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Limb-darkening coefficients of late-type stars

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Abstract. Linear and quadratic limb-darkening coefficients have been calculated by means of a least squares fitting to a sample of stellar model atmospheres corresponding to late-type stars. Theoretical predictions for the angular distribution of the emergent intensity, $I(\mu)$, have been computed on the basis of the Uppsala Model Atmosphere by Gustafsson et al. (1975). A range of effective temperatures from 4000 to 6730 K has been covered with $\log g$ values from approximately main-sequence stars up to the giants. Coefficients were computed for Strömgren uvby and Johnson *UBV* photometric bands. A comparison with previous available results and observations of the Sun is made. A simple expression for the interpolation of linear limb-darkening coefficients in the different photometric bands is also given.

A detailed discussion of the effect of irradiation of stellar atmospheres by a hotter companion star on the predicted limb-darkening coefficients is presented for the first time adopting realistic binary star parameters. An important difference, in the sense that brightness distribution becomes more uniform, is found for systems representative of classical Algol-type binaries.

Key words: stellar atmospheres – limb darkening – late-type stars – eclipsing binaries

1. Introduction

A theoretical prediction of limb-darkening coefficients for main-sequence and evolved stars is very important in the analysis of the light curves of eclipsing binaries. Popper (1984) and other authors have shown that even the most accurate light curves do not include enough information to empirically derive the intensity distribution function of stellar discs except for a few special cases. Values obtained from reliable model atmospheres should therefore be input during the analysis of the observed light curves.

Moreover, limb-darkening coefficients are important parameters in the determination of stellar angular diameters from observed fluxes as well as in the use of interferometric methods.

Since the pioneer work by Milne (1927) many papers have been devoted to the study of the limb darkening in the stellar atmospheres and their application to the analysis of binary stars. A linear approximation to the actual intensity distribution is currently adopted in the form,

$$I(\mu) = I(1)\,(1 - u(1 - \mu))$$

where $\mu = \cos\theta$ and θ denotes the angle formed by the line of sight and the direction of the emerging flux. $I(1)$ represents the intensity at the stellar disc center and u is known as the linear limb-darkening coefficient.

Grygar (1965) as well as Shul'berg (1973) already pointed out that this linear approximation may not be accurate enough, particularly for hot stars, in light of the differences found between individual values given by the fitting and the actual angular distribution of the emergent intensity. Several non-linear laws for the limb darkening have therefore been proposed (see e.g. Kinglesmith and Sobieski, 1970; Manduca et al., 1977; Wade and Ruciński, 1985 or Díaz-Cordovés and Giménez, 1990) but the more generally adopted quadratic approximation is expressed in the form:

$$I(\mu) = I(1)\,(1 - u_1(1 - \mu) + u_2(1 - \mu)^2)$$

where u_1 and u_2 denote the two non-linear terms of the quadratic limb-darkening law. In the case of cool atmospheres we have found, nevertheless, that the linear expression reproduces the model-computed values of $I(\mu)$ satisfactorily well.

Another point of some controversy in the calculation of limb-darkening coefficients is related to the mathematical method to derive them. While some authors prefer the classical fitting by least squares (Manduca et al., 1977), others adopt the constraint that integrated fluxes obtained from model atmospheres should be equal to that obtained by analytical integration of the linear or quadratic approximations mentioned above (Hosokawa, 1967; Wade and Ruciński, 1985). An intermediate solution, using weighted mean slopes, is used by Al-Naimiy (1978). Díaz-Cordovés and Giménez (1990) already found that differences between tabulations by different authors, for a given temperature and wavelength, are normally due to the method of computation rather than to the adopted model atmospheres themselves.

In all previous studies, stars were considered as isolated objects. We have also analysed the influence of irradiation by another source of energy on the angular distribution of emergent intensity. This approach allows us to provide more realistic estimations of limb-darkening coefficients and comes closer to the actual situation found in close binary stars.

