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The variable Herbig Ae star HR 5999*

XII. Its circumstellar extinction law

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Abstract. A study of the extinction law in the UV-visual-IR spectral regions has been made towards the variable Herbig Ae star HR 5999 at three brightness levels $V = 6^{\mathrm{m}}.9$, $7^{\mathrm{m}}.2$, and $7^{\mathrm{m}}.3$. For comparison we have made an equivalent study of its proper motion non-variable companion HR 6000, which is embedded in the same dark cloud. The extinction law towards HR 6000 appears to be normal in the considered wavelength range. This means that the origin of any anomaly in the extinction law towards HR 5999 should be caused by the dust grains in the circumstellar envelope of this star.

The circumstellar extinction law of HR 5999, characterized by the R_V value, has been studied using the extinction calculations by Steenman & Thé (1991), in which it is assumed that the small grains are depleted. We found that for the spectral region considered the value of R_V is larger than 5.8. For the UV alone we found for R_V^{UV} a range between 3.3 to 3.9.

Above mentioned law has also been studied quantitatively using the multiple scattering model based on the Monte Carlo method of Voshchinnikov, Molster & Thé (1996). We have found that the extinction curve near the state of maximum brightness ($V = 6^{\mathrm{m}}.9$) of HR 5999 can be produced by a nearly spherical (A/B = 1.5) shell, seen edge-on, and of which the dust grains of sizes smaller than about 0.01 μm are depleted. For the fainter brightness states, which we have also studied, additional extinction due to circumstellar dust clumps, obscuring the star, is assumed. From these conditions, we have found that the properties of the dust particles in the clumps differ from those in the shell. Among others, the smaller dust grains in the clumps are more depleted than in the above mentioned shell. The R_V^{cs} values found in the Monte Carlo calculations range from 2.5 to 3.2.

We suggest that the depletion of small grains is due to the sweeping effect of the radiation field of the central star.

Key words: pre-main sequence star – circumstellar matter – extinction law – multiple scattering – HR 5999

1. Introduction

The Herbig Ae star HR 5999 (HD 144668, V856 Sco) is one of the most studied Herbig Ae/Be (HAeBe) objects at optical, UV and IR wavelengths. Its most recent astrophysical characteristics can be found in Tjin A Djie et al. (1989, Paper VIII), Blondel et al. (1989, Paper IX), Pérez et al. (1994) and references therein. We give here several important parameters: Spectral type = A5–7 III–IVe, T_{eff} = 7,800 K, $\log g$ = 3.5–4.0, L = 36 $L_{\odot}$, $v \sin i$ = 180±20 km s^{-1}, R = 3.2 $R_{\odot}$, d = 140 pc (Hughes et al. 1993), M = 2–2.5 $M_{\odot}$, $t_{\mathrm{age}} = 5 \times 10^5$ yr.

The star is surrounded by an extended gaseous atmosphere and a relatively optically thick dust shell in its outskirts. Blondel et al. (Paper IX) found correlations between the variations of the stellar visual magnitude and the changes in the strength of several low excitation lines in the UV. These correlations are thought to be due to variations in the magnetic field structure, which influence the stellar wind velocity in the gaseous shell and, possibly, the extinction properties of the circumstellar dust more distant from the star.

It is known for some time that the extinction law towards HR 5999 in the visual, red and near-IR spectral regions, at maximum brightness, is anomalous (Thé & Tjin A Djie 1978, Paper I; Thé et al. 1981, Paper V). The value of $R_V = A_V/E(B-V)$ was found to be between 4 and 5. In Paper V (see Fig. 8), it is shown that the extinction law in the UV deviates somewhat from the average interstellar one. Hecht et al. (1984) reached the same conclusion. An interpretation of this anomalous behaviour at UV wavelengths has been given by these authors, in terms of dust formation and re-evaporation. However, a quantitative interpretation of the extinction law towards HR 5999 over the whole spectral region is so far not yet proposed.

Since HR 5999 is embedded in a dark cloud, we should realize that its extinction is contributed by the foreground interstellar

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* Based on observations obtained at the European Southern Observatory, La Silla, Chile, and on spectra in the IUE archive.

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medium, the dark cloud and the circumstellar matter. Normally it is not possible to disentangle these three components. In the case of HR 5999 we are fortunate that it has a proper motion companion HR 6000 (Bessel & Eggen 1972) located at an angular distance of about 45″ to the north, and embedded in the same dark cloud. In order to investigate the behaviour of the extinction law of the matter in the dark cloud we will also study the extinction characteristics towards HR 6000. The results can be used to justify the correction for foreground extinction towards HR 5999, using the data of HR 6000, and in this way to obtain its circumstellar extinction law. Furthermore, the existing polarimetric data for HR 6000 can also be used to exclude the interstellar and circumcloud polarization for HR 5999.

It is valuable to give here some characteristics and data of HR 6000. Andersen et al. (1984) concluded from optical spectroscopy that HR 6000 is a single, very slow-rotating, chemically peculiar Helium-weak late B or early A type star, without significant circumstellar matter. Later, Castelli et al. (1984, 1985) showed, from UV spectral data, that HR 6000 does not seem to fit in any of their classes of chemically peculiar stars, although it shares some characteristics with the HgMn group. The spectral type of A0/3 III, derived from spectral data, differs significantly from its spectral type derived from optical photometric data: B7 (Eggen 1984). The visual brightness of HR 6000 is $6\overset{\mathrm{m}}{.}65$, and is almost constant. An extended study of this star is given in the paper by Van den Ancker et al. (1996).

In this paper, we give the observational results of the extinction law from the UV to the IR as the star changes its brightness between $V = 6\overset{\mathrm{m}}{.}9$ to $7\overset{\mathrm{m}}{.}3$. An interpretation of these data is offered in terms of changes in the properties of the dust clumps rotating in the surrounding dust shell as it was supposed for the first time by Tjin A Djie & Thé (1978; Paper IV). Our modelling, which assumes multiple scattering, is based on the Monte Carlo code developed by Voshchinnikov & Karjukin (1994). It allows us to calculate the polarized radiation escaping from the non-spherical shell and construct the curves of circumstellar extinction and polarization (see also Voshchinnikov et al. 1996). Because HR 5999 was observed polarimetrically several times in the visual to IR (Bessel & Eggen 1972; Paper V; Hutchinson et al. 1994), we can use these polarization data to check the model parameters.

