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HD 139614, HD 142666 and HD 144432: evidence for circumstellar disks*

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Abstract. The morphology of the material surrounding Herbig Ae/Be stars is still a topic of debate. Distinct models with different geometry and optical thickness are found to be compatible with the observed IR excess. This indicates that it is not possible to resolve this question by only looking at the fluxes. Therefore, this paper compares three known Herbig Ae/Be stars with very similar energy distributions but with different photometric behaviour, showing different spectral line profiles and circumstellar extinction. These three Herbig Ae/Be stars are studied both photometrically and spectroscopically. It is found that the parameters from the Kurucz atmosphere model, fitting their spectral energy distributions, are very alike. Notwithstanding this similarity in spectral energy distribution, HD 142666 has several indications of CS material in the line of sight, while HD 139614 and HD 144432 do not show any of these indications. Therefore the inner dust shell of these stars is assumed to be not spherical, but rather flattened. The observed differences are then interpreted as a difference in CS disk inclination with respect to the observer. As a result, it is concluded that at least some of the Herbig Ae/Be stars are surrounded by disks and also that modeling energy distributions should be done while having other restraining observations in mind.

Key words: Herbig Ae/Be stars – stars: individual: HD 139614, HD 142666, HD 144432 – stars: circumstellar matter: pre-main sequence

1. Introduction

The Herbig Ae/Be stars (hereafter Haebe) are pre-main-sequence stars of intermediate mass, and so are somewhat more massive analogs of the T Tauri stars. A characteristic of all known Haebe stars is the presence of an IR excess due to thermal re-radiation of a circumstellar (CS) dust shell. The spatial distribution of the CS material causing this IR excess is still questioned: some authors argue for a disk-like distribution of the CS dust (Hillenbrand et al. 1992; Corcoran & Ray 1994; Marsh et al. 1995), while others favour a spherical symmetric model (Berilli et al. 1992; Lorenzetti et al. 1996). It appears that the observation of the IR energy distribution alone is not sufficiently constraining for a detailed geometrical model.

Hillenbrand et al. (1992) have elaborated a classification of Haebe stars in terms of the IR excess, and thus define three groups. Group I contains stars with a large IR excess, showing a slope $\lambda F_\lambda \sim \lambda^{-4/3}$; they interpret the objects of this group as being surrounded by a geometrically flat, optically thick CS accretion disk. Group II shows flat or rising IR spectra; these are interpreted as still younger objects where a major fraction of the gas and dust is not confined to a disk. The last group, G III, contains stars with small IR excesses, due only to gas. The scarce spatial information that is available confirms a picture in which the Group II sources, which are often resolved in the near-IR, are embedded in a loose environment that is hardly structured (Li et al. 1994). Group I sources are rarely spatially resolved, but Marsh et al. (1995) report a disk-like structure for the inner regions around AB Aurigae. These results suggest that the outer circumstellar regions, which are not gravitationally bound to the star, are close to spherically symmetric and that once this outer shell has disappeared a more disk-like circumstellar environment dominates the IR radiation. On the other hand, other authors, such as Lorenzetti et al. (1996), claim that a spherically symmetric dust model can account for most observations. Also Miroshnichenko (1997) successfully models the spectral shape of IR emission around Herbig stars with a spherical dust envelope. However, Sylvester et al. (1996), modeling the excess IR emission of Vega-like systems, some of which are known Herbig stars, conclude that the data are not in agreement with the hypothesis of a spherical envelope.

The conflicting results of these studies suggest that more and different observations are required to further constrain the models. Ideally, one would aim at high spatial resolution, but this is only attainable for a few nearby objects. The strategy developed in this paper is based on the spatial information that

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*** Research Assistant of the Fund for Scientific Research - Flanders can be obtained from spectroscopy of the circumstellar lines and from observations of the photometric variability, both of which probe the line of sight in the vicinity of the star. For this purpose, three known Herbig Ae stars with comparable spectral types (A7-A9) and very similar IR excesses were selected and observed.

