Observational aspects of Herbig Ae/Be stars and of candidate young A/B stars

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A possible T Tauri companion to the long-term photometric variable HR 6000

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Abstract. — From Strömgren uvby photometry, obtained during the last 14 years, we demonstrate that HR 6000 shows long-term photometric variations with a small (about 0.03 in u, 0.02 in v and 0.01 in b) amplitude. Whereas previous authors classified HR 6000 spectroscopically as A0/3 IIIp and photometrically as B7, we conclude that the observed properties of this system may be explained by inferring that HR 6000 is in fact a binary system, consisting of a B6 V star and a T Tauri companion. The combined spectrum of these two components may easily have been mistaken for a chemically peculiar early A-type star. This scenario also explains the observed small amount of infrared excess and the observed ROSAT X-ray flux of this system as arising from a T Tauri companion. Other tracers of this companion have not been detected in our studies. Detection of the T Tauri companion with near-IR spectroscopy may be possible due to the significant contribution of the companion to the total flux at these wavelengths.

1. Introduction

The peculiar A-type star HR 6000, together with the well-known Herbig Ae star HR 5999 forming the common proper motion binary system Dunlop 199, might very well be one of the most misidentified objects in the southern hemisphere. Numerous papers in the literature confuse HR 6000 for HR 5999. HR 5999, a well known photometrically variable Herbig Ae star, is located approximately 44° south of HR 6000, with about the same right ascension, and, at maximum brightness, about 0°1 fainter than HR 6000. Because of the confusion with HR 5999, HR 6000 was believed to be variable as well, and consequently named V856 Sco. In reality, all photometric data in the literature indicates that the brightness of the star is perfectly constant. Because the Pre-Main Sequence object HR 5999 and many T Tauri stars are located in its vicinity, HR 6000 is generally believed to be a young object itself.

Recent high-resolution techniques in the near infrared resolved the known faint companion of HR 5999, Rossiter 3930 (Stecklem et al. 1995). They reported an effective temperature of 3750 K, a radius of 3.5 R⊙ and a luminosity of 3.9 L⊙ for Rossiter 3930. Because of a common proper motion with HR 5999 and the youth of the latter it is recognized as a T Tauri companion of HR 5999.

From optical spectroscopy, Andersen et al. (1984) concluded that HR 6000 is a single, very slow-rotating (or seen pole-on), 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 stars. Furthermore, the spectral type derived from spectral data, A0/3 III, seems to differ significantly from its spectral type, as derived from optical photometric data, B7 (Eggen 1984).

Without any doubt the most striking feature about HR 6000 is that, according to EXOSAT (Thé et al. 1985) and ROSAT (Zinnecker & Preibisch 1994) observations, HR 6000 seems to be a strong source of X-rays. This is quite unexpected, since from a theoretical point of view mechanisms responsible for the production of X-rays in both earlier and later type stars do not seem to apply for Main-Sequence B6–A5 stars (e.g. Caillault et al. 1994). How these X-rays are generated remains unexplained at the moment.

2. The observations

During the last 14 years, HR 6000 was monitored by the ESO "Long Term Photometry of Variables" (LTPV) group, using the Strömgren Automatic Telescope (SAT; former Danish 50 cm telescope) at La Silla. This telescope is equipped with a simultaneous multicolor photometer on the Strömgren uvby system. Any systematic effects due to non-simultaneous measurements at the different passbands are therefore avoided. Immediately before and after each programme star measurement, two comparison stars (HD 143699 and HD 145191), located close to, and with roughly the same magnitude and colours as HR 6000, were measured to check whether the observed variations are real. Since parts of these observations were already published by Mannford et al. (1991) and by Sterken et al. (1993), and the other part will be published in a forthcoming publication by the ESO LTPV-group, these observations are not listed in this paper.