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In this paper we have calculated limb-darkening coefficients for standard as well as irradiated stellar atmosphere models. In the latter case, we assume values of the companion star as regards distance, size, and temperature, corresponding at best to classical Algol binaries.

2. Computational procedure

A new grid of flux-constant blanketed model atmospheres for cool stars obtained with the Uppsala Model Atmosphere code MARCS (hereafter referred to as UMA), described by Gustafsson et al. (1975) and Bell et al. (1976), has been used. Modifications to include relatively large values of $\log g$, extending the grid by Manduca et al. (1977) to dwarfs stars, were included (Vaz and Nordlund, 1985; Bell, 1988). Our calculations use the Opacity Distribution Function (ODF) files covering a range of effective temperatures from 4000 to 6730 K. Surface gravity was given different input values for each effective temperature in the range from 4.6 to 2.0, approximately covering stars from the zero-age main sequence up to giants. Two different values, namely 1.5 and 2.0, were adopted for the mixing-length parameter l/H_p but no significant differences in limb-darkening were found for given values of temperatures, $\log g$ and wavelength. All models presented here were calculated for the standard solar abundance, log $[A/H]=0.0$, but additional models were computed to check for the effect of small changes in metal content.

The angular distribution of the intensities was then calculated for 6 individual values of μ in each of the model atmospheres generated. In order to derive the corresponding limb-darkening coefficients, an appropriate convolution with the sensitivity functions of the most commonly used photometric filters was made. We have adopted for this purpose the uvby (Crawford and Barnes, 1970) and *UBV* (Landolt-Börnstein, 1981) bands as defined by Strömgren and Johnson respectively. The atmospheric transmission curve was taken from Landolt-Börnstein (1981), the reflectivity for the aluminium-coated mirrors was taken from Allen (1973) and the sensitivity of the 1 P 21 phototube from Kurucz (1979). We have used here a procedure very similar those described by Relyea and Kurucz (1978). It should be mentioned that, as indicated by Relyea and Kurucz (1978) there are many problems and systematic errors in the calculation of the theoretical colours.

We have used the two laws of limb darkening given above, linear and quadratic, to fit the relation between $I(\mu)/I(1)$ and μ by

Table 1.1

$T_{\rm eff}$	$\log g$	u	v	b	y	U	B	V
4000	2.00	0.99	0.95	0.91	0.84	0.98	0.92	0.82
4000	2.50	1.01	0.96	0.91	0.84	1.00	0.93	0.82
4000	3.00	1.02	0.97	0.92	0.83	1.02	0.93	0.81
4000	3.50	1.03	0.98	0.92	0.83	1.03	0.94	0.81
4000	4.00	1.03	0.97	0.90	0.81	1.02	0.92	0.79
4500	2.00	0.97	0.93	0.88	0.80	0.96	0.89	0.78
4500	2.50	0.99	0.93	0.88	0.80	0.98	0.90	0.78
4500	3.00	1.00	0.94	0.88	0.80	0.99	0.90	0.78
4500	3.50	1.00	0.94	0.87	0.79	1.00	0.90	0.77
4500	4.00	1.01	0.95	0.87	0.79	1.00	0.90	0.77
4500	4.50	1.01	0.95	0.87	0.79	1.01	0.90	0.77
4600	3.00	0.97	0.93	0.86	0.78	0.96	0.88	0.76
4700	3.44	0.99	0.93	0.86	0.78	0.98	0.88	0.76
5000	2.00	0.91	0.90	0.84	0.76	0.91	0.86	0.74
5000	2.50	0.93	0.91	0.84	0.76	0.93	0.86	0.74
5000	3.00	0.94	0.91	0.84	0.76	0.94	0.86	0.73
5000	3.50	0.96	0.91	0.84	0.75	0.95	0.86	0.73
5000	4.00	0.96	0.91	0.84	0.75	0.96	0.86	0.73
5000	4.50	0.97	0.91	0.84	0.75	0.97	0.86	0.73
5300	2.50	0.88	0.89	0.82	0.73	0.89	0.84	0.71
5300	3.44	0.92	0.88	0.82	0.73	0.92	0.84	0.71
5300	4.57	0.94	0.88	0.81	0.73	0.94	0.83	0.71
5460	3.44	0.90	0.87	0.81	0.72	0.90	0.83	0.70
5500	3.00	0.88	0.87	0.81	0.72	0.89	0.83	0.70
5500	3.50	0.90	0.87	0.80	0.72	0.90	0.83	0.70
5780	4.44	0.89	0.84	0.78	0.69	0.89	0.80	0.67
6000	4.50	0.87	0.83	0.77	0.68	0.87	0.79	0.66
6020	3.44	0.83	0.83	0.77	0.68	0.84	0.79	0.66
6300	3.44	0.80	0.82	0.76	0.67	0.82	0.78	0.65
6730	4.50	0.78	0.79	0.74	0.65	0.79	0.76	0.63