The contents of this paper are as follows. In the next Section the existing literature about the selected objects, HD 139614, HD 142666, and HD 144432, is discussed and the observations carried out in preparing this paper are summarised. The extinction and energy distribution are presented in Sect. 3, where the optical photometry is also discussed. Sect. 4 is devoted to the study of several important CS spectral features. The discussion of all these observations in Sect. 5 strongly argues for a disk-like distribution of the circumstellar dust around these stars.

2. Sample stars and observations

The three programme stars HD 139614, HD 142666, and HD 144432 were chosen during a study of objects selected by Oudmaijer et al. (1992) in their catalogue of SAO stars with an IR excess in the IRAS Point Source Catalogue. All three stars also occur in the list of possible Vega-type stars by Walker & Wolstencroft (1988).

HD 139614 is mentioned in several studies on Vega-type stars (e.g. Sylvester et al. 1996), but is certainly a member of the Haebe group, considering its spectral energy distribution in the IR, and its single-peaked Hα emission. HD 142666 and HD 144432 were identified as candidate Haebe stars, based on their IR excess and Hα emission. Both stars are also listed in the recent catalogue of Herbig Ae/Be and candidate Herbig Ae/Be stars by Thé et al. (1994).

Sylvester et al. (1996) discuss the three stars in a larger study of the energy distribution and infrared spectra of Vega-like systems. They attribute the fact that the IR excesses of these stars are much larger than that of Vega to the youth of these stars: in a $(J-H)$ versus $(H-K)$ diagram, they occur in the same region as the Haebe stars. The three stars are close to the Scorpius-Ophiuchus star formation region, which is consistent with a young age. Sylvester et al. (1996) note a significantly larger extinction towards HD 142666 than towards the other two stars. The temperature of a blackbody, fitted to the near-IR excess, lies in the same range (1500-1800 K) for all stars. HD 142666 and HD 144432 show several near-IR spectral features, such as silicate emission around 10 μm, which is very strong in the spectrum of HD 144432. The fractional luminosity of the dust, L_{IR}/L_*, is approximately the same (between 0.34 and 0.48).

Optical photometry for the program stars in the Geneva seven-color system was obtained using the 0.7m Swiss telescope equipped with the Geneva photometer at La Silla Observatory, Chile. For HD 139614, 7 observations were obtained during a period of 97 days, for HD 142666 over 128 observations were obtained distributed over 837 days, and HD 144432 was observed 18 times in 347 days. Near-infrared (JHKLM) photometry was obtained using the ESO 1m telescope equipped with the infrared photometer. In Table 2, all optical and near-infrared photometric data are given. For the U-, B- and V-values, a mean value of each is taken. The far-infrared data are from the IRAS Point Source Catalogue (1988) and are listed in Oudmaijer et al. (1992).

Table 1. Identification of the program stars. The identification and optical counterpart, the 1950 co-ordinates of the IRAS sources, the galactic latitude b and the spectral type are shown.

No	identification	α_{IRAS} h m s	δ_{IRAS} ° ' "	b deg	sp.type
1	HD 139614	15 37 22.9	-42 20 14	10	A7 Ve
2	HD 142666	15 53 43.3	-21 53 00	24	A8 Ve
3	HD 144432	16 03 53.6	-27 35 08	18	A9 Ve

Table 2. The average optical and near-IR photometry for the program stars.

No	m_U	m_B	m_V	m_J	m_H	m_K	m_L	m_M
1	9.01	7.58	8.26	7.75	7.34	6.76	5.68	5.49
2	10.27	8.52	8.81	7.34	6.72	6.04	4.97	4.69
3	9.10	7.61	8.15	7.21	6.69	6.14	5.14	4.90

Table 3. Interstellar and total extinction for the program stars

No	identification	$E[B-V]_{IS}$	$E[B-V]_{TOT}$
1	HD 139614	0.07	0.08
2	HD 142666	0.22	0.62
3	HD 144432	≤0.15	0.20

High resolution spectroscopic observations in the optical wavelength range were conducted with the CES-spectrometer mounted on the 1.4m CAT telescope of the ESO, La Silla observatory in June 1994 and May 1996. Three high signal-to-noise (S/N $\approx$ 100), high-resolution ($\lambda/\Delta\lambda \approx$ 55000) CCD-spectra for each program star were obtained. These spectra cover the NaI D and HeI (5865-5905 Å), H$_\alpha$ (6520-6600 Å) and P13 of HI (8655-8710 Å) wavelength ranges.