To achieve the highest accuracy in the corrections for extinction in the earth atmosphere, the measured magnitudes of HR 6000 were corrected, after applying a standard photometric reduction procedure, with the difference between the measured and averaged magnitudes of the comparison stars. The non-variability of the comparison stars was confirmed by comparing the standard deviations in their measurements against those for the other comparison stars in the ESO LTPV-programme. Average errors in the in this way obtained new Strömgren photo-

* Based on observations collected at the European Southern Observatory, La Silla, Chile, and on data collected in the long-term photometry of variables programme at ESO.
Fig. 1. Lightcurve of HR 6000 in the Strömgren u, v, b and y magnitudes. For clarity error bars are not given (but see text).
tometric data are $0^\circ.006$, $0^\circ.004$, and $0^\circ.006$ for $u$, $v$, $b$, and $y$, respectively. The resulting light curve of HR 6000 in the Strömgren $u$, $v$, $b$ and $y$ magnitudes is shown in Fig. 1. A long-term variability in the $u$, $v$ and $b$ magnitudes, with a period larger than the timescale covered by the observations, can be seen in this figure. The amplitude of the variations seems to be approximately $0^\circ.03 \pm 0^\circ.01$ in $u$, $0^\circ.02 \pm 0^\circ.01$ in $v$ and $0^\circ.01 \pm 0^\circ.01$ in $b$.

![Fig. 2. Intermediate-resolution spectrum of HR 6000 in the Hα wavelength range](image)

An intermediate resolution (1.9 Å pix$^{-1}$) spectrum of HR 6000, in the Hα wavelength range, was obtained in March 1991 (JD 2448321.7935) with the ESO 1.52 m telescope at La Silla. The exposure time was 30 seconds. During these observations the telescope was equipped with a Boller & Chivens spectrograph and a 1024 × 640 RCA CCD. The spectrum was reduced using MIDAS running under SUN/OS at ESO Headquarters.

The new spectral data are shown in Fig. 2. As can be seen from this figure, the Hα line profile looks quite similar to that of most main-sequence stars. No obvious anomalies or other strong spectral features can be seen in the wavelength range covered by these observations.

3. Astrophysical Parameters

A new estimate of the photometric spectral type of HR 6000 was made from the $UBV$ photometry by Kilkenny et al. (1985). Using the two-colour diagram ($B-V$)$_0$ versus ($U-B$)$_0$ diagram for Main-Sequence stars (Schmidt-Kaler 1982), we determined the intrinsic colours ($B-V$)$_0$ and ($U-B$)$_0$, assuming a reddening direction of $E(U-B)$/$E(B-V) = 0.72$, corresponding to that of a normal (i.e. $R_V = A_V/E(B-V) = 3.1$) extinction law. From these intrinsic colours we derive the colour excess $E(B-V)$, as well as the spectral type, using the catalogue of Schmidt-Kaler (1982). Since the intrinsic ($B-V$)$_0$ versus ($U-B$)$_0$ two colour diagram for stars of different luminosity classes is nearly identical, for the range of spectral types considered here, this method can not be used to determine the luminosity class. The resulting spectral type is B6, with $E(B-V) = 0^\circ.08 \pm 0^\circ.02$.

An extinction-free spectral energy distribution (SED) of HR 6000 was constructed using the simultaneous $UBV(RI)_C$ and $JHKL$ photometric observations by Kilkenny et al. (1985), the new Strömgren $uvby$ photometry and the Walraven $WULBV$ photometric data by Thé & Tjin A Djie (1978). This photometry was supplemented with ultraviolet data consisting of two IUE low-resolution spectra (LWR 11431 and SWP 14849), taken from the IUE archives. Because HR 6000 is too close to the bright infrared source HR 5999, no IRAS data of HR 6000 are available. To construct the extinction-free SED, the photometric data was dereddened using the normal extinction law of Steenman & Thé (1991). This SED was analyzed by comparing it with a Kurucz (1991) theoretical SED model with $T_{eff} = 14,000$ K, corresponding to the photometric spectral type of B6. In order to get a better comparison between the Kurucz model and the IUE spectral data, the latter were rebinned to the same resolution as the Kurucz models. No satisfactory fit could be obtained with the Kurucz model corresponding to the spectroscopic spectral type of A0-3 III as derived by Castelli et al. (1984, 1985) and Andersen et al. (1984).