Table 1.2

T_{eff}	$\log g$	u	v	b	y	U	B	V
4000	2.00	1.74	1.40	1.16	0.93	1.71	1.24	0.87
		0.84	0.50	0.28	0.10	0.82	0.36	0.06
4000	2.50	1.75	1.40	1.16	0.93	1.72	1.24	0.87
		0.83	0.49	0.27	0.10	0.81	0.35	0.06
4000	3.00	1.74	1.39	1.15	0.92	1.71	1.24	0.86
		0.80	0.47	0.27	0.10	0.78	0.34	0.06
4000	3.50	1.71	1.39	1.15	0.91	1.69	1.23	0.86
		0.76	0.46	0.26	0.09	0.75	0.33	0.05
4000	4.00	1.64	1.31	1.08	0.83	1.62	1.16	0.79
		0.69	0.39	0.20	0.03	0.67	0.27	0.00
4500	2.00	1.43	1.25	1.02	0.79	1.44	1.09	0.74
		0.52	0.36	0.17	−0.01	0.54	0.23	−0.05
4500	2.50	1.44	1.24	1.02	0.79	1.44	1.09	0.74
		0.51	0.34	0.16	−0.01	0.52	0.21	−0.04
4500	3.00	1.44	1.23	1.01	0.80	1.44	1.08	0.74
		0.49	0.32	0.15	0.00	0.50	0.20	−0.04
4500	3.50	1.43	1.22	1.00	0.80	1.43	1.07	0.75
		0.48	0.31	0.14	0.00	0.48	0.19	−0.03
4500	4.00	1.42	1.20	0.99	0.80	1.42	1.06	0.75
		0.46	0.29	0.13	0.01	0.46	0.18	−0.03
4500	4.50	1.41	1.18	0.98	0.79	1.40	1.05	0.75
		0.44	0.26	0.12	0.00	0.44	0.17	−0.03
4600	3.00	1.35	1.18	0.98	0.78	1.35	1.04	0.72
		0.43	0.28	0.14	−0.01	0.44	0.18	−0.04
4700	3.44	1.30	1.15	0.95	0.75	1.31	1.01	0.70
		0.35	0.25	0.10	−0.03	0.37	0.15	−0.06
5000	2.00	1.10	1.15	0.93	0.71	1.17	1.00	0.67
		0.21	0.28	0.10	−0.05	0.29	0.15	−0.08
5000	2.50	1.11	1.12	0.91	0.70	1.17	0.98	0.66
		0.21	0.24	0.08	−0.06	0.27	0.13	−0.09
5000	3.00	1.13	1.11	0.90	0.70	1.17	0.97	0.66
		0.21	0.22	0.07	−0.06	0.26	0.12	−0.09
5000	3.50	1.15	1.08	0.89	0.70	1.18	0.95	0.65
		0.22	0.19	0.06	−0.06	0.25	0.10	−0.09
5000	4.00	1.17	1.05	0.89	0.70	1.18	0.94	0.65
		0.23	0.16	0.05	−0.06	0.25	0.09	−0.09
5000	4.50	1.18	1.03	0.87	0.69	1.18	0.92	0.65
		0.24	0.14	0.04	−0.06	0.24	0.07	−0.09
5300	2.50	0.97	1.05	0.86	0.66	1.04	0.92	0.62
		0.10	0.19	0.04	−0.08	0.17	0.09	−0.10
5300	3.44	1.02	0.99	0.83	0.65	1.05	0.88	0.61
		0.11	0.12	0.01	−0.09	0.14	0.05	−0.11
5300	4.60	1.05	0.92	0.80	0.63	1.04	0.83	0.60
		0.12	0.04	−0.02	−0.11	0.12	0.00	−0.13
5460	3.44	0.97	0.95	0.80	0.63	1.00	0.85	0.59
		0.08	0.09	−0.01	−0.10	0.11	0.02	−0.12
5500	3.00	0.93	0.99	0.82	0.64	0.99	0.88	0.60
		0.06	0.14	0.02	−0.09	0.11	0.06	−0.11
5500	3.50	0.96	0.96	0.80	0.63	1.00	0.86	0.59
		0.08	0.10	0.00	−0.10	0.11	0.03	−0.12
5780	4.44	0.92	0.84	0.73	0.58	0.92	0.77	0.55
		0.03	−0.01	−0.06	−0.13	0.04	−0.04	−0.14
6000	4.50	0.85	0.79	0.70	0.56	0.86	0.73	0.53
		−0.02	−0.04	−0.08	−0.14	−0.01	−0.06	−0.15
6020	3.44	0.80	0.82	0.72	0.57	0.84	0.75	0.54
		−0.03	−0.01	−0.06	−0.13	0.00	−0.04	−0.14
6300	3.44	0.72	0.77	0.69	0.55	0.76	0.72	0.52
		−0.08	−0.06	−0.09	−0.14	−0.06	−0.08	−0.15
6730	4.50	0.65	0.68	0.63	0.51	0.66	0.64	0.48
		−0.14	−0.13	−0.13	−0.16	−0.15	−0.13	−0.17