Low-resolution spectroscopic observations in the near-IR were obtained with IRSPEC, mounted on the NTT, in La Silla in March 1995. We obtained spectra around 1.08, 1.64 and 2.16 μm, the regions of respectively HeI, FeII and Br_γ of HI.

3. Photometry

3.1. Spectral energy distribution

The reddening of the program stars was estimated as follows. First, the total extinction $E[B-V]_{TOT}$ was computed by comparing the observed $[B_2 - V_1]$-color with the intrinsic color which corresponds to the spectral type of the star (Meylan et al. 1980) and adopting $E[B-V]/E[B_2-V_1]$ = 1.31. The interstellar extinction $E[B-V]_{IS}$ was derived by computing the extinction as a function of distance modulus $m_V - M_V$ for B-stars near the line of sight (5^o or slightly more, if less than 20 B-stars with Geneva-photometry were found) of each program star. This method was developed by Cramer & Maeder (1979) who computed M_V for B-stars and by Cramer (1982) who computed the intrinsic color indices $[U-B]_0$ and $[B-V]_0$

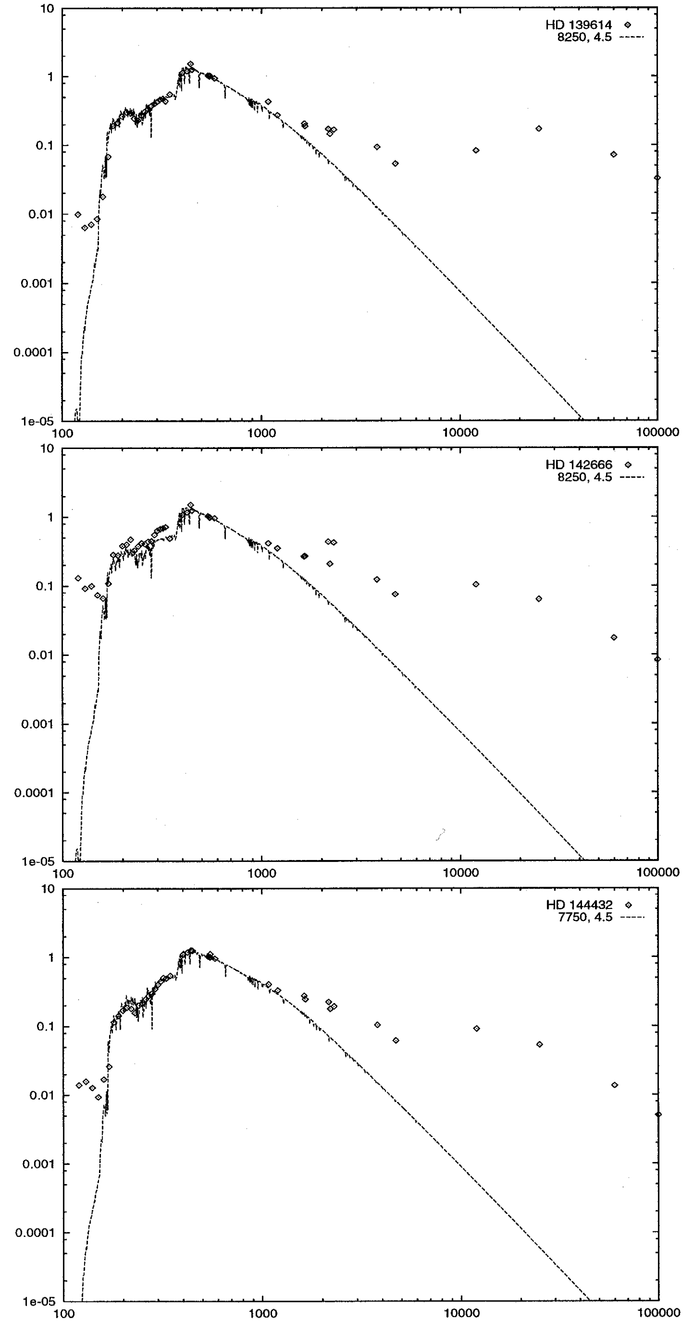