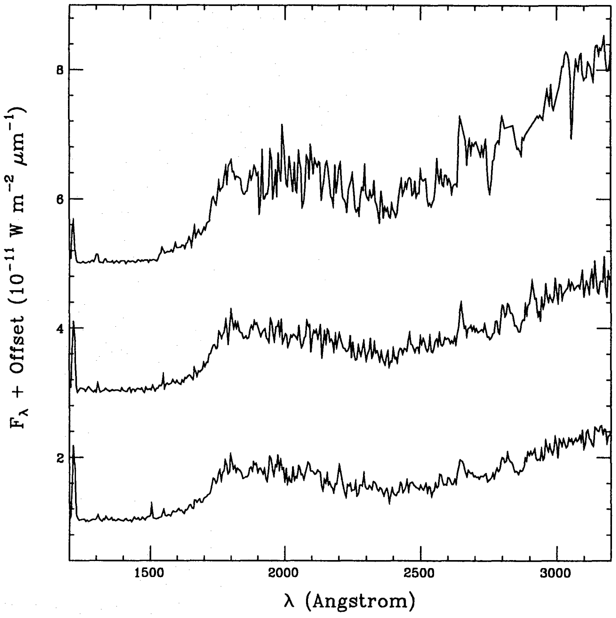

Fig. 1. UV spectra of HR 5999 for the selected low dispersion IUE images (SWP and LWP cameras). In the upper panel the LWP camera presents large noise at short wavelengths

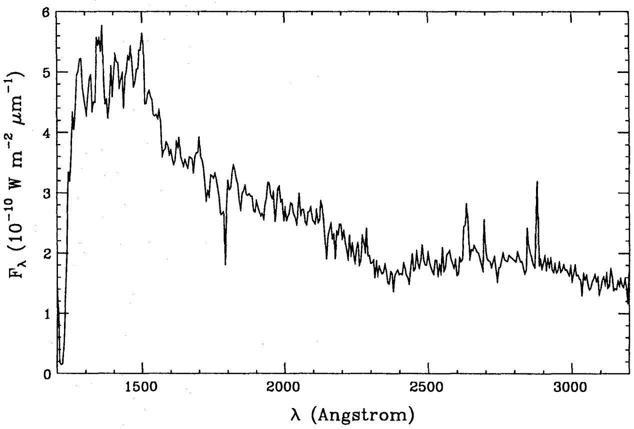

Fig. 2. UV spectrum of HR 6000 combined from a pair of low dispersion IUE images (SWP 14849 + LWR 11431)

2. The collected data

The present study is based primarily on data collected from the literature and UV spectra from the IUE spectral archives. Several unpublished photometric data are also employed.

2.1. The IUE spectra

Since 1978, HR 5999 was observed with the IUE 50 times (until July 1995) in low and high dispersion modes in the region covered by the LWP and SWP cameras. In recent years no follow-up study of this star has been pursued with IUE. Of these 50 images, 15 are in high dispersion. For the study of the UV extinction law we have to use the low dispersion spectra. Our archival search of well-exposed low dispersion SWP and LWP images taken quasi-contemporaneously yielded only three pairs which could be used for a complete determination of the UV extinction law. Either the remaining IUE images are overexposed or no counterpart for the SWP or LWP low dispersion images exist. The data of the images used are presented in Table 1. All these images were acquired in the large aperture, at V (FES) magnitudes of $6\overset{\mathrm{m}}{.}88$, $7\overset{\mathrm{m}}{.}18$ and $7\overset{\mathrm{m}}{.}29$. Fortunately, they cover a significant fraction of the visual variations detected with IUE. In Fig. 1, we display the total stellar spectra covered by both cameras for three acquisition times. No large structure or dramatic changes are noted in these three spectra.

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Table 1. Data for low-dispersion images of HR 5999 and HR 6000

Star	SWP	LWR/P	Year/Day	JD −2440000	t (SWP)	t (LWP/R)	V (FES)
HR 5999	SWP 20861	LWR 16706	1983/243	5577.950	6.00 min.	3.00 min.	7.18
	SWP 21276	LWR 16970	1983/285	5619.784	11.01 min.	3.58 min.	7.29
	SWP 42497	LWP 21267	1991/260	8517.506	10.00 min.	2.00 min.	6.88
HR 6000	SWP 14849	LWR 11431	1981/241	4845.558	25 sec.	18 sec.	6.65

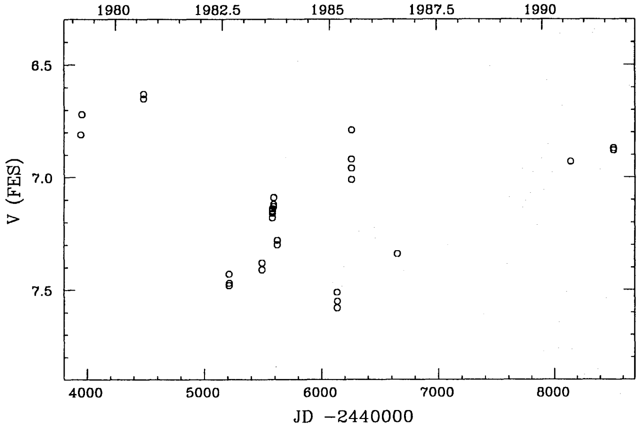

Fig. 3. V (FES) magnitudes for the acquisition time of IUE spectra of HR 5999

Table 2. Visual and infrared data of HR 5999 for different V (FES) values

V (FES)	W	U	L	B	V
6.88	−0.832	−0.650	−0.382	−0.176	−0.051
7.18	−0.970	−0.770	−0.495	−0.287	−0.139
7.29	−1.138	−0.926	−0.655	−0.443	−0.276
σ	0.013	0.010	0.011	0.009	0.008
V (FES)	u	v	b	y	
6.88	8.922	7.535	7.168	6.962	
7.18	9.152	7.784	7.414	7.205	
7.29	9.593	8.190	7.775	7.527	
σ	0.009	0.012	0.011	0.005	
V (FES)	U	B	V	R_c	I_c
6.88	7.531	7.288	6.951	6.742	6.508
7.18	7.776	7.531	7.188	6.839	6.598
7.29	7.851	7.616	7.257	6.984	6.736
σ	0.008	0.007	0.006	0.007	0.007
V (FES)	J	H	K	L	M
6.88	5.62	5.01	4.39	3.04	2.47
7.18	5.97	5.20	4.30	3.26	–
7.29	6.04	5.17	4.30	3.14	2.47
σ	0.03	0.03	0.02	0.05	0.05
IRAS	f_{12}	f_{25}	f_{60}	f_{100}	
f (Jy)	17.55	14.21	8.02	12.4	
σ	1.8	1.4	2.0	3.1	

There are 17 images of HR 6000 available in the IUE archives. The pair of well-exposed images taken almost simultaneously in 1981, viz. SWP 14849 and LWR 11431, is suitable for the study of the shape of the extinction law in the UV towards this star. Relevant data for these spectra are given in the last line of Table 1. The total stellar spectra covered by both cameras are displayed in Fig. 2.