least squares. Resulting coefficients are given in Tables 1.1 and 1.2 for the linear, u, and quadratic, u_1 and u_2, terms respectively. In Table 1.2, values of u_1 and u_2 are tabulated on top of each other for each model. It can be seen in Table 1.2, from the relative values of u_2 for the longer wavelengths, that the improvement of the fitting by introducing second terms is not so important as in the case of hotter stars.

We have found that the method of least-squares fitting better reproduces the behaviour of $I(\mu)$ than that by Wade and Ruciński (1985) and it is therefore more adequate in the analysis of binary stars, where the stellar disc surfaces are scanned during eclipses.

3. Non-irradiated models

As a check of the values calculated by us, in the cooler range, we have compared our results with those published by Manduca et al. (1977) who adopted essentially the same model atmospheres but used detailed synthetic spectra calculations when calculating $I(\mu)$.

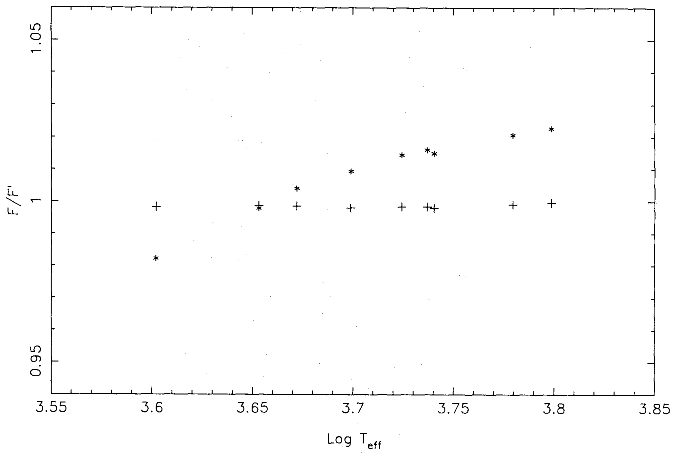

Fig. 1. The F/F' versus log $T_{\rm eff}$ relation for non-irradiated models. Linear (asterisks) and quadratic (crosses) fittings are shown. A systematic deviation is noted for the linear fit. See text for definitions of F and F'