Fig. 1. The energy distributions of HD 139614, HD 142666 and HD 144432. λF_λ is plotted normalised to the V-filter as a function of wavelength λ in nm. The observed points are fitted by a Kurucz atmosphere model. The three stars show an excess both in the UV and in the IR.

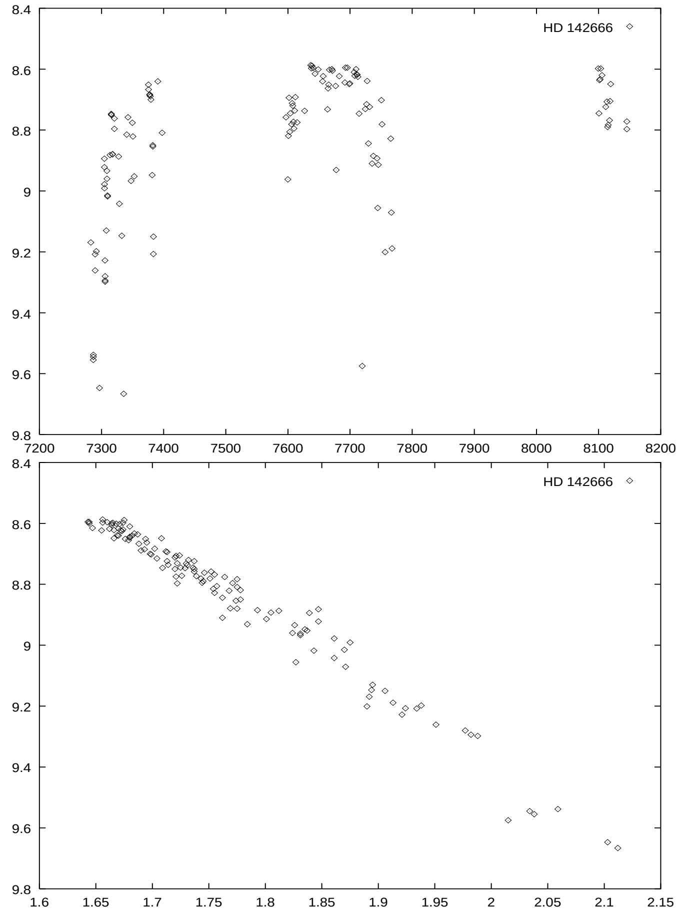

Fig. 2. Upper: The optical brightness m_V of HD 142666 as a function of JD (244+), showing substantial variability ($> 1.^m2$). Lower: The color-magnitude diagram $m_V - [U-B]$ for HD 142666. Here a linear relation can be seen between m_V and the color index $[U-B]$. The star reddens when it becomes fainter.

for B-stars. Combining these two methods, the above mentioned $E[B-V]$ vs. $m_V - M_V$ diagram could be made, and since Herbig Ae/Be stars are population I, $E[B-V]_{IS}$ could be estimated from M_V (Mihalas & Binney, 1981) . The $E[B-V]_{TOT}$- and the $E[B-V]_{IS}$-values for the stars are given in Table 3. For HD 139614 and HD 144432 the estimated interstellar and total reddenings agree fairly well, indicating that the amount of circumstellar reddening is small or negligible; for HD 142666 a substantial amount of circumstellar reddening occurs.

