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HD 147010: The Ap Star in the Reflection Nebula vdB 102 in Upper Scorpius Region

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Abstract. HD 147010, which is in the reflection nebula vd B 102, has been found to be a hot Ap silicon star rather than a normal A supergiant. From the *UBV and JHK* photometry of the star, colour excess $E(B - V)$ of 0·29 and the ratio of total-to-selective absorption R of 4·3 have been obtained. The high value of R implies bigger grain size and also confirms the association of the star with the nebula. The dereddened colours of the star can be fitted to a theoretical energy distribution with $T_{\rm eff} \simeq 13000 \pm 500$ K and $\log g = 3{\cdot}6 \pm 0{\cdot}2$. HD 147010 has also been found to be a spectrum variable; in particular, lines of Cr II show large intensity variations.

Key words: peculiar stars—spectrum variables

1. Introduction

Study of peculiar stars in young stellar aggregates like I Ori and Scorpio-Centaurus are thought to be particularly important because it would provide constraints on the timescales of possible mechanisms that explain both the abundance peculiarities and also the low rotational velocities (Hack 1976). Van Rensbergen, Hammerschlag-Hensberge and van den Heuvel (1978) concluded from the study of several galactic clusters that Ap and Am phenomena develop at a very early stage in the life of a star—during or before the arrival on the main sequence. Moreover, young stars embedded in nebulosities might still be in pre-main-sequence phase and thus might possess active and unstable atmospheres (*e.g.* Herbig Ae and Be stars). If one of these stars also happens to be peculiar, this might place further constraints on the mechanisms responsible for the origin of these peculiarities. Presently there seems to be mainly two hypotheses for explaining the abundance anomalies: the radiation-pressure-driven diffusion hypothesis (Michaud 1970, 1976) and the selective magnetic accretion of matter from normal interstellar medium (Havnes and Conti 1971) and its variations such as accretion of supernova-enriched material (Rajamohan and Pati 1980), or accretion from an evolved companion (van den Heuvel 1967; Guthrie 1968). Diffusion as well as accretion hypotheses predict a gradual development of the peculiarities during the main-sequence life of a star although for diffusion the time scales are rather short (~ 10^4 yr). One attractive suggestion by van Rensbergen, Hammerschlag-Hensberge and van den Heuvel (1978) was that the peculiarities might result from the accretion of solid particles (probably made up of silicon and iron peak elements) from the proto-planetary clouds. Recently Havnes (1979) has shown that grains may in fact be more important in an accretion process than the gas and he also suggests some qualitative tests for this hypothesis. Thus, a study of peculiar stars associated with dark clouds is of particular interest. We have undertaken to study these stars to see whether any systematic trends would emerge from their properties related to abundance and/or rotation. One such star seems to be HD 147010, which is located in the nebulosity vdB 102 (van den Bergh 1966) in upper Scorpius.

HD 147010 is classified as one of the peculiar A-type stars in the upper Scorpius region by Garrison (1967). This forms a group along with HD 147009, HD 147103, HD 147104 and HD 146834, as illustrated by Garrison (1967, Fig. 8). The two pairs HD 147009, 147010 and HD 147103, 147104 are in a small complex of reflection nebulae (vdB 102) with a heavy dust lane connecting them, and a faint nebulosity extends further from these two pairs to HD 146834. HD 146834 is classified as of spectral class K5 III and probably is not part of this complex. Both HD 147009 and HD 147010 are considered to be members of Scorpio-Centaurus stream by Garrison on the basis of proper motions. These two stars form a visual binary system with a separation of 47·1 arcsec (Jeffers, van den Boss and Greenby 1963).

The spectroscopic peculiarities of HD 147010 have been described by Garrison (1967, Fig. 3). 'The lines of Si II and Fe II are sharp and very strongly enhanced as in a supergiant at about A2. Other lines present are seen at this low dispersion (86Å mm^{-1} at H_γ)to be lines of Ti II, Fe I and Cr II. However, the weak Ca II K line is so shallow and broad that it is barely visible and the hydrogen lines are considerably broader than in a supergiant.... The spectrum is definitely inconsistent with the photometry.' Further, Garrison points out also that HD 147010 could not be classified as a shell star (like Pleione) because shell stars usually show a strong K line of Ca II in the shell stage, which is absent in HD 147010. Slettebak (1968) in his study of the rotational velocities of ScorpioCentaurus stars also gave a similar description of the spectrum of HD 147010. 'The spectrum is peculiar as pointed out by Garrison (1967). Helium appears to be faintly present and the Ca II K line is weak. The Balmer lines suggest luminosity class II or IV, but the lines of Si II and Fe II indicate still higher luminosity.' Thus it was not clear whether HD 147010 is an A2 supergiant or a peculiar star. However, recently Wolff (1981) has mentioned it as an Ap Si-Cr. We have obtained a wide variety of spectroscopic and photometric observations to study the nature of this star and in particular to see whether we could gather up any evidence for accretion of matter on to the star.