Table 2. Limb-darkening coefficients for the Sun

	u	v	b	y
Manduca et al. (1977)	0.89	0.85	0.78	0.68
Al-Naimiy (1978)	0.83	0.80	0.72	0.62
Wade and Rucinski (1985)	0.88	0.79	0.71	0.63
This paper	0.89	0.84	0.78	0.69
Observed	0.87	0.83	0.76	0.67

A good agreement is found (about 1.5%) for non-irradiated giants stars, which implies that the ODF (Opacity Distribution Function) approximation in the flux calculation is not too rough.

As a test of our least-squares fittings, we have compared the flux obtained by integration of the computed intensity distribution (F) and that derived from integration of the linear and quadratic approximations (F'). In Fig. 1, we show that there is a small but systematic effect in the ratio F/F' with effective temperature for the linear law. Both fluxes are equal around log $T_{\rm eff} = 3.65$ and differences go only up to 2% in the hottest and coolest models of the adopted temperature range. Fluxes are indistinguishable if the quadratic approximation is adopted. Results plotted in Fig. 1 correspond to the Strömgren y filter and models with log g around 3.5 but similar results are found independently of the surface gravity. With respect to wavelength, only the Strömgren u and Johnson U present some small differences between F and F'. Least squares fittings can thus be considered quite satisfactory with respect to the angle-averaged flux even though this was not included as an initial condition.

The method adopted by Wade and Ruciński (1985) requires that, for a value F of the integrated flux, the limb-darkening coefficients are:

$$u = 3\,(1 - F/I(1))$$

$$u_1 = (-519.57\,F + 100\,I(0.069) + 419.57\,I(1)/(80.13\,I(1))$$

$$u_2 = (-558.34\,F - 200\,I(0.069) - 358\,I(1)/(80.13\,I(1))$$

where 0.069 is the minimum value of μ in our model atmospheres which differs slightly from that used by Wade and Ruciński (1985). We have calculated the coefficients corresponding to the intensity distributions for our adopted models in Tables 1.1 and 1.2, and the derived values are found to be systematically smaller than those obtained by least-squares fitting. For the few model atmospheres within the range studied by Wade and Ruciński (1985) we obtain a very good agreement.

Finally, we have compared our results with observations of the solar photosphere. In Table 2, we have included for the uvby Strömgren filters, the predicted values of limb-darkening for the Sun given by Manduca et al. (1977), Al-Naimiy (1978) and Wade and Ruciński (1985). Observational values were calculated by least-squares fitting to the functional behaviour tabulated by Allen (1973). It can be seen that a general agreement is found in all wavelengths. Our values are almost identical to those by Manduca et al. (1977) because the same models and fitting methods were used though we adopted an updated version of the UMA. This agreement again supports the use of the Opacity Distribution Function (ODF) for calculating the fluxes. A small but systematic difference of 0.02 between our values and those derived from the observed angular distribution of the emergent intensity of the Sun is present. Differences in the adopted values of μ and in the interpolation of the observed intensity distributions for adopted wavelengths may partly explain this small difference.

Table 3. Coefficients of analytical approximation functions

	u	v	b	y	U	B	V
a	5.05	3.82	3.70	3.76	4.71	3.71	3.74
b	−1.13	−0.79	−0.77	−0.81	−1.04	−0.77	−0.81
c	0.020	0.003	−0.003	−0.006	0.020	0.000	−0.005

In order to facilitate interpolation in Table 1.1 for the linear limb-darkening coefficients, we have made a least-squares fitting to the function:

$$u(\lambda) = a + b \log T_{\rm eff} + c \log g$$

for each of the integrated photometric bands. The obtained coefficients are given in Table 3. These equations reproduce values given in the Table 1.1 with an average accuracy of 0.01 in u except for the u filter which shows a slightly higher dispersion. The range of valitity is obviously given by the models used in this paper. An almost negligible dependence on the stellar surface gravity, for a given temperature, is noted in the small values of the c coefficients.