The resulting SED is shown in Fig. 3. As can be seen from this figure, the quality of the fit to the Kurucz model is very good in the ultraviolet and the optical wavelength ranges, with a small amount of excess radiation above photospheric levels in the infrared. The presence of free-free emission cannot explain the infrared excess, since this effect will be much smaller than the observed excess, for the stellar temperatures considered here. To produce free-free emission HR 6000 would also need to have an extended atmosphere, in which Balmer emission lines would be formed, in clear contradiction with the spectral data shown in Fig. 2. Furthermore, it seems unlikely that the observed infrared excess is caused by reprocessing of stellar radiation by dust particles, as seen in many Herbig Ae/Be stars, since this infrared excess starts at relatively small wavelengths, corresponding to too high temperatures for dust particles to survive.

The most attractive explanation for the infrared excess might be to infer the existence of a cool (K or M type) companion around HR 6000. In view of the youth of the region in which HR 6000 is located, this companion must be a T Tauri star. To demonstrate that a T Tauri companion can indeed quantitatively reproduce the observed infrared excess of HR 6000 we computed a model for a T Tauri system with a 3,500 K central star and an accretion rate of $2 \times 10^{-7}$ M$_\odot$ yr$^{-1}$ following the prescription of Bertout et al. (1988). This T Tauri model was fitted to the observed infrared excess of HR 6000 and is also shown in Fig. 3. According to this model, the T Tauri star would have a $V$ magnitude of about 13.5, or about 6 magnitudes fainter than the B6 star, and thus will not contribute significantly to the observed visual magnitudes of HR 6000.

In order to obtain the position of HR 6000 in the Hertzsprung-Russell diagram, we computed the stellar luminosity using the following formula:

$$L_\star = 4\pi \int_0^\infty F_\lambda K_{\text{Kurucz}} d\lambda,$$

with $d$ the distance towards the programme star, and $F_\lambda K_{\text{Kurucz}}$ the Kurucz model, fitted to the extinction-corrected SED. If we adopt a distance towards HR 6000 of 140±20 pc, corresponding to that of the Lupus 3 star forming region (Hughes et al. 1993), $L_\star = 110 \pm 20$ L$_\odot$. The resulting HR-diagram, in which the evolutionary tracks and the birthline by Palla & Stahler (1993) are also plotted, is shown in Fig. 4. In the same diagram we also plotted the position of HR 5999 (Pérez et al. 1994), and the
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Position of the T Tauri model fitted to the SED, again computed using Equation (1). In the T Tauri case the determined luminosity includes the accretion luminosity. The horizontal error bar indicates the spread of the possible temperature range of the T Tauri component that was fitted to the SED of HR 6000. This temperature error also yields an uncertainty in the luminosity and is expressed, together with the influence of the one in the distance, in the error bar shown in Fig. 4. The errors in the measurements of the photometry are not significant compared to those mentioned before. In Fig. 4 we see that HR 6000 is located near the zero-age main-sequence in the HR-diagram.

It is also interesting to note that the ages, as derived from the isochrones by Palla & Stahler (1993), of HR 5999 (2 x 10^6 yr), and HR 6000 (> 10^6 yr) are compatible with the assumption that these two objects have been formed at the same time, from the same cloud. Therefore, we conclude that HR 6000 is most probably a B6 V star, physically located in the Lupus 3 star forming region. If we now assume that the T Tauri companions of HR 6000 and HR 5999 have also the same age as their massive counterpart, we can draw a region in Fig. 4 in which they must be located. The boarders of this region are determined by the local isochrones, 1 and 3 x 10^6 yr, and their temperature range. The derived luminosities are just an upper limit of the stellar luminosities as it contains, probably in both cases, an accretion contribution. The temperature range for the HR 6000 T Tauri component is 4,100 - 3,000 K and L_{tot} = 0.8 - 3.5 L_\odot.

In case of the HR 5999's T Tauri component Rossiter 3930, we have adopted T_{eff} = 3,750 K (Stecklum et al. 1995) and L_{tot} = 1.0 - 3.5 L_\odot. This luminosity was calculated using a
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revised value for the angular diameter of Rossiter 3930 of $(2 \pm 0.5) \times 10^{-4}$" (Stecklum 1995, private communication) and the distance of 140 $\pm$ 20 pc from Hughes et al. (1993).

In Fig. 4 we have also drawn the error bars of $T_{eff}$ and $L_{tot}$ for both objects together with the region interval as limited by the isochrones. It seems that Rossiter 3930 is somewhat hotter and more luminous than the possible T Tauri companion of HR 6000. However, in view of the large error-bars, the unknown spread in $T_{eff}$ of Rossiter 3930 and the unknown contribution of the accretion luminosity we assume that both objects are located in the same region as determined by the isochrones.

