Probing exoplanet clouds with optical phase curves

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Kepler-7b is to date the only exoplanet for which clouds have been inferred from the optical phase curve—from visible-wavelength whole-disc brightness measurements as a function of orbital phase. Added to this, the fact that the phase curve appears dominated by reflected starlight makes this close-in giant planet a unique study case. Here we investigate the information on coverage and optical properties of the planet clouds contained in the measured phase curve. We generate cloud maps of Kepler-7b and use a multiple-scattering approach to create synthetic phase curves, thus connecting postulated clouds with measurements. We show that optical phase curves can help constrain the composition and size of the cloud particles. Indeed, model fitting for Kepler-7b requires poorly absorbing particles that scatter with low-to-moderate anisotropic efficiency, conclusions consistent with condensates of silicates, perovskite, and silica of submicron radii. We also show that we are limited in our ability to pin down the extent and location of the clouds. These considerations are relevant to the interpretation of optical phase curves with general circulation models. Finally, we estimate that the spherical albedo of Kepler-7b over the Kepler passband is in the range 0.4–0.5.

Phase curves provide unique insight into the atmosphere of a planet, a fact well known and tested in solar system exploration (1–3). Disentangling the information encoded in a phase curve is a complex process however, and interpretations can be faced with degeneracies. The potential of phase curves to characterize exoplanet atmospheres, particularly in combination with other techniques, is tantalizing. Phase curves observed over all orbital phases (OPs) are available for a few close-in planets in the optical (passband central wavelengths \( \lambda < 0.8 \mu m \)) (4–15) and the infrared (1 \( \mu m \leq \lambda \leq 24 \mu m \)) (16–19). At infrared wavelengths the measured flux from hot planets is typically dominated by thermal emission. In the optical, both thermal emission and reflected starlight contribute, with the relative size of the contributions dependent on the measurement wavelength as well as on the temperature of the atmosphere and the occurrence of condensates (20–25).

Kepler-7b (26) is one of the ~1,000 planets discovered by the Kepler mission. Its inferred mass \( M_p = 0.44 M_J \); \( M_J \) for Jupiter) and radius \( R_p = 1.61 R_J \) result in an unusually low bulk density (0.14 g cm\(^{-3}\)) that is inconsistent with current models of giant planet interiors (27, 28). Kepler-7b orbits a quiet G-type star of effective temperature \( T_e = 5,933 \) K every 4.89 d (orbital distance \( a = 0.062 \) astronomical units) (6, 7), and tidal forces have likely synchronized its orbit and spin motions. Taken together these set a planet equilibrium temperature \( T_{eq} \leq 1,935 \) K.

Kepler photometry (0.4–0.9 \( \mu m \)) of the star–planet system has enabled the optical study of Kepler-7b (4–7, 10, 14). The inferred geometric albedo, \( A_e = 0.25–0.38 \) (4, 6, 7, 10, 14), reveals a planet of reflectivity comparable to the solar system giants (\( A_g = 0.4–0.5 \)), which is unexpectedly high for a close-in gas planet. Theory indeed predicts that the strong stellar irradiation that a planet in such an orbit experiences strips off reflective clouds, rendering the planet dark (\( A_g < 0.1 \)) (22, 25). The prediction is largely consistent with empirical evidence, and dark planets dominate the sample of known close-in giant planets (8, 13, 21, 29, 30). Exceptions exist, and other planets [51 Peg b, \( A_g \approx 0.5 \times (1.9/(R_p/R_\star))^2 \) at 0.38–0.69 \( \mu m \) (31); HD 189733b, \( A_g = 0.40 \pm 0.12 \) at 0.29–0.45 \( \mu m \) (32); and KOI-196b, \( A_g = 0.30 \pm 0.08 \) at 0.4–0.9 \( \mu m \) (33)] with elevated albedos suggest that we are beginning to sample the diversity of exoplanet atmospheres. Potentially compensating for strong stellar irradiation, Kepler-7b’s low surface gravity (417 cm s\(^{-2}\)) may help sustain reflective condensates lofted in the upper atmosphere that would increase the planet albedo (25).