2.2. The V (FES) magnitudes of HR 5999

By using a new FES calibration published by Fireman & Imhoff (1989) we have determined approximate V (FES) magnitudes for the acquisition times of the IUE images. HR 5999 is known for variability of $\Delta V \leq 1\overset{\mathrm{m}}{.}72$ (Pérez et al. 1992, paper X). The V (FES) magnitudes have been tested when simultaneous photometry was carried out (cf., Paper IX, for the 1983 and 1985 campaign) and the coincidence is always better than $0\overset{\mathrm{m}}{.}05$. It is noted that for earlier IUE images (e.g., during 1978) the FES counts were not recorded in the observing scripts, therefore, for such images their FES magnitudes are unknown. The V (FES) magnitudes are plotted as function of acquisition time in Fig. 3. Large variations in brightness are clearly present in short- and long-term scales. For example, Baade & Stahl (1989) detected a strong period of 48.68 days for the bright excursions ($V \leq 7\overset{\mathrm{m}}{.}3$) and a period of about 11.78 days for the photometric minimum ($V \geq 7\overset{\mathrm{m}}{.}3$). It is, therefore, important for the study of the UV extinction law to choose pairs of IUE spectra such as is explained in Sect. 2.1.

2.3. The visual and infrared data

It is well known that HR 5999 exhibits a strong infrared excess due to thermal re-radiation by the circumstellar dust grains. From unpublished observations we also know that it has a pronounced emission 10-μm feature. This infrared excess sets in at about $\lambda = 1.0\ \mu$m. For this reason near-IR magnitudes cannot be used for the study of the extinction law towards the star.

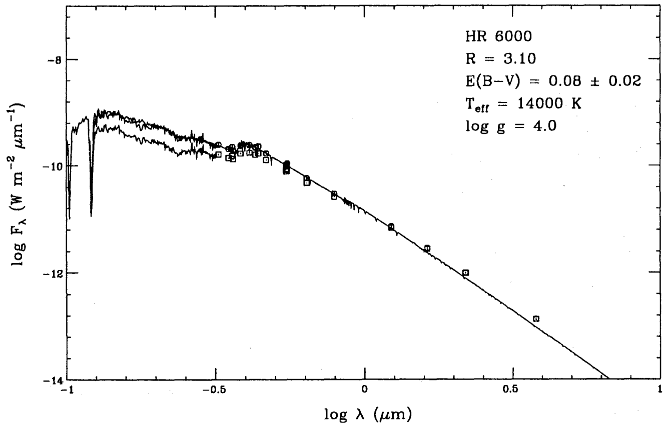

Fig. 4. Observed (squares) and extinction-corrected (circles) spectral energy distributions of HR 6000, compared to the Kurucz model of $T_{\rm eff}$ = 14,000 K, log g = 4.0 and solar abundance

Table 3. Visual and infrared data of HR 6000

Phot. Syst.	W	U	L	B	V
Walraven	−0.117	−0.082	0.046	0.115	0.092
σ	0.013	0.010	0.011	0.009	0.008
Phot. Syst.	u	v	b	y	
Strömgren	7.339	6.735	6.642	6.657	
σ	0.009	0.012	0.011	0.005	
Phot. Syst.	U	B	V	R_c	I_c
Johnson/Cousins	6.135	6.571	6.648	6.658	6.676
σ	0.008	0.007	0.006	0.007	0.007
Phot. Syst.	J	H	K	L	
Near-IR	6.68	6.64	6.58	6.47	
σ	0.03	0.03	0.02	0.05	

Since HR 5999 is an irregular variable ranging in visual magnitude from $V = 6\stackrel{\rm m}{.}74$ to $8\stackrel{\rm m}{.}46$, for the study of its extinction law we have to compare those visual data, which are made in different photometric systems (Walraven, Strömgren or Johnson) preferably taken simultaneously. If this is not possible, at least the V magnitude should be approximately the same.

Long series of visual observations were made by Thé & Tjin A Djie (1978, Paper I) in the Walraven system, by Thé et al. (1978, Paper III), in the Walraven and Strömgren systems, by Thé et al. (1981, Paper V) and Kilkenny et al. (1985) in the Strömgren and Johnson-Cousins systems. Near-IR data are also available (Paper V; Kilkenny et al. 1985, Hutchinson et al. 1994). Far-IR data were taken from the catalogue of co-added IRAS fluxes by Weaver & Jones (1992). In Table 2, we have collected all the data we have chosen from the various publications and which are ultimately used in the analysis of the IR extinction law of the matter in front of HR 5999.

In Table 3 we give the collection of data of HR 6000, used in our investigations.

3. The analysis of the data

In this section we will present the results of the analysis of the data of HR 5999 and HR 6000 for the determination of the extinction law in the UV-visual-IR and in the UV alone.

3.1. Binarity

It is known for some time that HR 5999 (= Rossiter 3930 A) has a close $3\stackrel{\rm m}{.}5$ fainter companion Rossiter 3930 B (Jeffers et al. 1963). These authors did not find any motion of B around A, and concluded that these stars do not form a physical pair. Eggen (1975) also mentioned that HR 5999 has a faint companion, and Thé et al. (1981, Paper V) expect that this companion is of spectral type K or M, since there are a number of T Tauri stars embedded in the same cloud as HR 5999 and HR 6000. More recently the pair Rossiter 3930 A and B has been studied by Stecklum et al. (1995) in the near infrared. They conclude that this system is indeed not forming a physical pair. The contribution of the flux of Rossiter 3930 B in the visual region, as estimated by Thé et al. (Paper V), is very small. Because in the investigation of the IR extinction law the near-infrared fluxes are not employed, the star Rossiter 3930 B will not play a rôle. For the same reason, in the study of the UV extinction law this star will also not be a disturbance.

