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Determination of the exoplanet HD 189733 b atmospheric structure based on the multicolor photometric transit observations obtained with the HST and at the Caucasian Mountain Observatory

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Abstract. The paper presents a study of the exoplanet HD 189733 b based on the multicolor photometric observations obtained by the Hubble Space Telescope as well as on the equipment of the Caucasian Mountain Observatory. It is shown that with all other parameters fixed, the radius of the planet obtained from the interpretation of the light curves varies, which may be a consequence of the presence of an extended Rayleigh atmosphere.

Keywords: planets and satellites: atmospheres, gaseous planets

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1 Introduction

During the transit of an exoplanet across the disk of the parent star, the brightness of the latter decreases due to both the planet itself and its atmosphere absorbing and scattering the light. The magnitude of the brightness decrease during transit should decrease as the wavelength increases. It is based on the fact that the longer the wavelength, the less the star radiation undergoes scattering in the exoplanet atmosphere. This is expressed as a decrease in the transit depth of the light curve. When this light curve is subsequently interpreted within the framework of the black opaque circle model, this leads to differences in the determined radius of the exoplanet.

Thus, from the interpretation of the photometric data for the transits of the same exoplanet obtained in filters with different wavelength bands, it is possible to judge about the presence of an extended atmosphere on the exoplanet as well as to obtain preliminary data on its nature and structure.

2 Observed data

For the study, the author has chosen a hot super-Jupiter exoplanet HD 189733 b. This planet was chosen both because of its characteristics such as a large transit depth, small orbital eccentricity, and the brightness of the star, and because it has been extensively studied and has a significant amount of spectroscopic and photometric data. In this paper, we processed the light curves obtained in 2007 by the Hubble Space Telescope (HST) during the observations of HD 189733 b (Pont et al. 2007). The observations were carried out in ten different filters in the wavelength range from $\lambda\lambda = 5500$–6000 Å to $\lambda\lambda = 10\,000$–$10\,500$ Å. Each light curve consists of 625 points with an individual accuracy of about $\sigma \approx 10^{-4}$.

We also subsequently interpreted the observations of this exoplanetary system obtained at the Caucasian Mountain Observatory (CMO) with the RC600 telescope on July 9, 2022 and September 27, 2022. In the first case, the observations were carried out in the g' filter (central wavelength 475 nm), the light curve consisted of 803 points with an individual accuracy of $\sigma = 0.0041$. The second transit was observed in the Ic filter (central wavelength 786.5 nm), the light curve consisted of 619 points with an individual accuracy of $\sigma = 0.0099$.

3 Interpretation of the light curves

The observed data were interpreted using software, written by the author (Bekesov et al. 2021), that approximates transit light curves using the least squares method. In the interpretation, it was assumed that the brightness distribution over the star disk has central symmetry and is described by a quadratic law. The limb darkening coefficients were taken from the theoretical calculations based on the models of stellar atmospheres (Eastman et al. 2013).

The length of the semimajor axis was fixed at $a = 0.03126$ AU, and the orbital period was $P = 2.2185752$ d (Rosenthal et al. 2021). The calculations were performed for three different eccentricities: 0, 0.01, and 0.02, with a fixed argument of pericenter $\omega = 270°$. These values were taken as corresponding to the existing estimates of the eccentricity for this planet (Bonomo et al. 2017).

The radius of the star and the orbital inclination were obtained from the interpretation of the light curve corresponding to a wavelength of 6750 Å with three free parameters. Subsequently, these values of the star radius and orbital inclination were used to interpret the remaining nine HST light curves. For the two light curves obtained at the CMO, all parameters except the radius of the planet were fixed. In this case, the same values were taken as in processing the HST observations.

The interpretation results for the space and ground-based observations are presented in Tables 1 and 2, respectively.

Table 1. Interpretation results for the HST transit light curves with fixed theoretical limb darkening coefficients and fixed $e = 0$.

λ, Å	Star radius, $R_\odot$	Linear coefficient	Quadratic coefficient	Orbital inclination, deg	Planet radius, km	Planet radius, R_J	Normalized χ^2
5750	0.756	0.60964	0.14806	85.72	82538 ± 130	1.1559 ± 0.0018	2.27896
6250	0.756	0.54384	0.18148	85.72	82542 ± 130	1.1561 ± 0.0018	1.35196
6750	0.756	0.50189	0.19045	85.72	82269 ± 130	1.1522 ± 0.0018	0.99531
7250	0.756	0.45994	0.21097	85.72	82000 ± 130	1.1484 ± 0.0018	0.96278
7750	0.756	0.42083	0.20747	85.72	81893 ± 130	1.1469 ± 0.0018	0.95105
8250	0.756	0.39202	0.21250	85.72	82003 ± 130	1.1485 ± 0.0018	1.00925
8750	0.756	0.36532	0.21735	85.72	81678 ± 130	1.1439 ± 0.0018	0.99496
9250	0.756	0.34140	0.22402	85.72	81785 ± 130	1.1454 ± 0.0018	0.91441
9750	0.756	0.32165	0.23343	85.72	81781 ± 130	1.1453 ± 0.0018	1.20305
10250	0.756	0.30189	0.24284	85.72	81678 ± 130	1.1439 ± 0.0018	1.20750

4 Modeling the atmosphere

For a preliminary assessment of the atmosphere structure, we took a simplified model in which the density distribution was described by the formula $\rho(h) = \rho_0 \exp(h/H)$, where ρ_0 is the gas density at the conditional surface, h is the height of an atmospheric layer, and H is the characteristic height.