Brightness temperatures for Kepler-7b inferred from occultations at 3.6 \( \mu m \) and 4.5 \( \mu m \) with Spitzer \( <1,700 \) K and 1,840 K, respectively (7) are well below the equivalent brightness temperature deduced from Kepler data (~2,600 K). This key constraint, placed in the framework of heat recirculation in the atmospheres of close-in giants, is evidence that the Kepler optical phase curve is dominated by reflected starlight rather than by thermal emission (7, 21, 34). Interestingly, the peak of the optical phase curve occurs after secondary eclipse (OP> 0.5), when the planet as viewed from Earth is not fully illuminated and longitudes westward of the substellar point are preferentially probed. This asymmetry hints at a spatial structure in Kepler-7b’s envelope caused by horizontally inhomogenous clouds (7, 21, 34). Subsequent investigations have identified other planets that show similar offset between occultation and peak brightness (4, 10). However, the lack of infrared measurements for these means that it has not been possible to rule out contamination in the optical by a thermal component as the cause of the asymmetry.

Recent work has used the optical phase curve of Kepler-7b to build brightness maps (7, 34), investigate the prevalence of reflected starlight over thermal emission (34), and explore plausible cloud configurations (35). No previous study has systematically connected the extent, location, and optical thickness of the cloud, or the composition and size of the suspended particles, to the measured phase curve. That exercise is the objective of this paper.

Significance

We investigate the potential of optical phase curves for the characterization of exoplanet clouds. In the case of the low-density, close-in giant planet Kepler-7b, its phase curve reveals that the planet clouds are optically thick and composed of poorly absorbing condensates. We also constrain the cloud particle size, which is an important parameter in the study of the photochemistry, wind dynamics, and cloud microphysics of the planet atmosphere. Our work establishes a valuable framework within which to investigate exoplanet atmospheres using upcoming flagship space missions such as the European Space Agency’s CHEOPS and PLATO and NASA’s TESS, which will all fly within the decade.

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Atmospheric Model

We set up an idealized atmospheric model of Kepler-7b that mimics a vertically uniform yet horizontally inhomogeneous cloud atop a gas sphere. In an initial exploratory investigation, six parameters ($\tau_c$, $\sigma_c$, $\Delta \phi_c$, $m_0$, $g_1$, and $r_g$) specify the optical properties of the cloud–gas medium. An analytical expression captures the inhomogeneity of the optical thickness $\tau(\phi, \psi, \tau_c, \sigma_c, \Delta \phi_c)$ for the prescribed cloud in the longitude ($\phi$) and latitude ($\psi$) directions (SI Appendix). Here, $\tau_c$ denotes the maximum vertically integrated optical thickness within the cloud, $\sigma_c$ yields a measure of its horizontal extent, and $\Delta \phi_c$ is the cloud offset eastward of the substellar point (Fig. 1). The fraction of photons that propagate further after collisions with cloud particles is set by the single scattering albedo $m_0$, whereas the photon propagation directions are dictated by a double Heney–Greenstein (DHG) phase function that has both forward and backward lobes (20, 36). The shape of the DHG phase function is parameterized by the asymmetry parameter $g_1$ of the forward component (SI Appendix). A Lambert-like surface of reflectance $r_g$ at the bottom of the cloud accounts for the effect of scattering from the gas below. The values explored for the six parameters are given in Table 1 and include $r_g = 0, 0.1, 0.2, 0.3$ and thus different degrees of absorption by the gas. A nonzero $r_g$ allows for partial back scattering from the gas and may be a more realistic representation of the atmosphere—alkalis and titanium/vanadium oxides can have broad spectral wings and are believed to be the main gas-phase absorbers in the Kepler passband (25, 37, 38). The selected $r_g$ values are motivated by photochemical and cloud formation models over a range of temperatures bracketing the conditions on Kepler-7b (22, 25).

![Prescribed cloud map for Kepler-7b](image)

**Table 1.** Input parameter values in the atmospheric model for the exploratory investigation (DHG scattering phase function within the cloud)

| Parameter | Grid values | Total |
|-----------|-------------|-------|
| $\tau_c$  | 1, 2, 5, 10, 20, 50, 100, 150, 200 | 9     |
| $\sigma_c$, ° | 5 → 60, step of 5 | 12    |
| $-\Delta \phi_c$, ° | 0 → 90, step of 5; 100 → 150, step of 10 | 25    |
| $m_0$     | 0.50, 0.75, 0.90, 0.95, 0.98, 0.99, 1 | 7     |
| $g_1$     | 0 → 0.95, step of 0.05 | 20    |
| $r_g$     | 0, 0.1, 0.2, 0.3 | 4     |

Our grid of synthetic phase curves contains 1,512,000 combinations of the six parameters.