To determine a possible upper-limit of the accretion luminosity ($L_{acc}$) we assume that both T Tauri objects have an upper mass of about 0.7 $M_\odot$, see Fig. 4. Given the maximum separation of 12.6 AU of HR 6000 and its companion (see next section) we derive $L_{acc} \approx 3.7 \times 10^{31}$ erg s$^{-1}$ by assuming a free fall from a distance equal to the first Lagrange-point of the $2 \times 10^{-7} M_\odot$ yr$^{-1}$ mass accretion. The mass applied here for HR 6000 is 3.5 $M_\odot$. In case of the upper luminosity of the region indicated in Fig. 4 $L_{acc} \approx 6.0 \times 10^{-3}$ L$_\odot$ and therefore negligible. If we assume a much lower limit of the area, e.g. a T Tauri companion with 0.3 $M_\odot$ and $L_\star \approx 0.15 L_\odot$, we derive $L_{acc}/L_\star \approx 2.6 \times 10^{-2}$. So, in this first approximation the accretion component does not contribute significantly to the total luminosity. A similar conclusion is reached for Rossiter 3930, by adopting a mass for HR 5999 of 2.5 $M_\odot$ (see Fig. 4), a separation of 240 AU at 160 pc (Stecklum et al. 1995) and the same accretion rate as for the HR 6000 T Tauri companion.

4. Discussion

As discussed in the previous sections, HR 6000 seems to be a quite peculiar system in a number of ways: Its spectroscopic spectral type does not seem to match its photometric colours, both in the UV and in the visual, it shows a small amount of excess radiation in the infrared, it is a long-term photometric variable, and it is a strong source of X-rays. All of these can be explained by inferring that HR 6000 is in fact a binary system, consisting of a B6 V and a cool companion. In view of the youth of the region in which both were formed, the cool companion must be a T Tauri star.

The explanation of HR 6000 being a B6 V star with a close T Tauri companion, does not contradict the speckle interferometry by Baier et al. (1985), who observed HR 6000 to be a point source with a diameter smaller than 0".09, corresponding to a separation of 12.6 AU at a distance of 140 pc. However, since the difference in visual magnitude between the main sequence and the T Tauri star will be about 6 magnitudes, and their detection limit was a magnitude difference of 2 - 3", they did not detect the T Tauri system. The technique of speckle interferometry was also used by Leinert et al. (1994) on a sample of 30 stars. It was concluded that a significant number, at least 23 $\pm$ 9%, of the studied HAEBe stars have companions.

In a binary system, the spectrum of a B6 V star may possibly be affected through interactions with the T Tauri system, such as tidal forces and accretion, so it could have been misclassified as an early A-type star, almost devoid of rotational line broadening, with chemical peculiarities. However, such interactions are very hypothetical because they can easily produce emission components of especially H$\alpha$ as seen in most young objects and binary systems. The photometric spectral type, on the other hand, will hardly be affected by such subtle effects, and yield the correct spectral type of the B6 V star. Note that no evidence of any stellar activity is found spectroscopically, which could explain the X-ray emission rather than the use of a T Tauri companion. This also indicates that HR 6000 has no active mechanisms to turn it into a Be phase. This contradicting view with HR 5999 will be discussed further.

In the infrared, where we observe a small amount of excess radiation above the photospheric radiation level of the B6 V star, we are probably starting to observe the continuum radiation of the T Tauri system. In such a case the non-existence of dust, by which a stellar wind could collide, does not explain the X-ray emission. If the accretion rate of a Classical T Tauri system varies, possibly due to interactions of this system with the B6 V star, it will vary in brightness, most noticeably in the ultraviolet, where we observe the boundary layer between the T Tauri and its accretion disk. Hence we will observe small variations in the integrated light of the B6 V and T Tauri star, with a larger amplitude towards bluer wavelengths, as observed.