4. Irradiated models

Irradiated models were generated by changing the upper boundary condition adopted by the model atmospheres (Gustafsson et al., 1975) as described by Vaz and Nordlund (1985). We have used the ODF tables and, in order to simulate the hotter component of classical Algol-type binaries, we have adopted model atmospheres given by Kurucz (1979) as indicated by Giménez and Claret (1989).

Surface angular distribution of the emergent intensity are very much perturbed by the external radiation field. In Fig. 2 we have plotted the ratio between F and F' as defined in the previous Section in terms of the effective temperature of the irradiated atmosphere using different configurations for the irradiating star. Although the scatter of the individual models is clearly larger than in Fig. 1 due to the effects produced by different irradiating stars, it can be seen that, as expected, the quadratic approximation reproduces the integrated fluxes better. Nevertheless, involved differences are always kept within an acceptable 2%.

In order to see the effect of irradiation on the computed model atmospheres, we have plotted in Fig. 3 the computed ratios $I(\mu)/I(1)$ for a star of effective temperature of 5890 K (a star

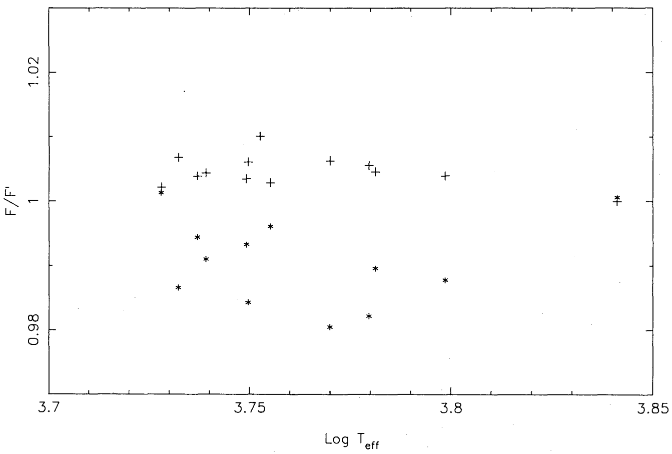

Fig. 2. The F/F' versus log $T_{\rm eff}$ relation for irradiated models. Symbols as in Fig. 1. Different levels of irradiation for the same initial model atmosphere have been included

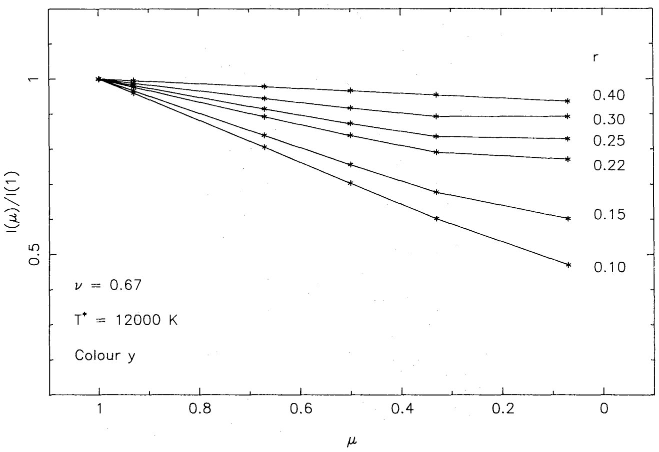

Fig. 4. Effect of the distance of the irradiating source on the emergent intensity distribution. Characteristics of irradiation as given in Fig. 3, but changing values of the relative radius. The effective temperature of the irradiated model depends strongly on the separation

