THE VARIABLE SHELL STAR HR 5999

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From spectroscopic observations Bessell and Eggen (1972) (hereafter called BE) have detected that HR 5999 (erroneously named HR 6000 by BE) is a shell star of spectral type A7 III-IV with hydrogen lines in emission. Photometric observations show subsequently that HR 5999 varies in brightness up to about 1 mag semiregularly with a period of about 1 month. Eggen (1975) believes that HR 5999 forms a pre-main sequence object.

With HR 6000, the star HR 5999 forms a visual double star system named Δ199; HR 5999 is the southern component. The angular separation is about 45". BE show that these stars have a common proper motion, and are, therefore, believed to form a physical pair.

Thé (1962) found 10 faint Hα-emission stars in the immediate surroundings of this double star system. Up till now only 1 star has been observed to be variable. The others are too faint to be observed well enough. It is, however, quite certain that these faint Hα-emission objects are all T Tauri stars, forming a very compact T association surrounding Δ199. This believe is especially strengthened by the fact that the whole system of Δ199 and the T association is seen at the centre of a very dark butterfly shaped nebula. Furthermore, as can be seen on Fig. 15 of Eggen's (1975) paper, a reflection nebulosity is located in the immediate environment of Δ199. The coordinates of the binary system are: R.A. = 16^h07^m; Dec. = $-39\overset{\circ}{.}0$ (1975).

BE found HR 6000 to be an Ap-type star. Recently, at the E.S.O., La Silla (Chile), Van den Heuvel obtained two Spectra of this star, and confirms BE's finding. The fact that an Ap-type star appears to be associated with a very young T association, and forms a binary system with a very young pre-main sequence star, is remarkable, and should, therefore, deserve more attention.

In this paper we will present the results of the analysis of our observations on the Walraven VBLUW system of the variable pre-main sequence shell star HR 5999. For further information about the Walraven system the following papers can be consulted; Walraven and Walraven (1960), Rijf et al. (1969) and Lub and Pel (1977). The observations were carried out in 1976 with the Walraven photometer attached to the 90 cm lightcollector of the Leiden Southern Station at Hartbeespoortdam (South Africa).

In Fig. 1 the light and colour curves of HR 5999 are shown. It should be mentioned here that V_w and the colour-indices on the Walraven system are given as logarithm's to the base 10 of the visual intensity and relevant intensity ratio's, respectively. The index w stands for Walraven. From Fig. 1 it is clear that the

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visual light intensity varies about one magnitude within approximately one month time. BE found also about the same period. The colour indices show that HR 5999 becomes slightly redder when it is fainter.

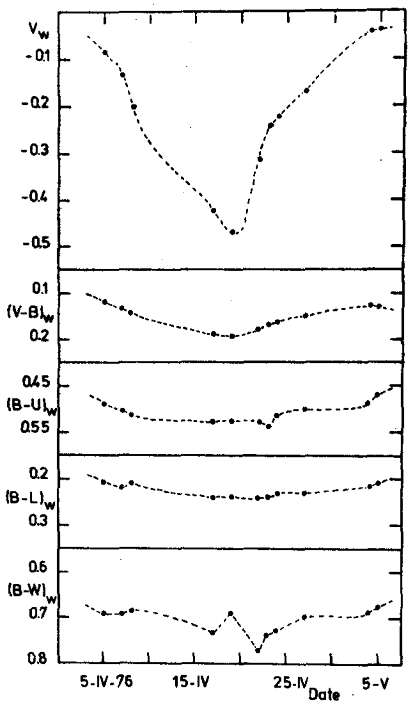

Fig. 1. The lightcurve and colour curves of the variable shell star HR 5999. The values of V_w and the colour indices are given as logarithms to the base 10 of the visual intensity and intensity ratio's, respectively.

In Fig. 2 the colour indices $(B-U)_w$, $(B-W)_w$ and $(B-L)_w$, and the visual intensity V_w are plotted against $(V-B)_w$. The Ap star HR 6000 is located close to the unreddened two-colour curves. By shifting it back along the reddening lines to these two-colour curves, we can obtain the colour excess due to the foreground interstellar medium, $E(V-B)_w = 0.025$, and the intrinsic colours of this star. Using the known relation $A_{V,W} = 3.2\ E(V-B)_w$ for the interstellar medium we can calculate the distance of the binary system Δ199 to be about 270 pc. BE found a distance of 300 pc but admit that it can be somewhat too large. We shall adopt for Δ199 a distance of 270 pc.