3.2. The UV-visual-IR extinction law

A method for the determination of the extinction law from UV to optical wavelengths has been explained by Steenman & Thé (1989). This method, named the Kurucz-model fitting procedure, was used to determine the extinction laws towards the stars HR 5999 and HR 6000. For the A_λ/A_V data needed in this method, we have used the calculated values by Steenman & Thé (1991) based on the enlargement of the lower size cutoff of the size distribution of the dust grains. It is important to note that the calculations of Steenman & Thé (1989, 1991) were made without scattering.

Employing the data in Table 3 and the adoption of $T_{\rm eff}$ = 14,000 K, log g = 4.0 and $E(B-V) = 0\stackrel{\rm m}{.}08$, we have determined, employing the Kurucz-model fitting procedure, an extinction law with R_V = 3.1 for HR 6000. The result is shown in Fig. 4. From this result we conclude that the extinction law of the matter in the dark cloud, where the stars HR 6000 and HR 5999 are embedded, is normal in the UV-visual-IR spectral region. Furthermore, we can also conclude that HR 6000 is not surrounded by an extended dusty atmosphere, which allows the use of the extinction calculations of Steenman & Thé (1989, 1991).

We have applied the same method to the star HR 5999 at three different brightness levels, corresponding to the V (FES) magnitudes as mentioned in Sect. 2.1. The data in Table 2 were used, together with the adopted $T_{\rm eff}$ = 7,800 K and log g = 3.5,

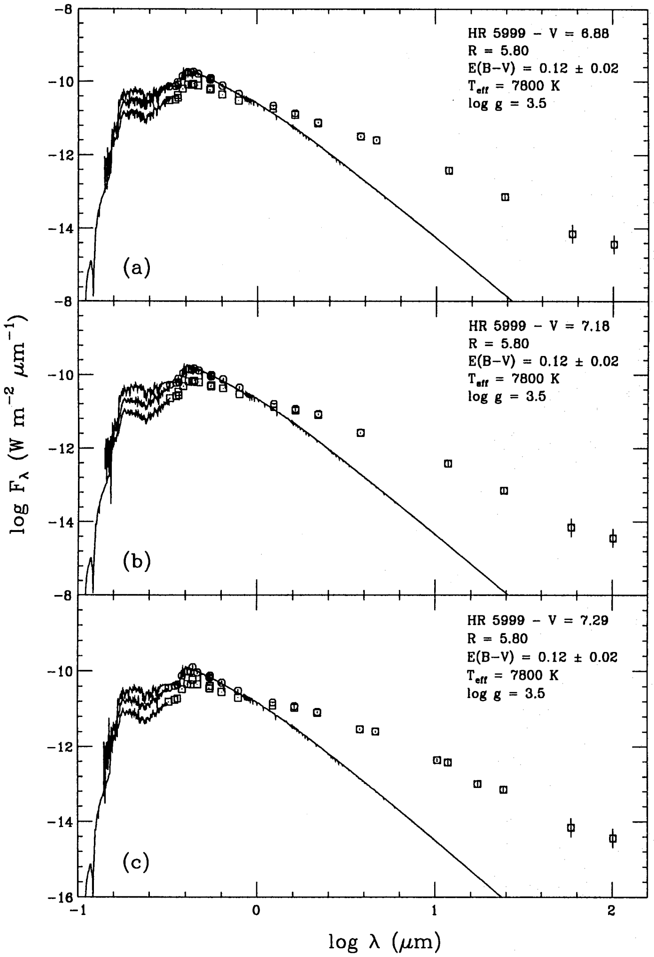

Fig. 5a–c. Observed (squares) and extinction-corrected (circles) spectral energy distributions of HR 5999 at different V (FES) values, compared to the Kurucz model of $T_{\rm eff}$ = 7,800 K, $\log g$ = 3.5 and solar abundance. **a** V (FES) = $6^{\rm m}.88$, **b** V (FES) = $7^{\rm m}.18$, **c** V (FES) = $7^{\rm m}.29$

corresponding to the stars' spectral type and $E(B-V) = 0^{\rm m}.12$. This value is the difference of the $E(B-V) = 0^{\rm m}.20$ for HR 5999 and $E(B-V) = 0^{\rm m}.08$ for HR 6000. Therefore, it applies only to the circumstellar matter around HR 5999, such as is also explained in the Introduction. The results are displayed in Fig. 5. The curves a, b and c in this figure are those for V (FES) = $6^{\rm m}.88$, $7^{\rm m}.18$ and $7^{\rm m}.29$, respectively. From the poor fit of the UV data to the Kurucz (1991) model, it is clear that for these V (FES) values the extinction laws are characterized by a larger value of R_V than the maximum value tabulated by Steenman & Thé (1991), $R_V = 5.8$. It is also possible that the far-UV extinction law shows different anomalies than those covered by the grid of anomalous extinction laws by Steenman & Thé.

3.3. The ultraviolet extinction law

We study the UV extinction law using comparison fluxes from an atmospheric model such as that of Kurucz (1991). The merits of using this method with respect to the pair-method have recently been discussed by Boggs & Böhm-Vitense (1989); they will not be addressed here.

For the calculation of the UV extinction curves with respect to an atmospheric model, we implemented the following equations:

$$E(\lambda - 2860) = (m_\lambda - m_{2860}) - (m_\lambda - m_{2860})_{\rm model}, \tag{1}$$

which is equivalent to,

$$E(\lambda - 2860) = 2.5 \log\left(\frac{F_{\lambda\ \rm mod.}}{F_\lambda}\right) - 2.5 \log\left(\frac{F_{2860\ \rm mod.}}{F_{2860}}\right). \tag{2}$$

It should be explained here that the extinction laws in the UV spectral region are better determined by scaling them with reference to a magnitude in the UV wavelength range itself instead of with respect to V. This will reduce the effects of errors in the optical photometry and mismatch errors. Following Boggs & Böhm-Vitense (1989) we have normalized the extinction curve at 2860 Å instead of at V, which is indicated in Eqs. (1) and (2). Before computing Eq. (2) for the different IUE spectra, a number of obvious emission lines were removed manually from the spectral data, since these are also not present in the comparison spectra. After computing Eq. (2), a smoothing filter was applied to the resulting extinction curve in order to increase its photometric significance.