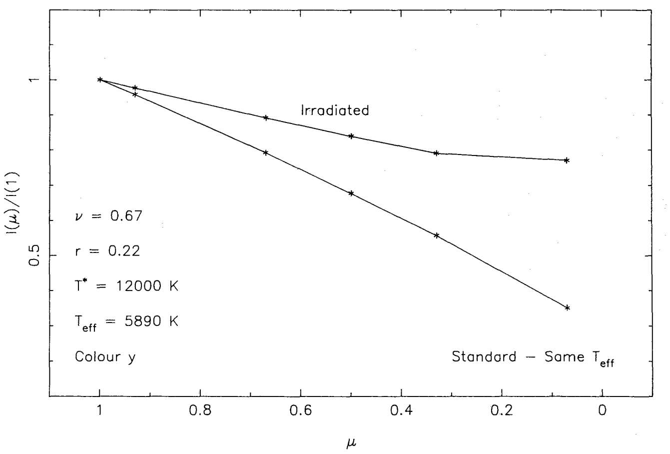

Fig. 3. Comparison between irradiated and non-irradiated models with the same effective temperature. Perturbed model corresponds to an atmosphere with an original effective temperature of 5300 K, irradiated by an external source of 12000 K with a relative radius 0.22 and $\nu = 0.67$ (see text for definitions of relative radius and ν)

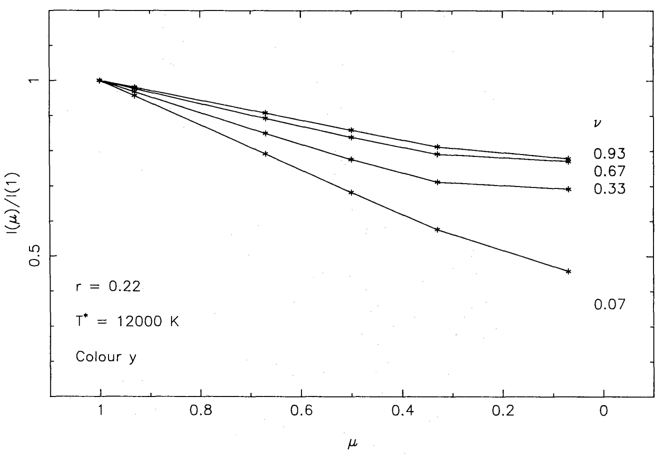

Fig. 5. Effect of changing the angle of incidence of the irradiating source on the surface of model atmosphere on the emergent intensity distribution. A value of 0.93 corresponds to an almost perpendicular incidence. The remaining irradiation parameters are the same adopted in Fig. 3

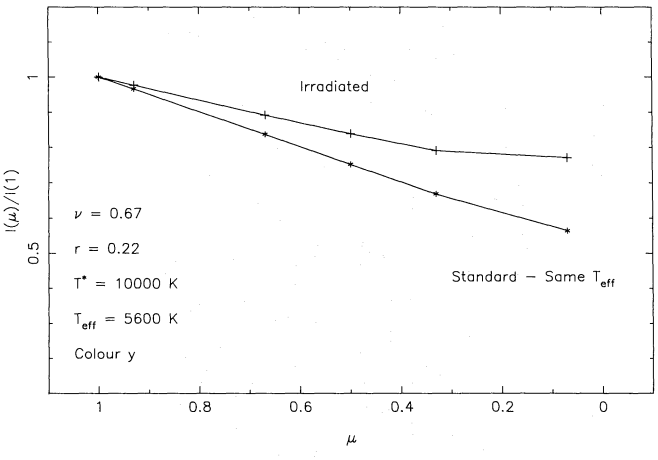

Fig. 6. Influence of changing the effective temperature of the irradiating source, at a fixed distance, on the emergent intensity distribution. Other parameters as given in Fig. 3

