A Study of the Candidates for Herbig Ae/Be Stars HD 35929 and HD 203024

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Abstract:

We carried out photometric observations of the two bright candidates for Herbig Ae/Be stars HD 35929 and HD 203024 over the period 1993-1996 in the wavelength range 0.3-2.5 μm and high-resolution spectroscopic observations of HD 203024. Small near-infrared excesses were detected in both stars. HD 35929 exhibits light variations at a $0^m.2$ level. In HD 203024, the optical variability does not exceed $0^m.1$; its spectrum shows an emission component of the Hα line. Estimates for the fundamental parameters of the stars were obtained: spectral type B9.5 V, color excess $E_{B-V} = 0^m.20$, and a distance of ~300 pc for HD 203024; spectral type A8 V, $E_{B-V} = 0^m.15$, and a distance of ~100 pc for MD 35929. The two stars are in a late evolutionary stage before the arrival at the main sequence; HD 35929 appears to be more evolved than HD 203024. The latter may belong to the star-forming region 1 Cep.

Article:

INTRODUCTION

Many early-type stars are surrounded by circumstellar shells, which are formed either by matter of the parent cloud, from which they originated, or by stellar wind. Emission lines and infrared excesses are the most pronounced indicators of the shells. In most cases, these properties are observed; the latter may be related to the emission of both circumstellar gas and dust. Dust in the shells is produced either in the outer regions of stellar wind in stars with strong outflow of matter or is left over since the formation of the star. The second case is generally realized for stars with weak stellar winds and long-wavelength infrared excesses, which cannot be explained by the gas emission alone. The discovery of such excesses in A-type main-sequence stars during the IRAS survey has increased the interest in the evolution of circumstellar shells around these stars. Stars of the same masses in the preceding evolutionary stage, Herbig Ae/Be stars, show fairly strong variability of light and parameters of the emission lines (see, e.g., Kolotilov 1977). Until recently, attention has been focused mainly on the Herbig Ae/Be stars, which are associated with or located near star-forming regions. The IRAS survey has also revealed fairly strong infra-red excesses in A-type stars that lie outside these regions and/or are not surrounded by visible nebulae. About twenty such stars were discovered during the identification of IRAS and SAO sources (Oudmaijer *et al.* 1992). They were subsequently included in the catalog of The *et al.* (1994) as candidates for Herbig Ae/Be stars. Despite being fairly bright ($7\text{-}9^m$), most of them are virtually unexplored: only the discovery of a long-wavelength infrared excess has attracted the attention of astronomers to them. Even the first photometric observations of the stars recognized by Oudmaijer *et al.* (1992) showed that their behavior differs greatly; some of them exhibit light variations with an amplitude as large as $2\text{-}3^m$ (e.g., HD 34282 and HD 142666), others (HD 58647) show essentially constant light (Bogaert and Waelkens 1991). Spectroscopic observations of HD 36112, which also belongs to this group, have revealed variability of emission-line profiles (Pogodin 1995). An analysis of infrared excesses in a large sample of Herbig Ae/Be stars, candidates for these objects, and β Pic stars (Miroshnichenko *et al.* 1996) has indicated that the infrared excesses in stars observed in nebulae are, on numerous occasions, not stronger than those in stars without nebulae. Thus, new observations of these objects are crucial for a detailed study of the evolution of stars and their shells immediately before the arrival at the main sequence. In this paper, we present the results of our observations of two such stars: HD 35929 and HD 203024.

OBSERVATIONS

We carried out photometric observations in the Johnson *UBVRIJHK* system between March 1994 and January 1996 with two telescopes of the Fesenkov Astrophysical Institute (Academy of Sciences of Kazakhstan)—the 1-m telescope of the Assy Observatory (March 1994) and the 1-m telescope of the Tyan'-Shan' Observatory near Alma-Ata Great Lake (January 1995—January 1996)--using the photometer/polarimeter of the Pulkovo Astronomical Observatory (Bergner *et al.* 1988). We performed our observations through a 26" aperture by subtracting the sky background at an angular distance of 84" using the differential method. A total of ten *UBVRI* observations of FID 35 929 and eleven observations of HD 203 024 were obtained. Their results are summarized in Tables 1 and 2.