To construct the spectral energy distributions, the UV and optical data were corrected for the total extinction. An average extinction curve (Savage & Mathis, 1979) was used with $R = A_V/E[B-V] = 2.75$, to calculate the reddening A_λ (in magnitudes) at each wavelength λ. Then

$$F_{\lambda,0} = 10^{A_\lambda/2.5} F_\lambda$$

where $F_{\lambda,0}$ is the intrinsic flux at wavelength λ, and F_λ the observed flux at wavelength λ.

The optical observations and near-UV observations were fitted by a LTE atmosphere model (Kurucz R.L., 1994) with parameters initially estimated from the spectral type and the luminosity class of the stars; in all cases a solar composition was adopted. After some iterations, a Kurucz model with T_{eff} = 8250 K and log g = 4.5 resulted in the best fit for HD 139614 and HD 142666, while HD 144432 needed a somewhat cooler (T_{eff} = 7750 K, log g = 4.5) model. In Fig. 1, the spectral energy distributions for the program stars are presented. In all three stars excess radiation is observed in the UV and the IR, caused by circumstellar gas and dust, respectively.

3.2. Optical photometric variability

The Geneva photometric data obtained for HD 139614 and HD 144432 do not show any significant variability; on the other hand, HD 142666 displays large ($> 1^m.2$) brightness variations. The visual magnitude (m_V) of this star as a function of the Julian Date (JD) is shown in Fig. 2. It should be noted that the star is most frequently in its bright state. A period analysis for this star was performed, but no period was found. Therefore it can be concluded that the variations are irregular.

In Fig. 2, the color-magnitude diagram $m_V - [U - B]$ for HD 142666 is shown. It can be seen that, for this star, there is a linear relation between m_V and the color-index $[U - B]$: the star becomes redder as the apparent magnitude decreases. This shows that HD 142666 is a member of class R (Red behaviour), as defined by Bibo & Thé (1991), in their study of the photometric variability of Herbig Ae/Be stars in a color-magnitude-diagram. The slope of the $(m_V, [U - B])$ curve is similar to that of the IS extinction law by Savage & Mathis (1979). This suggests that, like the Herbig Ae star HR 5999 (Bibo & Thé 1991), the brightness variations of HD 142666 can be ascribed to variable obscuration by CS dust. It can be concluded that the star HD 142666 shows nonperiodic Algol-like minima, and can be considered as a member of the UXor class.

4. Spectral observations

4.1. Optical spectroscopy

In Fig. 3 the optical high-resolution spectra of the three stars in the spectral regions around λ 5885 Å, λ 6563 Å, and λ 8685 Å are shown. The following features should be noted.

In HD 139614, H_α displays a single-peaked emission profile; the λ 5876 Å HeI line is seen as a broad CS emission profile; the NaI D_1 and D_2 lines are in absorption, with a width which is similar to that of the NI lines at 8680 and 8688 Å; the Paschen 13 line of HI (λ 8665 Å) appears in absorption.

HD 142666 shows a H_α double-peaked emission profile with a deep absorption reversal reaching well below the adjacent continuum; a broad HeI λ 5876 Å absorption is observed; the NaI D profile consists of a narrow, strong component, superimposed on a broader (Δv = 56 km s^{-1}) component; P13 is seen in absorption.

HD 144432 also shows a double-peaked H_α profile, with a deep absorption reversal going below the continuum, but here the red component is much stronger than the blue component; a broad HeI λ 5876 Å emission line is observed; the sodium lines appear in emission, with two narrow IS absorption components; P13 is now seen in emission.

A value for $v \sin i$ was derived from other spectra showing photospheric lines and a values of 13 km s^{-1} for HD 139614, 56 km s^{-1} for HD 142666 and 54 km s^{-1} for HD 144432 were found.