We shall turn our attention now to HR 5999. It is clear that the change of

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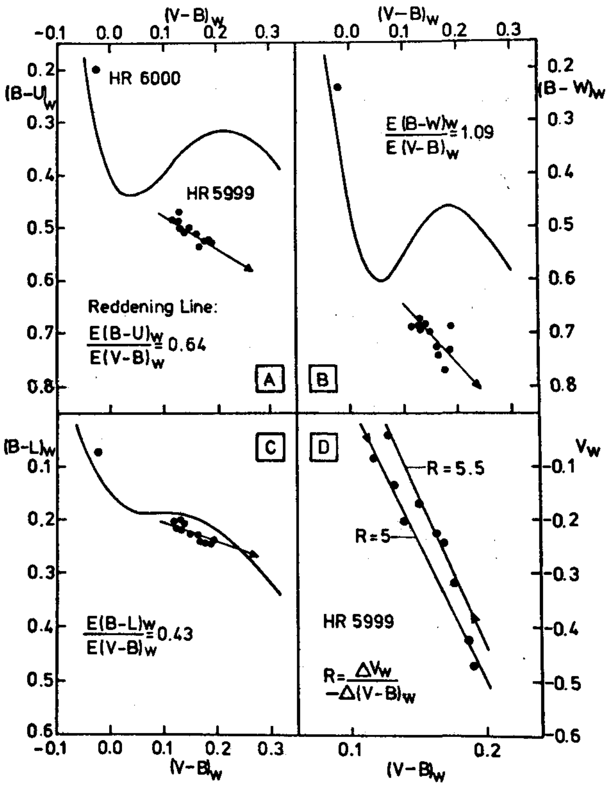

Fig. 2. The change of different colour indices and V_w as function of $(V-B)_w$. The R values in Fig. D give the ratio's of total to selective absorption.

colour indices, when the star changes in brightness, is always along the reddening lines. This means that most probably the change in brightness is due to dust grains in the immediate surrounding of the star, in its shell. This confirms what has been found by BE. Furthermore, from Fig. 2D we can derive that the ratio of total to selective absorption (R) is not like that for the interstellar medium; R is about 5 when the star becomes fainter, and changes to approximately 5.5 when it brightens up again. From this fact we can conclude that the physical characteristics of the dust grains in the shell are different from those of the interstellar medium. It should be mentioned here that BE do not find above mentioned anomalous value of R, because the scatter in their V_j versus $(B-V)_j$ curve (the index j stands for Johnson) is very large (see Fig. 4 in their paper).

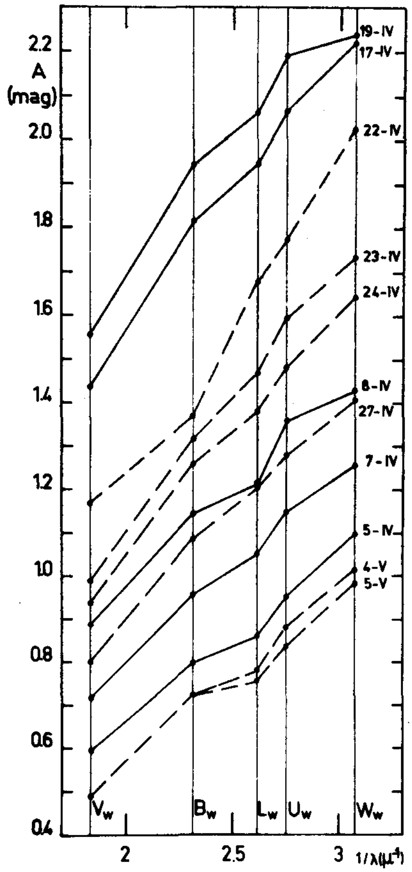

Fig. 3. The extinction (expressed in magnitudes) due only to the dust grains in the circumstellar shell of HR 5999 plotted as function of 1/λ. The dates (in 1976) on which the star was observed are given to the right of the curves. The full drawn curves give subsequently the extinction laws when the star becomes fainter, and the dashed curves when it brightens up again. The slope of these curves changes from a value of 0.4 when the star is bright, to 0.8 when the star is at its light minimum.