In the extinction curves based on the comparison with Kurucz model fluxes, we used the same $T_{\rm eff}$ and $\log g$ values for HR 5999 and HR 6000 as adopted in Sect. 3.2. The resulting extinction laws in the UV wavelength range, based on the comparison with Kurucz model fluxes, are presented in Figs. 6a, b and c for HR 5999, for the different V (FES) magnitudes, and in Fig. 7 for HR 6000. Note that in order to stress that the R-values derived from these figures apply only to the ultraviolet region we will indicate them as $R_V^{\rm UV}$. The determination of the $R_V^{\rm UV}$ values for HR 5999 was obtained by graphically fitting the different R_V-values as they were calculated by Steenman & Thé (1991) based on enlarging the lower size cutoff of the size distribution of the dust grains. As is indicated in Figs. 6a, b and c, the R-values become larger for fainter V (FES) magnitudes. They range between $R_V^{\rm UV} = 3.3$ and 3.9. The result for HR 6000 is $R_V^{\rm UV} = 3.1$

It is also possible to study the UV extinction law towards HR 5999 and HR 6000 by comparison with a star of similar spectral type and very low extinction (small E(B-V)); this method is commonly known as the "pair method". The comparison stars can be found in the UV spectral spectral atlas of Wu et al. (1983). For HR 5999 the star HD 76644 (A7 IV), $V = 3^{\rm m}.19$ and $E(B-V) = 0.00$ and for HR 6000 the star HD 90994 (B6 V, $V = 5^{\rm m}.07$ and $E(B-V) = 0^{\rm m}.01$) were found to be suitable. The results obtained by the pair-method for both stars are very similar to those using the Kurucz comparison fluxes as displayed in Figs. 6 and 7; therefore, they will not be shown here.

4. Modelling of the circumstellar extinction

In this section we will show the results of the theoretical modelling of the circumstellar extinction of HR 5999, by use of the

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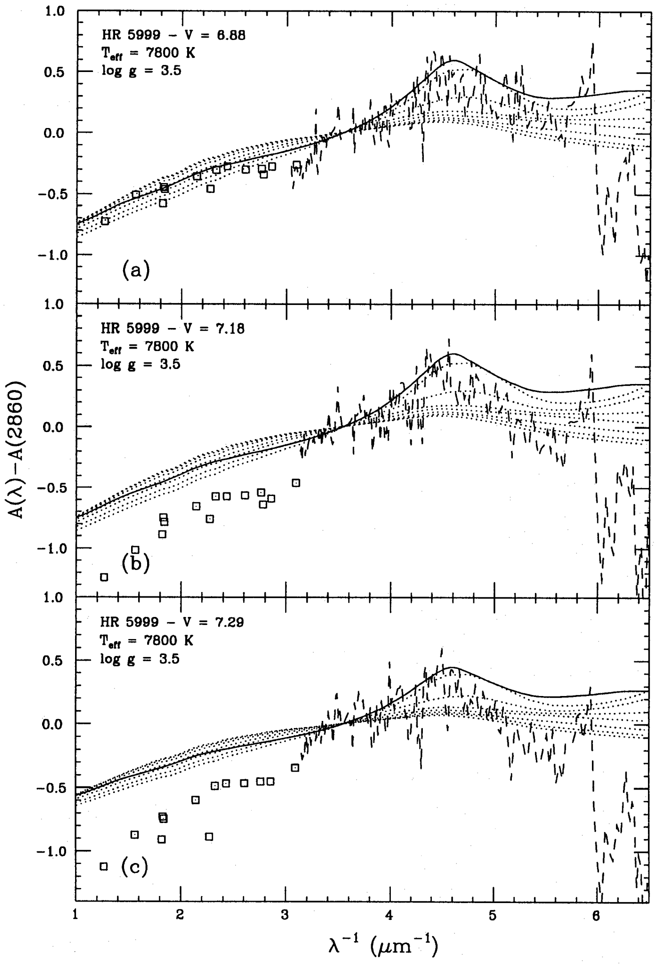

Fig. 6a–c. UV extinction curves of HR 5999 at different V (FES) using the Kurucz model of $T_{\rm eff}$ = 7,800 K, $\log g$ = 3.5 and solar abundance. The solid curve is the average normal extinction law taken from Savage & Mathis (1979). The different dotted curves, corresponding to R_V-values from 3.1 to 4.0, are from Steenman & Thé (1991). **a** V (FES) = $6\overset{\rm m}{.}88$, **b** V (FES) = $7\overset{\rm m}{.}18$, **c** V (FES) = $7\overset{\rm m}{.}29$

Monte Carlo method for multiple scattering, applied to its whole spectral region.

4.1. The model and its parameters

In our calculations of circumstellar extinction employing the multiple scattering model, we used a numerical code based on the Monte Carlo method. It allows us to estimate at the same time the polarized radiation escaping from a spheroidal circumstellar shell in which a star is lying in its center (see Voshchinnikov & Karjukin 1994 for details). The circumstellar extinction can be determined in the following way

$$A^{\rm cs}(\lambda) = -2.5\log\frac{I(\lambda)}{I_*(\lambda)} = -2.5\log\left[e^{-\tau_i^{\rm ext}(\lambda)-\tau_{\rm clump}^{\rm ext}(\lambda)}+\frac{I_{\rm sca}(\lambda)}{I_*(\lambda)}\right], \qquad (3)$$