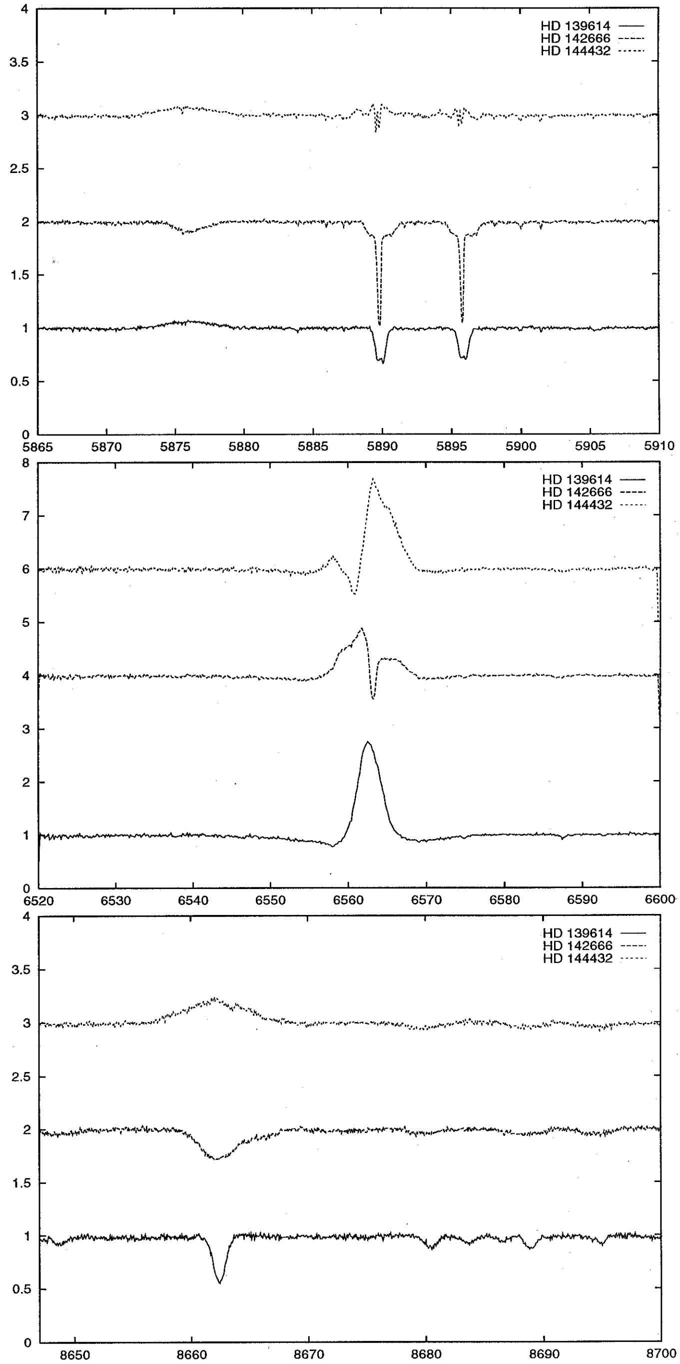

Fig. 3. Normalised spectra of the three program stars around λ 5885 Å, λ 6563 Å, and λ 8685 Å. The star HD 142666 shows CS absorption lines, while the stars HD 139614 and HD 144432 show CS emission lines.

4.2. Near-IR spectroscopy

In Fig. 4 the obtained near-IR spectra around the HeI 1.08 μm line are shown. The observed features are summarised in Table 4.

Table 4. Summary of the near-IR spectral features for the program stars.

No	identification	1.08 μm He I	1.64 μm Fe II	2.16 μm Br_γ
1	HD 139614	emission	no	emission
2	HD 142666	absorption	no	emission
3	HD 144432	inverse P Cygni	emission	emission

5. Discussion

As shown above, the three program stars, of spectral type A7-A9 Ve, have almost identical UV-optical energy distributions. The observed IR excesses are also very similar, and can be fitted with an optically-thin dust model, made up of both a cool and a hot component (Malfait et al. 1997). Sylvester et al. (1996) pointed out that high-resolution IR spectra indicate some differences between the dust features that are observed. The differences between these three stars become clearest, however, when the photometric behaviour and the circumstellar spectral lines are studied. It is the opinion of the authors that these differences are not intrinsic, but are mainly due to the circumstellar matter being confined to disks with different orientations with respect to the observer.