**Model Phase Curves**

We created a grid of possible atmospheric configurations that probes $\sim 1.5$ million combinations of the six parameters. The radiative transfer calculations were performed using a Monte Carlo algorithm specifically designed for horizontally inhomogeneous planets (39, 40). For each combination we solved the multiple-scattering problem and generated a reflected starlight phase curve as a function of the star–planet–observer phase angle $\alpha$. Our treatment assumes that the contribution to the optical phase curve from thermal emission is minimal, which is appropriate for Kepler-7b (7, 34), and that can be neglected. To compare with the measurements, we expressed the model results as planet-to-star brightness ratios

$$\frac{F_p}{F_*} = \left( \frac{R_p}{a} \right)^2 A_g \Phi(\alpha),$$

with the planet phase function normalized such that $\Phi(\alpha = 0) \equiv 1$. $F_p$ and $F_*$ are the brightness of the planet and the star, respectively. Kepler-7b follows a circular orbit of inclination angle $i = 85.2^\circ$ (6). Changes in $\alpha$ through the planet orbit were accounted for through $\cos(\alpha) = -\sin(i)\cos(2\pi OP)$.

We evaluated the $\chi^2$ statistic, weighted by the measurement uncertainties, for the difference in $F_p/F_*$ between observations and models (SI Appendix). By construction, the calculated $\chi^2$ is a six-parameter function $\chi^2(\tau_c, \sigma_c, \Delta \phi_c, m_0, g_1, r_g)$. We excluded from the summation measurements within the transit and secondary eclipse, which makes the total number of usable measurements $N = 1,244$.

**Phase Curve Interpretation**

We found minimum $\chi^2/N = 1.013, 1.009, 1.027$, and 1.076 for $r_g = 0, 0.1, 0.2$, and 0.3, respectively, with values of the model input and output (albedo) parameters at the minima listed in Table 2. Individual confidence intervals for each input parameter were estimated from the inequality $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} < 15.1$ by

**Table 2. Model input/output parameters for selected phase curves**

| Comment | Model input parameters | Inferred output parameters |
|---------|------------------------|---------------------------|
|         | $\tau_c$ | $\sigma_c$, ° | $-\Delta \phi_c$, ° | $m_0$ | $g_1$ | $\chi^2/N$ | $A_g$ | $A_i$ |
| Best, $r_g = 0.0$ | 100 | 25 | 65 | 1 | 0.40 | 1.013 | 0.274 | 0.455 |
| Minimal-$\chi^2$ set, $r_g = 0.0$ | 20–200 | 20–45 | 45–120 | 1 | 0.1–0.7 | $\leq 1.025$ | 0.24–0.31 | 0.42–0.49 |
| Best, $r_g = 0.1$ | 150 | 25 | 75 | 1 | 0.45 | 1.009 | 0.275 | 0.461 |
| Minimal-$\chi^2$ set, $r_g = 0.1$ | 50–200 | 20–40 | 55–120 | 1 | 0.05–0.7 | $\leq 1.021$ | 0.24–0.30 | 0.43–0.49 |
| Best, $r_g = 0.2$ | 150 | 25 | 80 | 1 | 0.50 | 1.027 | 0.276 | 0.487 |
| Minimal-$\chi^2$ set, $r_g = 0.2$ | 50–200 | 20–35 | 60–120 | 1 | 0.1–0.65 | $\leq 1.039$ | 0.25–0.31 | 0.46–0.51 |
| Best, $r_g = 0.3$ | 200 | 25 | 90 | 1 | 0.50 | 1.076 | 0.295 | 0.512 |
| Minimal-$\chi^2$ set, $r_g = 0.3$ | 50–200 | 15–35 | 60–120 | 1 | 0.15–0.6 | $\leq 1.088$ | 0.28–0.32 | 0.49–0.54 |
optimizing all parameters except $r_g$ and the one being considered (SI Appendix). Mathematically, the confidence intervals bracket the best-matching input parameters with a 99.99% probability (41, 42). For $r_g = 0, 0.1, 0.2, \text{and } 0.3$, the condition $\Delta \chi^2 \lesssim 15.1$ resulted in a total of 289, 197, 160, and 131 model phase curves, respectively, which we refer to as the minimal-$\chi^2$ sets.