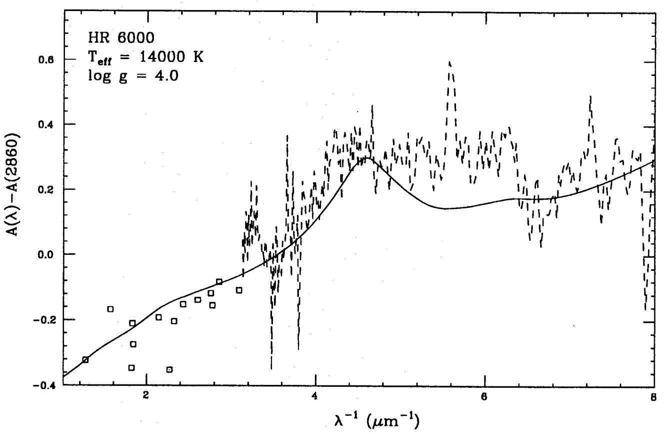

Fig. 7. The UV extinction law of HR 6000, using the Kurucz model of $T_{\rm eff}$ = 14,000 K, $\log g$ = 4.0 and solar abundance.The solid curve is the average normal extinction law taken from Savage & Mathis (1979)

where $I(\lambda)$ is the radiation intensity from the star with the shell. It is the sum of the stellar brightness [$I_*(\lambda)$] obscured by dust in the line of sight (in the shell and circumstellar clumps) and the scattered radiation [$I_{\rm sca}(\lambda)$].

The orientation of the oblate spheroidal shell with the aspect ratio A/B is defined by the viewing angle i changing from 0° (pole-on) to 90° (edge-on). Note that our model also allows to consider inhomogeneous shells with a central spherical cavity free of dust.

It is assumed that the shell contains a silicate-graphite mixture of spherical grains. The mixture parameters are: the minimum (a_-) and the maximum (a_+) radii of the particles, the index q of the power-law size distribution, and the ratio of the number densities of silicate and graphite grains $n_{\rm Si}/n_{\rm C}$.

A comprehensive study of the circumstellar extinction around pre-main-sequence stars was made by Voshchinnikov et al. (1996). In particular, they have shown that the best way to present circumstellar extinction curves is in forming the difference between the extinctions at two wavelengths, for instance $A(\lambda) - A(0.3\,\mu{\rm m})$. In this way it is possible to avoid the very peculiar extinction curves obtained in the standard normalization, because of the large amount of the scattered radiation in the visible wavelength region. We have used this recommendation in our modelling of the circumstellar extinction of HR 5999.

4.2. The theoretical extinction law

Voshchinnikov et al. (1996) formulated some criteria for preliminary estimating the dust shell parameters from observations. Using them, we can choose the orientation of the dust shell around HR 5999 close to edge-on. It is indicated by the large rotational velocity, the double-peaked H_α profile and the occurrence of deep minima accompanying the blueing effect. The intrinsic variable polarization provides the evidence of the non-sphericity of the visible shape of the shell, whereas the flat extinction in the UV tells us about the absence of very small grains. The 10 μm silicate feature seen in emission (from unpublished

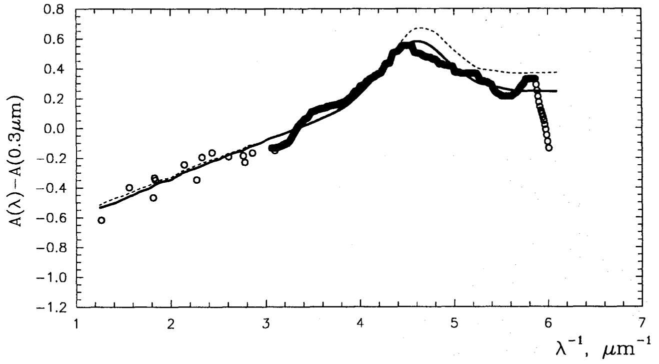

Fig. 8. Wavelength dependence of normalized circumstellar extinction of HR 5999 at V (FES) = $6\overset{\mathrm{m}}{.}88$. The solid and dashed curves represent the model calculations with parameters from Table 4 and for the standard MRN mixture, respectively

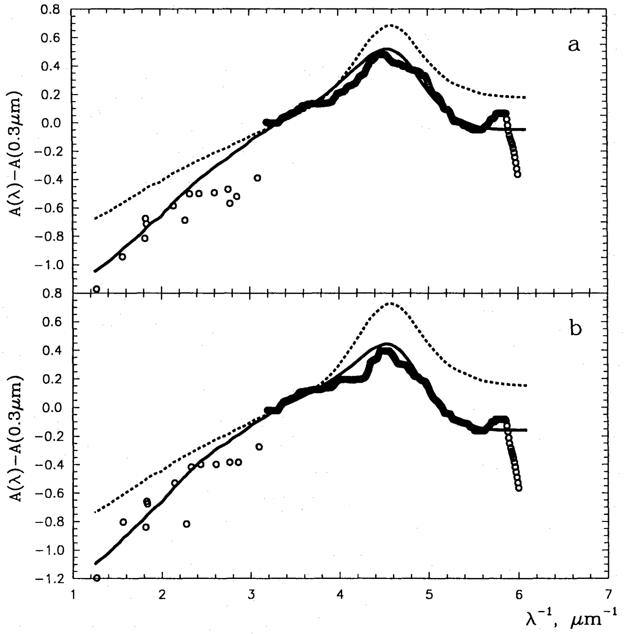

Fig. 9a and b. Wavelength dependence of normalized circumstellar extinction of HR 5999 **a** V (FES) = $7\overset{\mathrm{m}}{.}18$, **b** V (FES) = $7\overset{\mathrm{m}}{.}29$. The solid curves represent the model calculations with clump parameters from the last two columns of Table 4. The dashed curves show the model with the same grains in the shell and clumps

Table 4. Model parameters of dust shell around HR 5999

Parameter	Shell (V=$6\overset{\mathrm{m}}{.}88$)	Clump (V=$7\overset{\mathrm{m}}{.}18$)	Clump (V=$7\overset{\mathrm{m}}{.}29$)
a_-, μm	0.01	0.09	0.095
a_+, μm	0.25	0.13	0.13
q	3.6	3.4	3.6
$n_{\rm Si}/n_{\rm C}$	0.75	6.0	6.0
A/B	1.5		
i	90°		
$\tau_{90}^{\rm ext}(0.55\ \mu{\rm m})$	0.60	0.90	1.01
$A^{\rm cs}(V)$	$0\overset{\mathrm{m}}{.}39$	$0\overset{\mathrm{m}}{.}64$	$0\overset{\mathrm{m}}{.}74$
$E^{\rm cs}(B-V)$	0.12	0.26	0.30
$R_V^{\rm cs}$	3.2	2.5	2.5

observations), can apparently be considered as a weak indication that the opacity of the circumstellar shell is moderate.