The fact that HD 142666 shows irregular brightness variations, and reddens when becoming fainter, can be explained by assuming that the brightness decrease is caused by dense dust clouds revolving around the star. As this cloud intersects the line of sight, obscuration takes place, while the scattering and absorption of the starlight causes the stellar reddening. This process, called variable circumstellar absorption is the most popular explanation for Herbig Ae/Be stars with 'nonperiodic Algol-like minima', for which UX Ori is the prototype (Grinin et al. 1994).

A very basic calculation leads us to the conclusion that a brightness change of 1.2 magnitude can be caused by an opaque (optical depth τ_{cloud} = 1.1) dust cloud acting as a natural coronograph, obscuring the stellar surface. These clouds have typical sizes of several stellar radii (Grinin & Tambovtseva 1995). From the initial reddening it can be deduced that the size a of the dust particles is only slightly larger than that of the ISM, and for a a value of 0.1 micron can be asumed. For silicate grains the effectivity factor Q_{ext} is about 0.5 for visual wavelengths (Grinin V.P., private communication). An expression for the optical depth of a cloud is:

$$\tau_{cloud} = \pi a^2 Q_{ext} N_d L_{cloud} \quad (1)$$

with L_{cloud} its characteristic size and N_d the mean number density of grains in the cloud. The size of the cloud is estimated to be $10R_\odot$, or about $10^{12}cm$. From (1) and τ_{cloud} = 1.1 a mean number density $N_d = 7.10^{-2}cm^{-3}$ is calculated and finally the mass of the dust in the cloud is estimated as $M_d = 10^{20}g$ (Grinin V.P.,private communication).

The nature and orbit of these clouds, however, is still a matter of debate (Herbst et al. 1994). In an UV and optical study of UXors by Eaton & Herbst (1995) a color reversal (first reddening when fading, then becoming bluer) is shown for several Herbig Ae/Be and TTS stars. In Fig. 2 of Eaton & Herbst (1995) it can be seen that this reversal only takes place when the star is already obscured by 1.6 magnitude, an amount of obscuration which is never reached in HD 142666. So, the fact that HD 142666 shows reddening while fading, but not a color reversal, as is observed in UX Ori (Grinin et al. 1994) is because the stellar light is not dimmed enough.

