Limb and gravity-darkening coefficients for the space mission CHEOPS

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ABSTRACT

The goal of this Research Note is to provide the theoretical calculations of the limb-darkening coefficients (LDC) and gravity-darkening coefficients (GDC) for the space mission CHEOPS. We use two stellar atmosphere models: ATLAS (plane-parallel) and PHOENIX with spherical symmetry covering a wide range of effective temperatures, local gravities, and hydrogen/metal. These grids cover 19 metallicities ranging from 10^{-5} up to 10^{+1} solar abundances, $0 \leq \log g \leq 6.0$ and 2300 K $\leq T_{\rm eff} \leq$ 50000 K. The specific intensity distribution was fitted using six approaches: linear, quadratic, square root, logarithmic, power-2, and a series with four terms. The calculations of the GDC were performed for both stellar atmosphere models adopting an improved formulation.

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NUMERICAL METHODS AND RESULTS

To facilitate the identification of the coefficients contained in their respective tables we summarize the corresponding formulae below:

the linear Schwarzschild (1906), Milne (1921)

$$\frac{I(\mu)}{I(1)} = 1 - u(1-\mu), \tag{1}$$

the quadratic law Kopal (1950)

$$\frac{I(\mu)}{I(1)} = 1 - a(1-\mu) - b(1-\mu)^2, \tag{2}$$

the square root law Díaz-Cordovés&Giménez (1992)

$$\frac{I(\mu)}{I(1)} = 1 - c(1-\mu) - d(1-\sqrt{\mu}), \tag{3}$$

the logarithmic law Klinglesmith&Sobieski (1970)

$$\frac{I(\mu)}{I(1)} = 1 - e(1-\mu) - f\mu\ln(\mu), \tag{4}$$

the power-2 law Hestroffer (1997)

$$\frac{I(\mu)}{I(1)} = 1 - g(1-\mu^h), \tag{5}$$

and a four terms law Claret (2000)

$$\frac{I(\mu)}{I(1)} = 1 - \sum_{k=1}^{4} a_k(1-\mu^{\frac{k}{2}}), \tag{6}$$

where $I(1)$ denotes the specific intensity at the centre of the disk and $u, a, b, c, d, e, f, g, h$, and a_k are the corresponding LDC. The μ's are given by $\cos(\gamma)$, where γ is the angle between the line of sight and the outward surface normal. The model atmosphere intensities were convolved with the transmission curve of CHEOPS (SVO Filter Profile Service). The LDC were computed adopting the least-square method (LSM). For models with spherical symmetry we adopt the r method for the cases of Eqs. 1-6. For a detailed description of this method, see Claret (2017) and Claret (2018).

For the calculation of the GDC the following equation was adopted following the improvements introduced by Claret&Bloemen (2011) :

$$y(\lambda, T_{\rm eff}, \log[A/H], \log g, V_\xi) = \left(\frac{d\ln T_{\rm eff}}{d\ln g}\right)\left(\frac{\partial \ln I_o(\lambda)}{\partial \ln T_{\rm eff}}\right)_g + \left(\frac{\partial \ln I_o(\lambda)}{\partial \ln g}\right)_{T_{\rm eff}}. \tag{7}$$

where λ is the wavelength, $I_o(\lambda)$ the intensity at a given wavelength at the centre of the stellar disc and V_ξ is the microturbulent velocity. We note that the expression $\left(\frac{d\ln T_{\rm eff}}{d\ln g}\right)$ can be written as $\beta_1/4$. Therefore we have

$$y(\lambda, T_{\rm eff}, \log[A/H], \log g, V_\xi) = \left(\frac{\beta_1}{4}\right)\left(\frac{\partial \ln I_o(\lambda)}{\partial \ln T_{\rm eff}}\right)_g + \left(\frac{\partial \ln I_o(\lambda)}{\partial \ln g}\right)_{T_{\rm eff}}, \tag{8}$$

where β_1 is the gravity-darkening exponent (GDE), a bolometric quantity. The GDE is a function of the physical conditions in the upper layers mainly for stars presenting convective envelope. Therefore the GDC tables consist of two lines per model: the first line refers to the first term of Eq. 8 considering $\beta_1 = 1.0$, and the second line refers to the second term of this equation. We separate the two contributions so that the value of β_1 can be extracted from suitable tables, as for example those by Claret (1998) and Claret (2004), or adjusted during the synthesis of the light curves. Thus the first term only needs to be multiplied by the value of β_1 extrated from the mentioned tables (or iterated). For more details about the calculations and the effect of convection in the GDC, see Claret&Bloemen (2011) and Claret et al. (2020).

The calculations of LDC and GDC adopting another stellar atmosphere models can be provided to interested readers upon request. Tables 1-14 (see Table A1) and the ReadMe file are available in electronic form (ASCII) at XXXXXX. or directly from the author. They contain the GDC and the LDC $u, a, b, c, d, e, f, g, h$ and a_k as a function of the effective temperature, log g, log$[A/H]$ and V_ξ for the CHEOPS transmission.

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TableA 1. Gravity and limb-darkening coefficients for the CHEOPS photometric system

Name	Source	range $T_{\rm eff}$	range log g	log [A/H]	Vel Turb.	Filter	Fit/equation/model
Table1	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 1, r method
Table2	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 2, r method
Table3	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 3, r method
Table4	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 4, r method
Table5	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 5, r method
Table6	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	LSM/Eq. 6, r method
Table7	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 1
Table8	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 2
Table9	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 3
Table10	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 4
Table11	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 5
Table12	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	LSM/Eq. 6
Table13	PHOENIX-COND	2300 K-12000 K	2.5-6.0	0.0	2 km/s	CHEOPS	GDC $y(\lambda)$
Table14	ATLAS	3500 K-50000 K	0.0-5.0	-5.0–+1.0	0–8 km/s	CHEOPS	GDC $y(\lambda)$