Table 2. Interpretaion results for the transit light curves from the CMO.

Observing date	Filter	Orbital inclination, deg	Planet radius, km	Planet radius, R_J	Normalized χ^2
2022.07.09	g'	85.72	$83614\ ^{+498}_{-535}$	$1.1710\ ^{+0.0070}_{-0.0075}$	0.820982
2022.09.27	Ic	85.72	$80496\ ^{+1423}_{-1589}$	$1.1274\ ^{+0.0199}_{-0.0223}$	0.829820

The modeling was carried out using a numerical method in which the planet atmosphere was divided into thin rings, for each of which the optical thickness along the line of sight τ was calculated:

$$\tau(\xi) = 2\int_{\xi}^{R_\mathrm{a}} \frac{\sigma(r) r\, dr}{\sqrt{r^2 - \xi^2}}, \tag{1}$$

where ξ is the target distance, $r = r_0 + h$, r_0 is the radius of the opaque circle, and R_a is the radius of the planet with the atmosphere. The volumetric opacity coefficient $\sigma(r)$ was considered proportional to the density of the atmosphere. Also, in accordance with the Rayleigh law, it was assumed that it is proportional to λ^{-4}.

To estimate the transit depth, the author introduced the concept of an effective radius, i.e., the radius of the opaque circle at which the transit depth at the midpoint would correspond to that obtained when simulating the transit with given characteristics of the atmosphere.

Using the above assumptions, the inverse problem was solved by varying three parameters: the opacity coefficient at the surface at a wavelength of 5750 Å, the radius of the opaque core, and the characteristic height of the atmosphere. The values of these quantities for which the sum of the squares of the differences between the effective radii and the radii of the planet obtained from the interpretation of the light curves turned out to be the smallest were chosen as optimal.

The opacity coefficient of the conventional surface at a wavelength of 5750 Å for all three eccentricities turned out to be equal to $1.5 \cdot 10^{-4}$ km^{-1}, which in the approximation of an atmosphere consisting of molecular hydrogen corresponds to a particle concentration of $2.1 \cdot 10^{18}$ cm^{-3} or about 3.487 mol/m^3. The characteristic height also turned out to be equal to $H \approx 1000$ km for all the three eccentricities. At the same time, the radius of the opaque core for the zero eccentricity was determined as 81 400 km, and for eccentricities of 0.01 and 0.02 it was 82 100 km and 82 800 km, respectively.

Figure 1 shows the radii obtained from the interpretation of the space and ground-based observations for a circular orbit with the model effective radii superimposed.

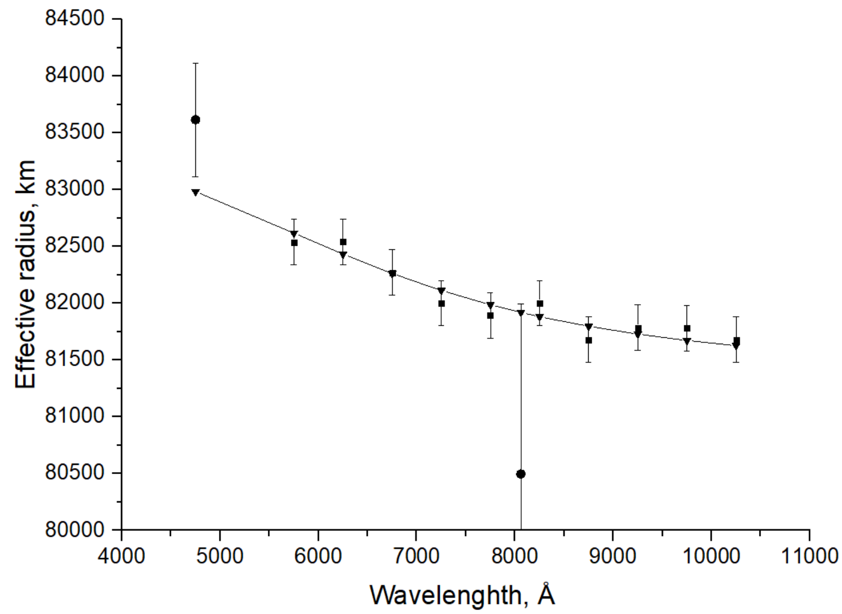

Fig. 1. Dependence of the exoplanet HD 189733 b radius on the wavelength based on the light curves obtained by the Hubble Space Telescope (squares) and our light curves in the g' and Ic filters (circles). The triangles connected by a line show the modeling results for the Rayleigh atmosphere.

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