Table 1. *UBVRI* photometry for HD 35929

JD 2400000+	*V*	*U–B*	*B–V*	*V–R*	*V–I*
49427.08	8.22	0.00	0.34	0.45	0.77
49735.16	8.13	0.11	0.41	0.27	0.56
49738.21	8.18	0.05	0.40	0.32	0.58
49740.20	8.14	0.13	0.42	0.35	0.62
49741.21	8.10	0.14	0.43	0.26	0.56
49742.20	8.15	0.16	0.40	0.26	0.46
49744.19	8.10	0.15	0.40	0.28	0.55
50096.25	8.04	0.16	0.53	0.25	0.50
50101.23	8.07	0.15	0.47	0.36	0.64
50107.23	8.13	0.11	0.41	0.34	0.64

Table 2. *UBVRI* photometry for HD 203024

JD 2400000+	*V*	*U–B*	*B–V*	*V–R*	*V–I*
49942.34	8.87	0.13	0.13	0.16	0.22
49943.36	8.89	0.06	0.17	0.16	0.25
49944.29	8.87	0.06	0.20	0.16	0.27
49949.36	8.92	0.06	0.17	0.20	0.34
49953.34	8.88	0.10	0.19	0.15	0.22
49955.27	8.91	0.06	0.15	0.19	0.35
49956.33	8.93	0.06	0.13	0.20	0.30
49957.36	8.86	0.06	0.19	0.18	0.30
49960.27	8.95	0.03	0.15	0.13	0.23
49963.25	8.91	0.03	0.15	0.20	0.35
49964.26	8.92	0.05	0.09	0.23	0.34

The accuracy of flux measurements for the stars under study in each photometric band was no worse than 1%. At some dates, we performed infrared observations simultaneously with optical photometry. Their results are discussed in the next section. The comparison stars were HI) 35 659 (spectral type A3) in the *UBVRI* bands and BS 1784 in the MK bands for HD 35 929 and HD 201731 (A3), HD 202 986 (FO), and BS 8162, respectively, for HD 203 024. We took *BVR* photometry for the comparison stars from the catalog of Kornilov *et al.* (1991) and infrared photometry from the catalog of Gezari *et al.* (1993); the *U*—*B* and *R*—*I* color indices were obtained by us. In January—February 1995, five *WBVR* observations of HD 35929 were performed by T.M. Pogrosheva with the 48-cm telescope of the Tyan'-Shan' Observatory (Table 3).

Table 3. *WBVR* photometry for HD 35929

JD 2400000+	*V*	*W–B*	*B–V*	*V–R*
49748.148	8.13	–0.04	0.40	0.39
49750.145	8.10	–0.03	0.38	0.38
49770.105	8.12	–0.03	0.38	0.39
49773.090	8.11	–0.02	0.38	0.39
49774.102	8.13	–0.03	0.39	0.39

M.A. Pogodin obtained CCD spectra of HD 203 024 on January 11, 1996 in the regions 5850-5918 and 6526-6594 Å with a resolution of $\lambda/\Delta\lambda \sim 30000$ using the coude spectrograph of the 2.6-m Crimean Astrophysical Observatory telescope. In the reduction of the observations, we corrected the data for the Earth's orbital motion.

ANALYSIS OF OBSERVATIONS

The available information on the objects under consideration is rattier scanty. So far, these stars have not been studied separately; only Oudmaijer *et al.* (1992) recognized them as candidates for Herbig Ae/Be stars. What they also have in common is that they have not been reported previously as emission-line objects. In this section, we consider the basic properties of the stars under study, which can be determined from an analysis of published and our data.