Furthermore, it is interesting to note that the derived X-ray luminosity of HR 6000 by Thé et al. (1985) and by Zinnecker & Preibisch (1994), $L_x = (1.1 \pm 0.2) \times 10^{31}$ erg s$^{-1}$, is identical to that observed by Strom et al. (1990) for the K-type T Tauri stars in the Lynds 1641 dark cloud, giving a natural explanation for the observed X-ray flux as arising in the T Tauri system. By assuming the upper-limit of the total luminosity of 0.8 $L_\odot$ for the T Tauri companion, we derive $L_x/L_{tot} = 3.5 \times 10^{-3}$. Indeed this value can be typical for weak-line T Tauri stars (e.g. Strom et al. 1990) in cases of very low extinction.

We must note here that in the previous section we have used the upper-limit of the luminosity of the T Tauri companions as derived from the limitations in age. This luminosity includes the accretion contribution which, in case of an accretion rate of $2 \times 10^{-7} M_\odot$ yr$^{-1}$, has no significant contribution. Let us consider the case that the accretion luminosity is significant, e.g. $L_{acc} \approx L_x$. We must therefore take into account a much higher accretion rate of $\sim 10^{-5} M_\odot$ yr$^{-1}$ by assuming an 0.7 $M_\odot$ T Tauri companion of HR 6000 and the other astrophysical parameters as used before.

A higher accretion rate will also result in a higher disk contribution in the SED (Fig. 3), so in order to keep a good fit, the T Tauri companion itself must contribute less. A slightly hotter and less luminous T Tauri companion is possible and will result in a slightly better fit, but again the area limited by the isochrones in Fig. 4 puts some hard constraints on these values and, therefore, on the accretion-rate and stellar luminosity.

Given the maximum luminosity of the T Tauri companion of HR 6000 of 0.8 $L_\odot$, the luminosity ratio with HR 6000 will be about 140. This explains also the non-detection of spectroscopic tracers in our low resolution spectrum, such as Li I $\lambda$ 6702 Å, of the T Tauri companion as discussed by Martin (1994).

We have seen that in spite of some small differences in the astrophysical parameters of HR 5999 and Rossiter 3930 compared with the HR 6000 system both systems have much in common. Having the same age the HR 5999/HR 6000 common proper motion pair is an unique quadruple system. Mass and age determinations of HR 5999 and HR 6000 are also obtained by Hughes et al. (1994). For HR 5999 their masses of 2.53 and 2.66 $M_\odot$ agree well with ours. In the case of HR 6000 they obtain lower masses than we: 2.10 and 2.26 $M_\odot$. This is because they have taken it to be an A-type pre-main sequence star instead of the B6 V star it really is.
The main difference between HR 5999 and HR 6000 is that HR 5999 shows many typical Herbig Ae characteristics, such as a strong IR-excess up to IRAS colours, photometric and spectroscopic variability and strong emission lines in the UV, optical and red spectra, whereas HR 6000 shows a complete lack of such indications.

If we look at Fig. 4 this picture seems to be logical. HR 5999 is a pre-main sequence star whereas HR 6000 is a young main-sequence object. The higher mass of HR 6000 is probably the origin of the faster removal of circumstellar material as compared to HR 5999. It could therefore be interesting to use HR 6000 as a probe to test for characteristics of young main-sequence stars, analogue to less massive and maybe less young counterparts such as Vega-type objects. Maybe the peculiar spectral characteristics of HR 6000 are really even due to its youth, and we are dealing with a unique higher-mass counterpart of the α Boo phenomenon here.

Stecklum et al. (1995) discussed a more effective clearance of the outskirts of the circumstellar material around HR 5999 as being due to the T Tauri companion. What is left is then an unaffected inner disk area being responsible for all observable characteristics. We must note here that it is generally believed that HR 5999 is seen disk on (Pérez et al. 1993 and references therein). Such a clearance in combination with the higher mass of HR 6000 could explain the lack of detected circumstellar material. This effect could be much stronger for HR 6000, because the T Tauri companion of HR 5999 is located about 20 times further away, compared to the HR 6000 case. Furthermore, a pole-on orientation in our line-of-sight could again suppress typical Herbig Ae/Be characteristics.

Apart from the direct detection of the binary of HR 6000, possibly by near-IR spectroscopy, the most interesting of HR 6000 is probably that it is seen without any pollution of circumstellar material, which is rather unique for such young objects. This being “naked” makes this object an extremely good probe for learning about the chemistry of young objects by the use of high resolution spectroscopy.

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