2. Observations

All the spectroscopic observations have been obtained with 1-m telescope at Kavalur with the Cassegrain spectrograph. A Varo image intensifier has been used to secure the red and near-infrared spectrograms. The journal of observations and the details of the spectrograms are given in Table 1.

All the available (published) photometric observations both in *UBV* (Hardie and Crawford 1961; Moreno and Moreno 1968) and in Strömgren system along with the β index (Glaspey 1971) are given in Table 2.

It was shown by Groote and Kaufmann (1981) that 60 per cent of the Ap and Bp stars they studied exhibit infrared excess at 4·8μm. In particular, they claim that younger stars possess more infrared excess. Thus it was felt that if HD 147010 has a circumstellar shell it might give rise to enhanced emission at infrared wavelengths in the form of either free-free emission from ionized gas envelope or thermal radiation from heated dust. So photometric observations of the star were obtained in *JHK* bands also. The *JHK* photometry of HD 147010 was done in 1981 February using a liquid-nitrogen cooled InSb detector of Physical Research Laboratory, Ahmedabad, with the 1-m telescope at Kavalur. Standard stars near HD 147010 (Whittet and van Breda 1980) have been observed along with HD 147010 to minimise extinction errors. The magnitudes are on Johnson's system and are given in Table 2. The typical errors in the magnitudes are 0·07 mag. The conversion to flux has been done using Johnson's (1966) calibration.

Table 1. Details of spectrograms obtained.

Plate no.	Date U. T.			Emulsion Central wavelength	Dispersion Å mm^{-1}	Exposure min
δ 2064	1973	March	15·897	IIa–0 4000	47	64
δ 1403	1981	February	7·915	IIa–D+Varo H_α	22	97
δ 1459	1981	February	20·928	IIa–D+Varo H_α	22	153
δ 1499	1981	February	26·917	IIa–0 λ 4000	22	172
δ 1510	1981	March	4·893	IIa–D+Varo H_α	22	171
δ 1515	1981	March	5·922	IIa–0 λ 4000	22	225
δ 1606	1981	April	9·814	IIa–D+Varo λ 7774	130	30
δ 1628	1981	April	11·834	IIa–D+Varo λ 5870	22	120
δ 1646	1981	April	23·808	IIa–D+Varo λ 5870	22	86
δ 1812	1982	February	14·929	IIa–0 λ 4000	22	155

Table 2. Colour indices of HD 147010.

V	*B–V*	*U–B*	*b–y*	m_1	c_1	*B*	*J*	*H*	*K*	Reference
			0·125	0·122	0·512					1
7·41	0·16	–0·25				2·769				2
7·38	0·162	–0·274								3
							6·67	6·63	6·69	4

References:
1. Glaspey (1971) 2. Hardie and Crawford (1961) 3. Moreno and Moreno (1968)
4. present investigation.

3. Luminosity class

One of the main uncertainties about HD 147010 is the luminosity class, *i.e.* whether it is an A supergiant as indicated from the lines such as of Si II, or an Ap star close to the main sequence (Garrison 1967). It is well known that λ7774 feature of OI is a good indicator of luminosity class for stars between spectral types B to early G (Keenan and Hynek 1950; Osmer 1972; Rao and Mallik 1978). If HD 147010 is a normal A2 supergiant, a strong absorption feature of λ7774 is to be expected. Spectrograms of the star obtained at a dispersion of 130 Å mm^{-1} do not show any absorption feature at λ 7774, whereas *α* Cyg—the standard A2 supergiant—shows a very strong absorption of λ 7774. Also, λ 7774 line is present on the spectrograms of HR 2618 (B6 III) obtained at the same dispersion. Thus it is seen that HD 147010 is not a normal A-type supergiant and could be of luminosity class IV or so, as already commented by Slettebak (1968).