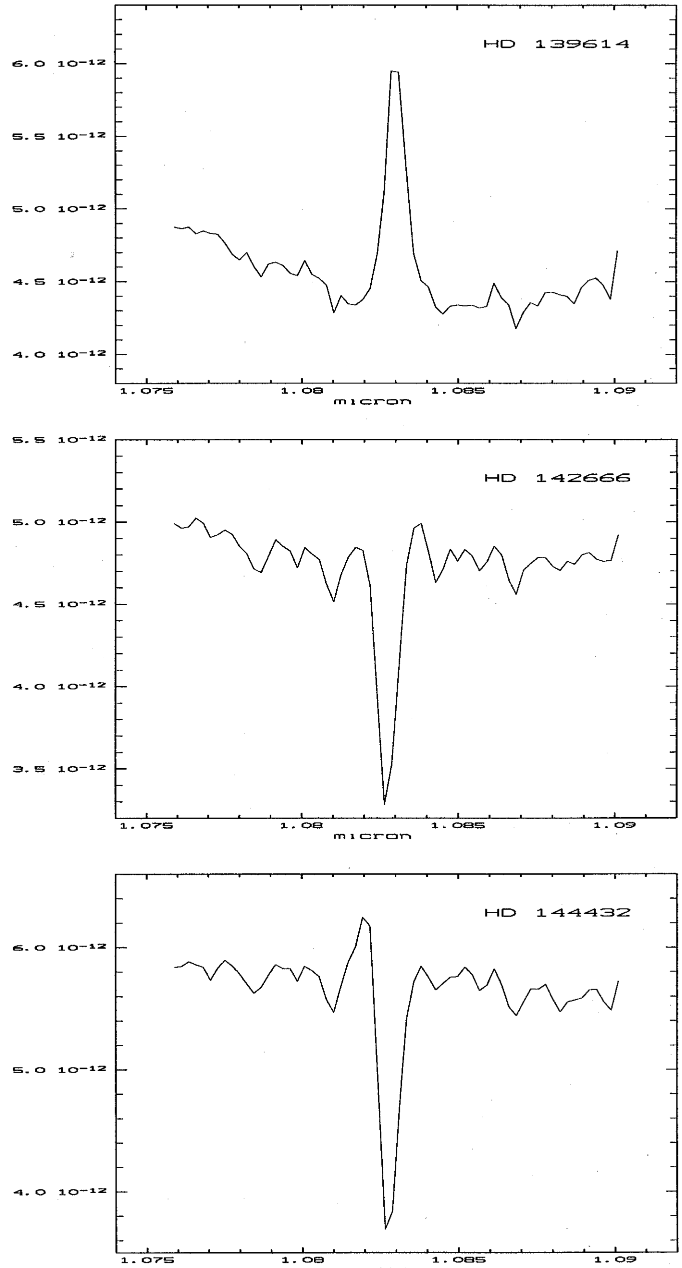

Fig. 4. The three program stars around the HeI λ 1.08 μm; flux is in arbitrary units. The star HD 142666 shows HeI in absorption, while the star HD 139614 shows CS emission lines, and HD 144432 shows an inverse P Cygni feature.

The amount of circumstellar reddening that HD 142666 shows at maximum brightness indicates that HD 142666 has a substantial amount of CS material in the line of sight, while the two fairly constant stars HD 139614 and HD 144432 do not show evidence for material in their line of sight, since they do not show appreciable circumstellar reddening.

Regarding the stars HD 139614 and HD 144432, it is probable that these dense clouds (if present) do not appear in their line of sight, as these stars do not show any substantial brightness changes. Absence of such clouds in the line of sight and a negligible amount of CS extinction, together with the observation of an IR excess caused by CS dust, is a clear indication of a disk structure around the star oriented pole-on with respect to the observer.

The hypothesis that the photometric behaviour of HD 142666 is caused by a disk orientated edge-on, and that the non-variability of the stars HD 139614 and HD 144432 suggests a more pole-on orientated disk is consistent with the observations of CS spectral features described in this paper. The optical CS lines HeI λ 5876 Å in both stars, and NaI D in HD 144432, show emission profiles, while they are seen in absorption in HD 142666. IRSPEC data of the HeI 1.08 μm line further confirm this interpretation, HD 142666 being the only star showing pure absorption, while the other two stars show the same (CS) features in emission.

An alternative explanation for the difference in photometric behaviour of the program stars might be a difference in dust distribution: consider a spherical symmetric envelope in which the CS material around HD 142666 is in a clumpy distribution but homogeneous around the two other stars. This model could indeed account for the photometric behaviour of the stars, but not for the observed difference in CS extinction at maximum brightness and the CS spectral lines. The three stars show a very similar IR excess, so the total amount of dust must be roughly equal. However, the CS extinction for HD 142666 at maximum brightness, when there are no clumps in the line of sight, is still much larger than for the other two stars. This crucial difference cannot be explained by a spherically symmetric envelope.

If the small value observed for the $v \sin i$ of HD 139614 is considered, it is not unlikely that this object is seen pole-on. The other two stars, HD 142666 and HD 144432, have almost the same $v \sin i$ value, implying that, if this interpretation is to hold, HD 142666 must be rotating more slowly than HD 144432.

6. Conclusion

The spectral energy distribution, the photometric behaviour and spectral lines of the Herbig Ae stars HD 139614, HD 142666 and HD 144432 were analysed. From this analysis, it became clear that *in sé* these three stars are almost identical: their SED and spectral type are much alike. The observed differences in spectral features, CS extinction and photometric variability can be very well explained by assuming a different viewing angle for a circumstellar disk whose morphology is very similar in the three cases.

In the introduction, it was stated that the modeling of the SEDs of Haebe stars leads to conflicting results, and that additional observations of different kinds are necessary as further constraints. Among these observations, studies of the variability of the circumstellar absorption and emission appear to be useful.

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