Projected 2D $\chi^2$ maps were obtained for each $r_g$ by optimization of all input parameters except the two on the axes and $r_g$ (Fig. 2 for $r_g = 0.1$; SI Appendix, Figs. S8–S10 for $r_g = 0, 0.2, \text{and } 0.3$). The maps provide insight into how particular parameter combinations compensate for one another to produce degeneracies in the interpretation of the measured phase curve. They also help visualize the inferred confidence intervals.

Only prescribed clouds that are optically thick at their center ($\tau_c \gtrsim 20$) reproduce the observations well. The constant-$\chi^2(\sigma_c, \Delta \phi_c)$ contours show that the best-matching $\sigma_c$ and $\Delta \phi_c$ values are correlated in continua of $(\sigma_c, \Delta \phi_c)$ combinations that begin from narrow ($\sigma_c \sim 15^\circ$) clouds moderately displaced ($\Delta \phi_c \sim -45^\circ$; westward) from the substellar point and extend to much broader patterns centered near or beyond the western terminator. This is evidence that a variety of clouds provide comparable net scattering from the planet’s visible day side and reproduce the brightness peak after secondary eclipse.

We also find that cloud particles with near-zero absorption ($\sigma_0 \sim 1$) must be invoked and that low $\chi^2$ s are obtained within a broad interval of $g_1$ values. The asymmetry parameters for the
The degeneracy in the observation-model fitting is best appreciated in Fig. 3. Top. It confirms that many of the model phase curves in the minimal-χ² sets are virtually indistinguishable to the naked eye, even though they correspond to very different cloud configurations. In the Venus case, a combination of whole-disk measurements of brightness and polarization was required to reveal the composition and size of the upper cloud particles (1, 44, 45).

Cloud Particle Optical Properties

We attempted to connect the constraints placed on the single scattering albedo and asymmetry parameter by the minimal-χ² sets to the composition and particle size of plausible condensates. These are critical properties in the study of the photochemistry, wind dynamics, and cloud microphysics of planetary atmospheres. We used Mie theory (46) to calculate values for σ₀ and g, using particle parameters such as the effective radius (rₑff) and real and imaginary parts of the refractive index (nᵢ and nᵢ) at a midband wavelength of 0.65 μm (SI Appendix). A key outcome of the Mie calculations is that only condensates with nᵢ ≤ 0.003 are consistent with the limits of σ₀(rₑff, nᵢ, nᵢ) ≥ 0.99 and g(rₑff, nᵢ, nᵢ) ≤ 0.6 that we established based on the investigation of the minimal-χ² sets.

We identified four candidate cloud components that have both condensation temperatures of 1,000–2,000 K, relevant to the equilibrium temperature of Kepler-7b (47, 48), and nᵢ ≤ 0.003: two silicates (Mg₂SiO₄ and MgSiO₃), perovskite (CaTiO₃), and silica (SiO₂). Without further information it is not possible to favor one candidate above another. Due to differences in their refractive indexes, we were able to tentatively constrain the particle effective radius for each of them. For the silicates (nᵢ = 1.6 and nᵢ = 10⁻⁴ in the optical, www.astro.uni-jena.de/Laboratory/OCDDB), we found that only Mie-scattering particles with rₑff = 0.04–0.16 μm complied with the inferred limits on σ₀ and g. In turn, for perovskite [nᵢ = 2.25 and nᵢ = 10⁻⁴ (48, 49)], the range of effective radii is rₑff = 0.02–2 μm. And for silica [nᵢ = 1.5 and nᵢ = 10⁻⁴ (50)], rₑff = 0.004–0.16 μm.

Significant optical thicknesses and moderately small particle sizes suggest that Kepler-7b’s cloud might be vertically extended and reach high in the atmosphere (35). This idea appears consistent with the expectations for low-gravity planets (25) and with a plausible cloud base at the 10⁷ bar level. Vigorous atmospheric winds, as predicted by 3D models (51), could well keep micron-sized and smaller particles aloft at such pressures (21).

It is appropriate to verify the above conclusions with a full Mie multi-scattering treatment. The DHG approximation is a convenient but simplified approach to particle scattering. A more thorough treatment of the multi-scattering problem would have used particle phase functions derived from, e.g., Mie theory and would have explored separately the impact of nᵢ, nᵢ, and rₑff on the model phase curves. At present, such a treatment is computationally prohibitive, which justifies our adoption of the DHG parameterization for the exploration exercise.