4. Reddening, effective temperature and gravity

Based on the spectral type of A2, Garrison (1967) obtained a value of colour excess $E(B - V)$=0·12 for HD 147010, whereas Moreno and Moreno (1968) obtained a value of $E(B - V)$=0·29 based on its membership of Scorpio-Centaurus association; the latter authors also obtained a photometric spectral type of B6. It has been shown by Schild, Neugebauer and Westphal (1971) that the stars of upper Scorpius obey the interstellar extinction law characterized by the ratio of total-to-selective absorption $R \sim 3$. With this value of R and adopting Garrison's estimate of $E(B - V)$, the $(U - B)_0$ colour of HD 147010 would be much too blue for the spectral type A. A comparison with the theoretical energy distribution computed by Kurucz (1979) shows that if the spectral type is assumed as A2 corresponding to $T_{eff} \simeq 9500$ K, then the observed U flux can only be satisfied if log g is lower than 1·5; *i.e.* the star has to be Ia supergiant. As already mentioned, the strength of λ 7774 feature indicates that it is not a normal supergiant. Moreover, the model normalised at 0·55 μm shows that the theoretical fluxes in the J, H and K passbands are much less than the observed ones. The same result is obtained by a comparison of the fluxes of the star with the observed fluxes of 78 Vir—another Ap star with the same $(B - V)_0$. The value of $E(B - V)$=0·29 leads us to a theoretical energy distribution corresponding to a model with T_{eff} = 13000 K and log $g \sim 3{\cdot}5$ [corresponding to $(B - V)_0 = -0{\cdot}13$] which can fit the reddening-corrected observed U flux, although the infrared fluxes predicted are much less than observed (see Fig. 1). The difficulty persists for every plausible value of $E(B - V)$ if R is assumed to be ~ 3. The value of $E(B - V)$=0·29 for HD 147010 seems to be consistent with the estimate of $E(B - V)$=0·33 for

Table 3. Equivalent widths.

Star	θ	log g	λ 4128 Si II	λ 4130 Si II	λ 4471 He I	λ 4481 Mg II
			W_λ (mÅ)			
HD 14392	0·38	3·7	220	240	160	240
HD 68351	0·38	3·7	350	310	10	250
HD 147010*			190	200	120	220

* measured on plate δ 1499.

HD 147009 (based on a colour-spectral-type relation; Garrison 1967) which is only 47·1 arcsec away and appears to be embedded in the same reflection nebula.

The infrared colours (*J–H*, *H–K*) of HD 147010 do not indicate a presence of infrared excess. It was shown by Whittet and van Breda (1980) that in (*J–H*, *H–K*) plot for early type stars, the single Be stars and nebular shell stars occupy a separate region (higher $H - K$ index for a given $J - H$) whereas high-luminosity shell stars (supergiants and Of stars) and normal stars follow a blackbody line. The $J - H$ and $H - K$ colours of HD 147010 place it on the normal and shell star position. However, as shown earlier, HD 147010 is not a high-luminosity star. Thus a different value of *R* seems to be required to bring the infrared and visual photometry in agreement with the theoretical energy distribution. It is known that stars embedded in the dark clouds have a high value of *R*. Whittet (1974) has found that the stars associated with reflection nebulosities generally have R=4·2 while those not associated with nebulosities have R=3·3. Further, it was shown by Whittet, van Breda and Glass (1976) that *R* reaches a maximum of 4·3 in the central molecular cloud regions of Scorpio-Ophiuchus region. Thus it seemed that since HD 147010 is embedded in the reflection nebula $R \sim 4{\cdot}3$ is appropriate. The colours of HD 147010 have accordingly been corrected using this value of *R* also (using the relations given in Whittet and van Breda 1980) and are shown in Fig. 1 along with the theoretical energy distribution for a model with T_{eff} = 13000 K and log g= 3·5 (Kurucz 1979) normalised at *V*. The observations match quite well with the theoretical energy distribution. Thus the value of *R* in this region seems to be ~ 4·3.