In our theoretical modelling we assume that when V (FES) = $6\overset{\mathrm{m}}{.}88$ we are dealing with the circumstellar shell without disturbance by clumps of dust. For the other V (FES) values the brightness of HR 5999 is dimmed by dust clumps. The normalized extinction curve for V (FES) = $6\overset{\mathrm{m}}{.}88$ and the theoretical curve are plotted in Fig. 8. The model parameters for the solid curve are given in the second column of Table 4. They show that the shell is optically not very thick ($\tau_{90}^{\rm ext}(0.16\ \mu{\rm m}) < 1.5$) and its shape is close to spherical. The dashed curve shown in Fig. 8 is drawn for standard MRN mixture ($a_- = 0.005\mu$m, $a_+ = 0.25\mu$m, $q = 3.5$, $n_{\rm Si}/n_{\rm C} = 1.07$). The shell parameters are the same as indicated in Table 4. In this case, the coincidence of theory with observations is not so good in the UV. Note that the changes of shell shape and viewing angle are firstly important for polarization and do not have strong influence on the circumstellar extinction (see Voshchinnikov et al. 1996 for details).

The values obtained as result of the calculations are given in the last three rows of Table 4. The difference between the model parameter $\tau_{90}^{\rm ext}(0.55\ \mu{\rm m})$ and the value of the circumstellar extinction $A^{\rm cs}$ is due to the presence of scattered radiation, which in this case is quite important. Our calculations were made for a homogeneous shell with an internal cavity parameter $r_0/B = 0.1$. As was shown by Voshchinnikov et al. (1996), the normalized extinction of shells seen edge-on are almost independent of the inhomogeneity parameters. However, they are influencing the circumstellar polarization.

Fig. 9 shows the wavelength dependence of the extinction for V (FES) = $7\overset{\mathrm{m}}{.}18$ and $7\overset{\mathrm{m}}{.}29$. The theoretical extinction curves are obtained for the shell model using the same parameters as in Fig. 8. However, the additional extinction from the circumstellar clumps occulting the star is included. Such a model of variable circumstellar extinction was developed for the explanation of the behaviour of colours and polarization in deep minima of HAeBe stars (see Voshchinnikov 1989 for details). Note also that the variable extinction can explain the variability of the emission lines in the spectra of HAeBe stars (Grinin & Tambovtseva 1995).

It is for the first time that this model is applied to observations from the UV to the near-infrared (about 1 μm). The extinction corresponding to the brightness variation in the V passband is added in the first term of Eq. (3). The dashed curves in Fig. 9 are plotted for the case when the same grains are both in the shell and in the clouds. Evidently, it shows a large discordance with the observations. The solid curves show the model calculated for a quite narrow size distribution, in which the particles with

$a < 0.09$ μm are absent. The parameters of this dust mixture are given in the last column of Table 4.

From Table 4 we can conclude that the circumstellar extinction law in the UV of the star HR 5999 range from R_V^{cs} = 2.5 to 3.2. This is qualitatively in agreement with the values obtained in Sect. 3.3 for the ultraviolet extinction law R_V^{UV}.

4.3. Polarization

The results of polarimetric observations of HR 5999 and HR 6000 were published by Bessel & Eggen (1972), Thé et al. (1981, Paper V) and Hutchinson et al. (1994). For HR 6000, the degree of polarization shows very small variations and the positional angle is constant. The wavelength dependence of the polarization looks like that of the interstellar one, and can thus be used to correct the observational data of HR 5999 for interstellar and circumcloud effects.

The polarization of HR 5999 is variable both in magnitude and positional angle, and anticorrelates with the stellar brightness. Unfortunately, the polarimetric observations of Bessel & Eggen (1972) and Thé et al. (1981, Paper V) were made very much earlier than the IUE spectra. For our very rough estimates we used two observations made by Hutchinson et al. (1994) in 1987 when the brightness of HR 5999 was $V = 6\overset{m}{.}84$. After subtraction of the polarization of HR 6000, we obtain $P(B) \approx 0.48\%$ and $P(I_c) \approx 0.57\%$. The results of our calculations for the model defined in Table 4 are $P(B) \approx 0.45\%$ and $P(I_c) \approx 0.46\%$. It is surprising that the coincidence of the theoretical results with the observations is quite good despite of the strong dependence of polarization on the brightness level (Voshchinnikov 1989). Note also that the non-simultaneous observations of extinction and polarization, as well as of the IUE images, which are separated by 8 years, leave the possibility open that some variations may be attributed to the changes of the dust shell characteristics, caused by the dissipation of dust grains or the injection of them during the destruction of circumstellar clouds.

5. Depletion of small grains

In general our results sofar show that the circumstellar extinction law of HR 5999 is anomalous. It can be explained by assuming that the average size distribution of the dust grains causing the extinction of the light of the central star is larger than normal. This abnormality is due to the depletion of small grains (< 0.01 μm), which in the UV have a stronger influence than when the grains are oversized. Typical characteristics of the UV extinction law towards HR 5999 is that at the 2200 Å wavelength region and the far-UV the extinction is lower than normal. This is due to the fact that the small graphite and silicate grains, are depleted (Steenman & Thé 1991). The question can be asked now, what are the physical causes of this depletion?

The depletion of small dust grains can be caused a) by the sweeping effect of the radiation of the central star such as discussed extensively by Voshchinnikov & Il'in (1983) and b) by selective evaporation of the mantles of small grains as proposed by Herbst (1976).

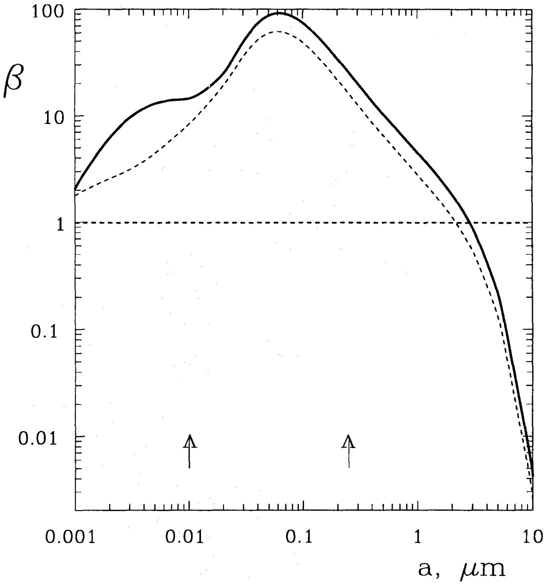

Fig. 10. The sweeping efficiency for graphite (solid curve) and silicate (dashed curve) grains in the shell of the star HR 5999. The arrows show the lower and upper cutoffs of the dust distribution (from Table 4) employed in our calculations.

