wavelengths, which yields a bandpass-integrated geometric albedo,
\[
A_g = \frac{\int A_{g,\lambda} \lambda F_\lambda \text{ d}\lambda}{\int \lambda F_\lambda \text{ d}\lambda},
\]
where \(F_\lambda\) is the spectral energy distribution of the star, and \(\mathcal{F}\) is the bandpass filter. For the HD 209458 star, we obtained \(F_\lambda\) from the HST Calibration Database CALSPEC\(^4\) (Bohlin et al. 2014). The bandpass filters for the CHEOPS, MOST, and TESS telescopes were downloaded from the SVO filter service (Rodrigo et al. 2012; Rodrigo & Solano 2020). The factor of \(A\) in the integrands accounts for the conversion of energy into photon flux.

### 3. Results

From the simultaneous fit to all visits, we find the occultation depth to be \(L = 20.4^{+3.2}_{-3.3}\) ppm (Fig. 1). This is consistent with the average over individual fits (Fig. 2, Table 2). \(L = 21.4^{+3.3}_{-3.4}\) ppm. Adopting the simultaneous fit and subtracting a 2.2 ppm contribution from thermal emission, we find a geometric albedo \(A_g = 0.096 \pm 0.016\).

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\(^{1}\) https://github.com/exocline/HELIOS-K
\(^{2}\) https://dace.unige.ch
\(^{3}\) The FITS file hd209458_stisnic_006.fits available at http://www.stsci.edu/hst/observatory/crds/calspec.html

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**Table 2.** Measured occultation depths.

| Visit | Mid occultation (BJD–2459400) | Depth [ppm] | \(\sigma\) [ppm] |
|-------|-----------------------------|------------|----------------|
| 1     | 23.20009                    | 14.8       | 11.6           |
| 2     | 30.24419                    | 31.9       | 9.3            |
| 3     | 33.77430                    | 25.2       | 9.8            |
| 4     | 37.29726                    | 10.3       | 8.3            |
| 5     | 47.86952                    | –1.6       | 10.8           |
| 6     | 58.44554                    | 21.8       | 10.1           |
| 7     | 61.97386                    | 31.0       | 9.5            |
| 8     | 69.01787                    | 24.5       | 9.9            |
| 9     | 76.06736                    | 40.4       | 10.0           |
| 10    | 79.59218                    | 17.1       | 13.2           |

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*References*

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2. Polyansky, O. et al. (2018). *Astron. Astrophys.* 613, A4.
3. Grimm, M. & Heng, K. (2015). *Astron. Astrophys.* 585, A1.
4. Grimm, M. et al. (2021). *Astron. Astrophys.* 650, A77.

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In the left panel of Fig. 3, we show examples of geometric albedo spectra $A_\lambda$, derived assuming an atmosphere of the same chemical composition as the star (with $X_{Na} = 2.19 \times 10^{-6}$ and $X_{H_2O} = 5.56 \times 10^{-4}$ from chemical balance). If $H_2O$ is the only absorber present, then we obtain a CHEOPS bandpass-integrated geometric albedo of $A_g = 0.41$, which is much higher than the measurement. If Na and $H_2O$ are included, then we obtain $A_g = 0.11$; if only Na is considered, we obtain $A_g = 0.12$. This confirms the prediction of Sudarsky et al. (2000): one reason why hot Jupiters are dark in the optical/visible range of wavelengths is absorption by the resonant doublet of Na (see also Seager & Sasselov 2000).

In theory, the geometric albedo is a monochromatic quantity. In practice, the bandpass-integrated geometric albedo $A_g$ differs when it is measured by the MOST, CHEOPS, and TESS space telescopes because the bandpass filters cover different ranges of wavelengths (left panel of Fig. 3). Our calculations indicate that Na is the dominant absorber in shaping the albedo spectrum across optical/visible wavelengths (Seager & Sasselov 2000; Sudarsky et al. 2000). In the right panel of Fig. 3, we compute $A_g$ for all three bandpasses and allow the relative abundance (by number) of Na to vary. The measured CHEOPS geometric albedo of $0.096 \pm 0.016$ is consistent with the theoretical geometric albedo derived from a stellar Na abundance. This does not rule out the possibility that other relative abundances of elements may reproduce $A_g$, but the close match between the measured and predicted $A_g$ from the simplest hypothesis of an atmosphere with the same chemical abundance as the star is remarkable.