The equivalent widths of H_γ and H_δ computed from the above theoretical model are consistent with the observed equivalent widths of H_γ and H_δ (9·8 Å and 9·0 Å respectively; Rajamohan 1976). Once T_{eff} is fixed (13000 ± 500 K), the observed

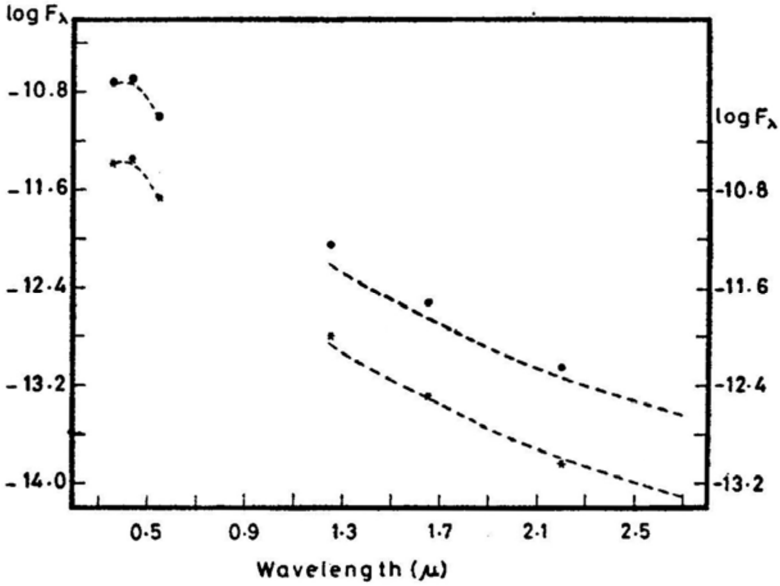

Figure 1. The energy distribution of HD 147010 corrected for different reddening values of R = 3·0 (filled circles) and 4·3 (asterisks). The dashed curve represents the theoretical energy distribution given by Kurucz (1979) for T_{eff} =13000 K and log g=3·5 normalised at *V* (0·55 μm). The scale for the lower curve is marked on the right-hand side.

equivalent widths of H_γ and H_δ yield log g =3·7 on a comparison with the theoretical equivalent widths of Kurucz (1979). Thus, the colours between 0·36 μm and 2·2 μm and the equivalent widths of hydrogen lines are both consistent with a theoretical model of HD 147010 with T_{eff} = 13000 ± 500 K and log g = 3·6 ± 0·2. In these estimates of T_{eff} and log g, it has been assumed that the theoretical energy distribution computed from line-blanketed models of normal stars (Kurucz 1979) is applicable to the *UBV* and *JHK* colours of HD 147010—which is apparently an Ap star. It is known that for Ap stars T_{eff} determined from *UBV* colours alone is an overestimate (Shallis and Blackwell 1979). However, Stepien and Muthsam (1980) have shown that the corrections needed to transform $U - B$, $B - V$ colours of Ap stars to the colours of normal stars of corresponding T_{eff}, are usually small for hot Ap stars (not exceeding 0·07 in $U - B$ and 0·03 in $B - V$). Thus our use of these colours along with the infrared colours (which are not affected by blanketing) could cause errors of only a few hundred degrees in the estimation of T_{eff} .

5. The line spectrum

The above estimate of T_{eff} and log g show that the star is a late B-type star and thus the presence of strong λλ4128, 4130 lines of Si II seen by Garrison indicates that it belongs to the class of hot Ap stars. Wolff (1981) mentions this as an Ap Si-Cr star.

One of the primary results of this study is that HD 147010 is a spectrum variable and the intensities of some of the lines vary in strength with time. Particularly, lines due to Cr II show major changes in intensity, whereas lines due to Si II and to some extent Fe II do not appear to show such variations. Also, a few other lines seem to vary in an opposite phase with respect to Cr II lines. This effect is conspicuously seen in the lines of λ4012·54 and λ 4002·90 as shown in Fig. 2.