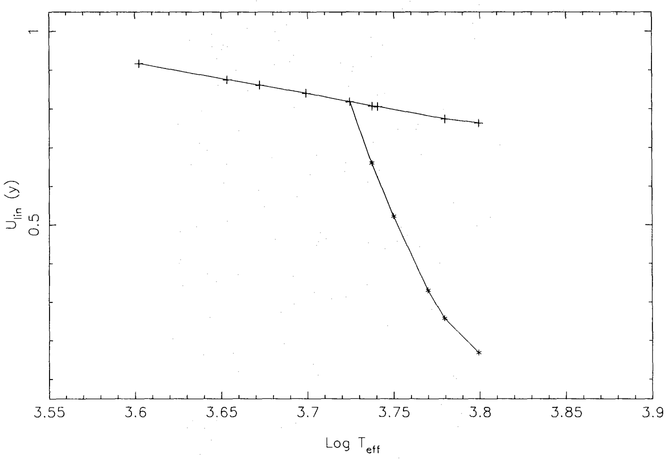

Fig. 7. Linear limb-darkening coefficients as a function of the effective temperature. Crosses correspond to standard models and asterisks denote the position of irradiated atmospheres. These latter models were calculated for the same original effective temperatures with an irradiating source of 12000 K, $\nu = 0.67$ and several relative radii, namely, 0.10, 0.15, 0.22, 0.25, and 0.30 respectively

originally having a temperature of 5300 K, irradiated by another star of 12000 K at such distance that the relative radius of the irradiating star is 0.22), and an isolated star having the same temperature and surface gravity. It is clear that a quadratic law reproduces the behaviour of irradiated atmospheres better and linear coefficients should be much smaller. Furthermore, the limb-darkening of irradiated models depends strongly on the relative distance of the irradiating star, on the cosine of the angle of incidence of the irradiating flux ν, and on the effective temperature of the companion, T^* (see Figs. 4, 5, and 6). The effect of distance, expressed in terms of the relative size of the surface of the irradiating star with respect to the orbital radius, is shown in Fig. 4. Already, for a value $r = 0.4$, irradiation is so large that the perturbed model atmosphere reproduces some of the characteristics of the external irradiation field. In Fig. 7, we have plotted the linear limb-darkening coefficient for the Strömgren y filter as a function of log $T_{\rm eff}$ together with the effect in the unperturbed model of 5300 K of irradiation by a 12000 K star located at increasingly small distances from the surface sense of making the stellar discs closer to an uniform bright distribution, is clearly seen in this Figure.

All this should be considered as a qualitative description. Two important physical aspects of irradiation could not be yet taken into account, namely, the effect of circulation currents in transporting the incident energy and the geometrical shape of the component stars in close binaries like classical Algols. A plane-parallel has been adopted in all computations.

5. Conclusions

For the standard models, we have found a good agreement of our results with those by Manudca et al. (1977) for the low gravity models as well as with tabulations by Días-Cordovés and Giménez (1990) for the cool end of their revision of Wade and Ruciński (1985) calculations, using again Kurucz's models but through a least-squares fitting. As expected, in all models analysed in the present paper, quadratic approximations provide the best fit to the actual distribution of light. The method adopted by Wade and Ruciński (1985) represents an operational rather than a physical approach. The fact that this method provides a priori the correct total flux does not imply that it reproduces the behaviour of the function $I(\mu)/I(1)$ with μ. Indeed, the actual points $I(\mu)$ calculated with the model atmospheres are not used in obtaining the coefficients except through the integrated value or a pivotal selected point in the case of non-linear laws.

Irradiated models, for which no previous study is available, show limb-darkening coefficients very different from those of the non-irradiated models with the same effective temperature and $\log g$. This means that the use of coefficients computed from non-irradiated model atmosphere is not the correct procedure in the case of some types of binaries like classical Algols. Nevertheless, it is certainly more complicated to introduce the effect of irradiation in the prediction of theoretical coefficients for limb darkening since we have to take into account a number of additional parameters such as the relative distance between the two stars and realistic values for the effective temperatures, in coherence with the parameters of the system studied.

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