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The knowledge of the value of R for the circumstellar shell is important for the derivation of the total amount of extinction due only to the dust grains in the shell. We have derived this extinction (in magnitudes) for the different Walraven effective wavelengths. The results are then plotted as function of $1/\lambda_{eff}$ in order to have some idea about the behaviour of the extinction law in the the circumstellar shell, during the change of brightness of HR 5999. Fig. 3 depicts the extinction law curves for different dates of measurements. It is clear that the curves are not only shifted to larger extinction, but that the direction coefficients change along with this shift from approximately 0.4 to 0.8. It is of interest to mention that the direction coefficient for the extinction law of the circumstellar shell indicate that during the brightness variation of the star the physical conditions of the dust grains in the shell (spatial density, size, albedo, temperature and chemical composition) are perhaps changing also. Recently, Dr. Smyth of the Royal Observatory of Edinburgh, told me that he had made several observations of HR 5999 in the infrared up to about 3 μm. He found quite a large infrared excess (of the order of 2 mag) for this star. This indicates that the energy of the star absorbed by the dust grains, for a large part, is re-emitted as heat in the infrared. It is of interest to make a thorough study of this star in the infrared (if possible simultaneously with observations in other wavelength regions) in order to know whether it exhibits a variation of brightness in the infrared, and if so, how large this variation is, and whether it is coupled with the change of brightness in other wavelengths. Combined spectral and photometric observations of this star will also be very useful in making a model of the dusty gas shell of HR 5999, and in understanding the brightness variation of this star.

One more important observational fact, found by BE, is that the percentage polarisation of HR 5999 varies from 0.34 to 1.13 and the position angle from 20^{o} to 150^{o} along with the change in brightness. This indicates again that the dust grains in the circumstellar shell undergo physical changes during the brightness variation of the star.

Because the distance of the binary system is known, and the total absorption due to interstellar and circumstellar dust particles can be calculated it is possible to determine the absolute visual magnitude (M_V), to estimate the absolute bolometric magnitude (M_{bol}) and to derive an effective temperature of HR 5999. We have found: $M_{V,j} \approx -0.9$, $M_{bol} \approx -0.92$ and $T_{eff} \approx 8500$ ^{o}K. In terms of Larson's (1972) theory of stellar pre-main sequence evolution the star itself is called the stellar core or protostar. From the data obtained, we can first of all notice that in the Hertzsprung-Russel diagram the protostar is located about 3^{m} above the main sequence; being associated with a young T Tauri group it must then be a pre-main sequence object. It is of interest, therefore, to understand the state of evolution of the protostar. The best fit to Larson's (1972) evolutionary tracks can be found in his Fig.6, for a protostar of 3 $M_{\odot}$ with a radius of 7 $R_{\odot}$. The initial temperature and density of the interstellar cloud are, for this case, 10 °K and 10^{-20} g.cm^{-3}, respectively. At this stage the age of the protostar is around 7 x 10^5 years; this is not in contradiction with the probable age of the surrounding T association. According to Larson the protostar is then still in the stage of growth by accretion of infalling material of the cloud. (The free fall time of the model and initial conditions such as mentioned above is about 6 x 10^5 years). In fact the envelope is still opaque to the protostellar radiation, and thus it should not be possible to observe the protostar. For the explanation of the visibility of the core, Larson has suggested that for protostars more massive than about 3 $M_\odot$ the infall of matter onto the star will eventually be halted and reversed by radiation pressure. In this way most of the matter in the envelope can be dissipated and the star brightens up in a time scale of about one year. In the case of HR 5999 apparently not all of the matter in the envelope was blown away; it is partly remaining as a dusty shell around the star, causing its variability in light intensity.

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D I S C U S S I O N of the paper by THÉ and TJIN A DJIE:

DE LOORE: I have a question about the Ap star. Is it really not variable? Because it is a Si-star! Normally all these silicon stars show large variations in brightness. Should it have perhaps a very long period?

THÉ: From our observations we have not found any variation of brightness of the Ap star. In the papers by Bessell and Eggen (1972) and Eggen (1975) no variation in brightness of this star has been reported. Whether it should perhaps vary in brightness with a very long period, we do not know. More observations are needed to answer your question.

FRIEDJUNG: Is this an emission line star? How do you know that the colour variations are not due to the emission lines?

THÉ: Yes, it is an emission line object. The effect of the lines would be small. The strong emission in Hβ and Hα does not disturb the photometry, because Hβ is lying at a wavelength

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where the sensitivity of the Walraven photometer is more or less zero, and Hα is completely outside the V_W-passband.

DEAN: Dr. M. Smyth and I have found a 2 magnitude IR excess at 3.4μ for HR 5999. This may be due to a dust cloud radiating thermally at 1400K.

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