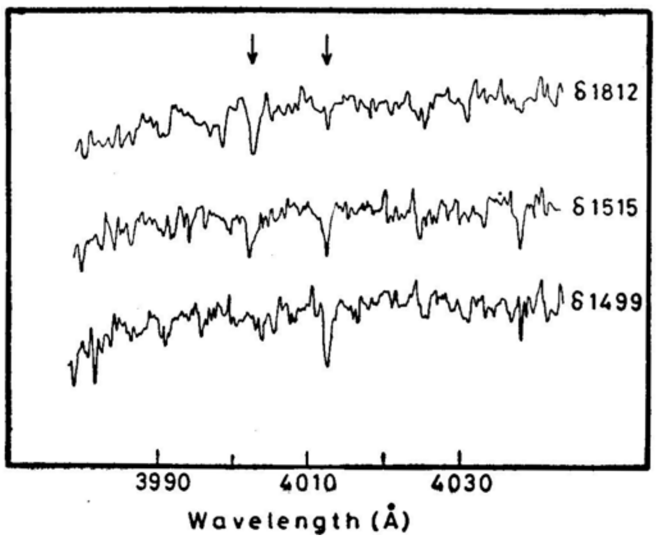

Figure 2. Density tracings of the three plates δ 1499, δ 1515 and δ 1812 in the region of λ4000. The arrows point to the two lines λ4002·9 and λ4012·5, which show changes in strength with antiphase.

λ 4012·54 is mainly due to Cr II (multiplet 183) whereas the identification of 4002·90 is not certain. λ 4012·54 is quite strong on plate δ 1499. Other lines due to Cr II are also quite strong on this plate (e.g. λ 3979 of multiplet 183, λλ 4242·38, 4261·92, 4269·28 etc.), whereas λ 4002·90 is quite weak or absent. On plate δ 1515, obtained a few days later (see Table 1), both λ 4012·54 and λ 4002·90 are of roughly equal strength and on the plate δ 1812, λ4012·54 is very weak but λ 4002·90 is very strong. Also, the other Cr II lines are very weak on δ 1812. These changes appear to be gradual. There are other lines which behave similar to λ 4002·90 feature, particularly lines of λλ 4082·2, 3998·95, 3874·7 and 3959·6. Presently, we cannot provide definite identifications for these features from the spectroscopic material available. It is known in α^2 CVn (Si-Cr-Eu star) which also shows large variations of Cr lines, that the lines which vary with opposite phase to Cr lines are mostly due to rare earths (Burbidge and Burbidge 1954). Probably such a phenomenon is also applicable in HD 147010.

The He I lines appear to be extremely weak for a star of spectral type B6. Our plate material (Table 1) shows that He I λλ 6678, 5876 may be marginally present, while λ 4026 and others are extremely weak or absent. On the blue plates, λ 4471 appears weaker than λ 4481 of Mg II, which itself is weak. The equivalent widths of Si II λλ 4128, 4130 (which do not seem to vary in strength with time), λ 4481 of Mg II and λ 4471 of He I have been measured on the plate δ 1499. These are shown in Table 2 along with the data for two other Si λ 4200 stars with the same T_{eff} and log g (Norris 1971, and Searle and Sargent 1964). The equivalent widths—in particular of λ4471 of He I and 4481 of Mg II—should be considered as upper limits. These are given here for a qualitative comparison. However, the equivalent width of λ 4471 He I places HD 147010 in the same place as Si λ 4200 stars and helium-weak stars in the plot between W (λ 4471) and θ_e (Norris 1971). Thus He I is quite weak in HD 147010, which is apparently a common characteristic of Ap stars. The equivalent widths of λλ 4128, 4130 of Si II also place this star in the same region occupied by Si λ4200 stars in the plots of W (λ 4481, Mg II)/W (λ 4130, Si II) and W (λ 4130) versus $B - V$ or θ_e (Norris 1971; Searle and Sargent 1964). From the relationship between equivalent width and Silicon over-abundance (Searle and Sargent 1964), one obtains a value of ~ 0·6 (±0·2) for [Si/H].

Apart from λλ4128, 4130 several other lines of Si II are also present— λ 3855, 3856, 3862, 4075,4076 and even high excitation lines of λ 3954 and λ 4200. Contrary to the description given by Garrison that K line of Ca II is a broad shallow line, we find it

Table 4. Observed radial velocities.

Date U. T.		Radial velocity km s⁻¹	p.e. km s⁻¹	Dispersion Å mm⁻¹
1920 May	12·297*	− 8·2	3·8	36
1921 April	29·359*	−14·7		36
1921 July	22·161*	− 3·5		
1973 March	15·897	− 8·1	9·8	47
1981 February	26·917	− 6·9	4·0	22
1981 March	5·922	− 6·1	4·7	22
1982 February	14·929	(− 4·6)		22

*Abt (1973)

to be a sharp line. Many moderately strong lines of Fe II are also present along with lines of Ti II. There appears to be some change in the shape of some Balmer lines. On one plate (δ 1403) H_α shows a sharp red edge.