Voshchinnikov & Il'in (1983) have calculated the *sweeping efficiency*

$$\beta = F_{pr}/F_g, \quad (4)$$

i.e. the ratio of radiation pressure force and the attractive force of gravitation, for spherical and cylindrical grains, for different types of material (graphite, iron, ice, obsidian, basalt and SiC) and for 5 different types of stars (C6 III, M5 III, G2 V, B5 V and O5 V). It is of interest to discuss the sweeping efficiency for the dust grains in the circumstellar region of HR 5999 (T_{eff} = 7,800 K; Sp.T. A5–7 III–IVe). For this purpose we have calculated the sweeping efficiency β for HR 5999. The result is shown in Fig. 10, in which β is plotted against the grain size. From this figure it follows that $\beta > 1$ for grains with radii $a \lesssim 2\mu$m. This means that the submicron particles must be blown away from the shell during the lifetime of the star. However, the *charged* particles may survive for quite a long time in a shell possessing a regular (toroidal) magnetic field.

Furthermore, it should be noted that small grains of size < 0.03 μm are usually uncharged, so that magnetic fields have no influence on them. For this reason the sweeping effect of the radiation field of the central star will not be hampered by the presence of magnetic fields (Il'in & Voshchinnikov 1993). For HR 5999 with T_{eff} = 7,800 K, we can thus draw the conclusion that the small dust particles (with radius smaller than 0.01 μm) in the regions at the boundary of its circumstellar disk are depleted, due to the sweeping effect of the radiation of the central star.

The effect of *evaporation* of the small dust grains will now be discussed. In his study of the evaporation of grains in H II regions due to the intense radiation field from O-type stars, Herbst (1976) employs the general formula for the evaporation time scale:

$$\tau_{\rm evap} \;=\; 3\,\nu_o^{-1}\;\exp(D/T)\;\ln(a/a_c) \qquad (5)$$

in which ν_o is the vibrational frequency of the atoms perpendicular to the grain surface, D is the temperature equivalent of the adsorption energy, T is the grain temperature, whereas a and a_c are the initial radius and some core radius of the dust grains, respectively. Since in our case we are interested in the time scale for the depletion of small grains, with sizes smaller than 1 μm, we can take for example $a = 0.01$ μm and $a_c = 0.001$ μm, so that $\ln(a/a_c)$ is about 2.5. In HAeBe circumstellar environments the grain temperature T is about 1500 K. If we assume, following Herbst, that $D \approx 5500$, then $\exp(D/T)$ is about 55. Since the vibrational frequency is 10^{12} s^{-1}, we can calculate that the evaporation time scale for our case is $\tau_{\rm evap} = 4 \times 10^{14}$ sec, which is about 12×10^6 yr. Since HAeBe stars are an order of magnitude younger, we believe that the effect of evaporation on small dust grains is not enough to deplete these grains in the circumstellar disk markedly. We can therefore draw the conclusion that the depletion of small grains in the circumstellar disks of HAeBe stars can be explained by the sweeping effect of the radiation field of the central star.

6. Conclusions

The common proper motion stars HR 5999 and HR 6000, also known as the visual double star system Δ199, are embedded in a dark cloud belong to a star forming region characterized by the presence of young T Tauri stars. Since the colour excess $E(B-V)$ of HR 6000 is quite low, we believe that the system is not severely embedded in the cloud. The larger value of $E(B-V)$ for HR 5999 is due to extra reddening by its circumstellar matter. From our study of the extinction law towards HR 6000, a non-variable star, which has only a very small excess of near infrared radiation, probably due to a T Tauri companion (van den Ancker et al. 1996), it is apparent that the extinction properties of the dark cloud are normal. The anomalous extinction found towards HR 5999 must then be caused by the circumstellar dust grains located in the shell and clumps of this star.

From our study of the extinction law in the circumstellar environment of HR 5999, based on the extinction calculations by Steenman & Thé (1991), we found that in the whole UV-visual-IR spectral region the R_V value is >5.8. In the UV alone, however, the extinction law is less anomalous; it is determined by $R_V^{\rm UV}$ values ranging from 3.3 to 3.9. The extinction over the whole spectral region, has also been investigated using the theoretical multiple scattering model of Voshchinnikov et al. (1996) based on the Monte Carlo method. In this investigation we have assumed that in the case when the star is at maximum brightness, the circumstellar shell is not disturbed by dust clumps. We have found that the shell is almost spherically symmetric, and is oriented edge-on relative to the line of sight. The derived $R_V^{\rm cs}$ value is 3.2 (see last row in Table 4). At lower brightness the light of the star is disturbed by the appearance of dust clumps in the line of sight. In this case we found that the $R_V^{\rm cs}$ value can range between 2.5 to 3.2, given in the last row of Table 4. They correspond to a lower size cut-off of approximately 0.09 μm.

Evidently, the anomaly in the extinction, derived using the Monte Carlo method and the one employing the non-scattering model in the UV alone, do not differ very much. However, it differs markedly from the results with the non-scattering model applied to the whole UV-visual-IR spectral region. This discrepancy is most probably caused by the fact that in the last mentioned model the influence of scattering is ignored. It seems that the only correct way to determine the extinction law towards stars surrounded by dust shells is by taking into account the scattered radiation.

The theoretical Monte Carlo method tells us more than the classical extinction model. The parameters found in this method are listed in Table 4. For instance, the calculations of the polarization properties of the dust grains in the circumstellar environment of HR 5999 shows, that they are in good agreement with the observed ones. This result give us confidence of the correctness of the Monte Carlo calculations.

As to the depletion of small grains in the circumstellar disks of HAeBe stars, we have shown that it is mainly due to the sweeping effect of the radiation field of the central star.

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