### 4. Conclusions and discussion

The right panel of Fig. 3 demonstrates that the TESS geometric albedo is expected to be $\lt 0.03$ for $X_{Na} \sim 10^{-6}$. This translates into an occultation depth of $\lt 6$ ppm in the TESS band from purely reflected light. When we add a 8.5 ppm thermal contribution as estimated from the model atmosphere (Sect. 2.1), we obtain a total expected occultation depth of $\lt 15$ ppm. This is not detectable by TESS because we estimate that its 3σ detection threshold would be $\sim 50$ ppm for an observation duration of a single sector (corresponding to $A_g = 0.25$).

As already pointed out by Heng et al. (2021), reflected-light phase curves that are free of clouds are expected to have a distinct shape associated with Rayleigh scattering (Fig. 4). Using Monte Carlo simulations of observations, we find that the noise must be lower than 4.5 ppm per hour of the phase curve in order to distinguish Rayleigh from isotropic scattering with better than 95% confidence. This will be challenging to achieve considering the variability of the star (Rowe et al. 2006, 2008). Fortunately, confusion of the orbital phase with stellar rotation modulation will be mitigated by their very different timescales (the rotation period is about two weeks, as inferred from Casasayas-Barris et al. 2021).

The measured geometric albedo of HD 209458 b is consistent with a cloud-free, stellar-metallicity atmosphere. This corroborates the findings of Sudarsky et al. (2000), who predicted that “Class IV roasters”, as they called them, have low geometric albedos due to absorption by alkali metals (see also Seager & Sasselov 2000).

Our result demonstrates the unique capability of CHEOPS to measure the geometric albedo through ultra-high-precision photometry of occultations at optical wavelengths. It is highly desirable to apply this technique to a larger sample to improve our understanding of planetary atmospheres and their energy balance. A publication is in preparation by the CHEOPS consortium to present updated and more detailed performance estimates for various scenarios, derived from experience with the first two years of data.
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## Appendix A: Assumed and derived parameters

### Table A.1. Assumed and derived parameters.

| Parameters from literature | Symbol | Value   | Units | References / Comment |
|----------------------------|--------|---------|-------|----------------------|
| Period                     | $P_0$  | 3.52474859 | days  | 1                    |
| Transit time               | BJD$_0$ | 2 452 826.629283 | days  | 2                    |
| Planet-to-star radii ratio | $R_p/R_\star$ | 0.12175 ± 0.00011 | -    | 3, 4, 5, 6           |
| Normalised semi-major axis | $a/R_\star$ | 8.807 ± 0.051 | -    | 1, 3, 6, 7           |
| Orbital inclination        | $i$    | 86.744 ± 0.022 | deg   | 3, 6, 7, 8           |
| Transit depth              | $D$    | 14822 ± 28 ppm | Calculated from $R_p/R_\star$ |
| Transit duration           | $T_{14}$ | 0.12840 ± 0.00096 | days | Calc. from $P_0$, $a/R_\star$, $i$, and $R_p/R_\star$ |

### Fitted parameter priors

| Symbol | Prior | Units | Comment |
|--------|-------|-------|---------|
| Occultation phase width | $W$ | $N(0.03643, 0.00054)$ | $W = T_{14}/P_0$ |
| Occultation depth | $L$ | $U(1, 200)$ ppm | Except visit 5$^\dagger$ |
| Impact parameter | $b$ | $N(0.5002, 0.0090)$ | Calculated from $a/R_\star$ and $i$ |
| Time of inferior conjunction$^\ddagger$ | $T_0$ | $N(T_0, 0.01)$ days | Calculated from $P_0$ and BJD$_0$ |

### Fitted parameter posteriors

| Symbol | Posterior | Units | Comment |
|--------|-----------|-------|---------|
| Occultation phase width | $W$ | 0.0366 ± 0.0003 | |
| Occultation depth | $L$ | 20.4 ± 3.3 ppm | |
| Impact parameter | $b$ | 0.5000 ± 0.007 | |
| Time of inferior conjunction$^\ddagger$ | $T_0$ | 0.156 ± 0.003 days | Add 2 459 453 for BJD |

**Notes.** The table shows parameters fixed from the literature and parameters fit using priors, with their posteriors. For the parameters with multiple references, we computed a weighted average. References: (1) Stassun et al. (2017), (2) Bonomo et al. (2017), (3) Evans et al. (2015), (4) Boyajian et al. (2015), (5) Albrecht et al. (2012), (6) Torres et al. (2008), (7) Southworth (2010), (8) Knutson et al. (2007). $^\ast$N and $^\ast\ast$U denote normal and uniform distributions, respectively. $^\dagger$For visit 5, the occultation depth was derived with an unconstraining prior $U(-\infty, \infty)$ because the MCMC analysis did not converge with the constrained one. $^\ddagger$Also called mid-transit epoch.

**Fig. A.1.** Correlation plots for the fitted parameters.