Although the strength of several lines appear to be variable, the radial velocity of the star essentially remains constant. All the published measures of radial velocity of the star (Abt 1973; Wilson and Joy 1950) along with the measures of our four blue plates are given in Table 4. There is no significant variation in radial velocity and the mean valueis—7 km s^{-1}. This probably indicates that the star is not a spectroscopic binary.

6. Discussion

HD 147010 seems to be imbedded in the nebulosity vdB 102 and appears to be the source of illumination, although van den Bergh (1966) gives HD 147009 as the source. The $E(B - V)$ and R value estimated earlier show that HD 147010 is at least 1 mag brighter than HD 147009 and also earlier in spectral type. Use of Hubble's relation as given by Brück (1974) for the diameter, estimated to be illuminated by HD 147010 is about 305 arcsec which agrees with the diameter of the reflection nebulosity measured on the J plate of SRC sky survey.

The large value of $R = 4{\cdot}3$ derived for the grains around HD 147010 is similar to the extinction properties of grains around stars like ρ Oph, which are also imbedded in the reflection nebula. This high value of R is attributed to the particles larger than those causing the interstellar extinction. If they are approximated to be spherical dielectric grains (silicates) then the Mie scattering calculation indicates particles of radii greater than 0·2 μm. In the picture presented by Havnes (1979) for accretion of grains on chemically peculiar (CP) stars, relatively large grains approach the CP star and are heated whereas small and/or light grains are pushed away. At least around HD 147010, this requirement of large grains for accretion seems to be partly met.

Recently Wolff (1981) has discussed the rotational velocities of Ap stars in clusters. She obtained a value of $\leqslant 20$ km s^{-1} for the $V \sin i$ of HD 147010 (consistent with our spectroscopic material). In the plot between the $V \sin i$ and age (Wolff 1981, Fig. 2), HD 147010 occupies the lowest position for the stars of the same age ($\sim 2 \times 10^7$ yr according to Wolff) and deviates appreciably from the mean relation. However, the age of upper Scorpius sub-group of the Scorpio-Centaurus association could be much less ($\sim 5 \times 10^6$ yr) and the deviation of the position of HD 147010 would be much more.

The above estimate of $V \sin i$ indicates a low rotational velocity of the star, although the $\sin i$ value is unknown. The approximate value of $\sin i$ could be estimated if the spectrum variability discussed earlier is found to be periodic and also if it is assumed to be due to rotation. An estimate (admittedly uncertain) depending on the behaviour of line strengths on our four blue plates indicates a period of 5–7 days. Further, the radius of the star estimated to be 3 $R_\odot$ from M_v and T_{eff}, leads to a rotational velocity ~27 km s^{-1}. Wolff has presented arguments in favour of mass accretion processes being responsible for the magnetic breaking resulting in the low rotational velocities for Ap silicon stars, although at which stage in the evolution (main sequence or pre-main sequence) this starts operating is far from clear. If the process is operative for

HD 147010 also, then the lower-than-normal velocity might indicate higher rate of mass accretion.

As indicated earlier, *JHK* magnitudes of HD 147010 do not show the presence of infrared excess. In contrast, Groote and Kaufmann (1981) have detected infrared excess at 4·8 *μ*m in 60 per cent of Ap and Bp stars. At least in a few cases, infrared excess seems to be due to circumstellar grains. Further infrared observations at 4·8 *μ*m and longer wavelengths are desirable to ascertain whether HD 147010 would also show some excess.

We have observed this star as the first of a sample of Ap stars situated in the regions of dark clouds to see whether any common trends emerge. Presently, one other peculiar star connected with dark clouds seems to be HR 6000 which is helium-weak and also shows the presence of lines due to P II (Bessell and Eggen 1972). HR 6000 is the visual companion (45 arcsec away) to one of the bright pre-main-sequence shell star HR 5999 and is associated with the dark cloud complex containing several T Tauri stars (Eggen 1975; Thé and Tjin A Djie 1981). The *UBV colours* of both HD 147010 and HR 6000 are in a very close agreement. It would be interesting to investigate the rotational velocity and any other spectroscopic anomalies common to these two systems.

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