To assess the conclusions on the inferred values of rₑff, we produced model phase curves specific to silicate, perovskite, and silica clouds. The new grid differs from the one summarized in Table 1 mainly in that we now omit the DHG parameterization. Instead, we implement particle scattering phase functions and single scattering albedos σ₀ obtained directly from Mie theory. For each particle composition (and corresponding nᵢ, nᵢ values), we sample rₑff from 0.001 μm to 100 μm to produce the needed input to the multiple-scattering problem. By forming χ²(rₑff, σ₀, Δϕᵢ, rₑff, rᵢ) for each composition and confidence intervals Δχ² < 15.1 for each model input parameter, we confirm that the above conclusions based on the DHG parameterization are overall valid. Specifically, for rₑff we infer confidence intervals of 0.1–0.32 μm (silicates), 0.08–0.2 μm (perovskite), and 0.1–0.4 μm (silica). Smaller particles result in excessive absorption, whereas particles that are too large lead to unobserved back scattering at...
small phase angles in the planet phase curves (SI Appendix, Fig. S3). These particle radii are preferred over those found from the DHG parameterization.

**Planet Albedos**

Both the geometric $A_g$ and spherical $A_s$ albedos quantify the overall reflecting properties of a planet (SI Appendix). For the minimal-$\gamma$ sets, we infer $A_g \sim 0.2-0.3$ and $A_s \sim 0.4-0.5$ (Table 2). An $A_s \sim 0.5$ means that Kepler-7b reflects about half of the visible-wavelength radiation that it receives. Most of the stellar output for $T_e = 5,933$ K is emitted over the Kepler passband, and thus the derived spherical albedos are also first-order approximations to the Bond albedos $A_B$ that impact directly on the energy budget and equilibrium temperature of the planet. Taking $A_g \sim 0.5$, we obtain an estimate for the planet equilibrium temperature (assuming no heat recirculation) of $T_{eq} = 1,935/2.14 \sim 1,630$ K.

**Multicolor Phase Curves**

Our investigation of Kepler-7b has shown that high-precision broadband optical photometry can help characterize exoplanet atmospheres. In the coming decade, photometric missions such as CHEOPS (52), PLATO (53), and TESS (54) will provide optical phase curves of numerous targets. Over the same period, the James Webb Space Telescope will provide the necessary infrared-discrimination power to separate the planet components due to reflected starlight and thermal emission. Future exoplanet missions will then be able to obtain multicolor and spectrally resolved phase curves.

We have explored the added value of multicolor data. We produced model phase curves at $\lambda = 0.4 \mu$m, 0.65 $\mu$m, and 0.9 $\mu$m based on our best-matching solutions of the Kepler-7b data. Again, we assumed that thermal emission at all wavelengths considered is negligible and accounted for wavelength-dependent changes in $\tau_c$ and $g_1$ by assuming that the dominating cloud particles have $r_{eff} = 0.1 \mu$m, $n_s = 1.5$, and $n_t = 0$. The synthetic phase curves (Fig. 3, Bottom) and the differences between them of up to 20 ppm suggest that multicolor observations will provide additional constraints on cloud properties.

**Relevance to General Circulation Models**

There are other approaches to interpret optical phase curves. One of these is based on general circulation models (GCMs), which jointly treat the dynamics, energetics, and chemistry of 3D atmospheres (16, 55–57). GCMs often omit clouds, however, a simplification likely to affect the simulated atmospheric fields. In addition, emitting clouds will affect the overall planet brightness, as clouds potentially reflect much of the visible-wavelength incident starlight. Our finding that a continuum of cloud patterns is consistent with Kepler-7b’s optical phase curve suggests that more than one GCM solution will also reproduce a given observed optical phase curve. We have shown that difficult-to-constrain factors such as the extent and location of the cloud pattern (dependent on the condensation of available atmospheric substances and on whether the cloud forms locally or is transported from the night side by planet-scale winds) or the asymmetry parameter (dependent on the cloud particle microphysics) may compensate for one another and result in visually equivalent optical phase curves. The credibility of GCM-based predictions of optical phase curves is sensitive to these considerations: ignoring them may lead to the misinterpretation of available and future optical data.

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