HD 35929. The star lies near the star-forming region 1 Ori A (Shevchenko 1989), but, as will be shown below, it is much closer to the Sun. Photoelectric photometry for the star in the Strömgren system was published by Olsen (1983) and Perry (1991). Its visual magnitude and the continuum energy distribution over the same wavelength range are very similar to ours. Our observations in the Johnson system are in good agreement with the *WBVR* photometry (Kornilov *et al.* 1991), It follows from the statistical relation between the *U-B* and *W-B* colors for 304 bright dwarfs and sub-dwarfs of spectral types A5—F9 that *W*—*B* = -0.04 corresponds to *U*—*B* = 0.05. This value is somewhat lower than the observed color index $\overline{(U-B)}$ = 0.15 in the Johnson system due possibly to either the use of the bluer comparison star HD 35640 (W-B = -0.24) or a temporary increase of this color index in HD 35929 itself, which we have also observed previously (see Table 1).

In the HD catalog, the spectral type was estimated as A5; however, based on the *uvby* photometry, Olsen (1979) classified the star as gF5. The β index (Perry 1991) corresponds to the spectral type F3—F4 V (Strajzhys 1977). Our mean optical color indices suggest that the star appears to be of spectral type A8 V and slightly reddened, $E_{B-V} = 0^m.5$ (Fig. 1). The color indices of another candidate for Herbig Ae/Be stars, HD 36112, which are plotted in Fig. 1 and which lie virtually on the same reddening line as the color indices of HD 35929, also imply the spectral type A8 V (Pogodin 1996). This reddening line also intersects the line of normal colors for dwarfs near the spectral type B9. This spectral classification of the star is unlikely, because the color excess in this case is $E_{B-V} = 0^m.47$, suggesting the presence of at least small polarization. The polarization was measured by Yudin and Evans (1996). It is 0.08% in *V*, a value that is close to the mean measurement error. In addition, the ratios of the color excesses at wavelengths from 0.3 to 0.9 μm for the normal color indices of type A8 all correspond to the mean interstellar ratios (Savage and Mathis 1979); i.e., in this spectral region there is no excess emission which may be associated with a circumstellar shell. The disagreement with the classification of Olsen (1979) results from the fact that reddened A—F stars of luminosity class V and unreddened stars of luminosity class DI cannot be separated in the Strömgren system (Strajzhys 1977). The discrepancy between the observed β index and the index of type A8 may be due to the presence of a weak emission feature in the Hβ line. We plan to perform spectroscopic observations to refine the classification of the star and to search for emission lines in late 1996 through early 1997. The star was observed in the ultra-violet from the TD-1 satellite (Thompson *et al.* 1978). 'These data are in good agreement with the model spectral energy distribution for a dwarf with an effective temperature of 8000 K (Kurucz 1979), which approximately corresponds to the spectral type A8 (Fig. 2a).

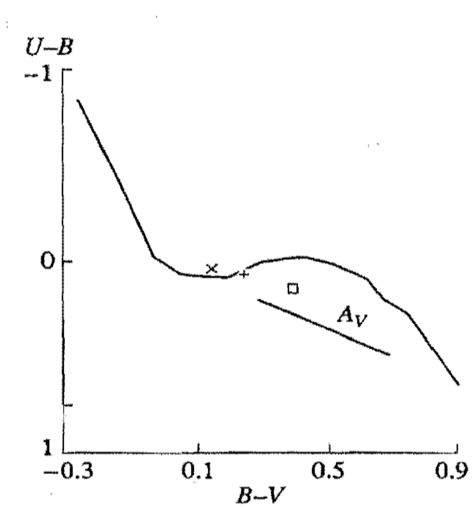

Fig. 1. The (*U–B*)–(*B–V*) diagram. The normal color indices of dwarfs (Straizhys 1977) are indicated by the solid line. The positions of the stars are marked by different symbols: □ for HD 35929, × for HD 203024, and + for HD 36112. The segment with A_V is the vector of interstellar reddening.

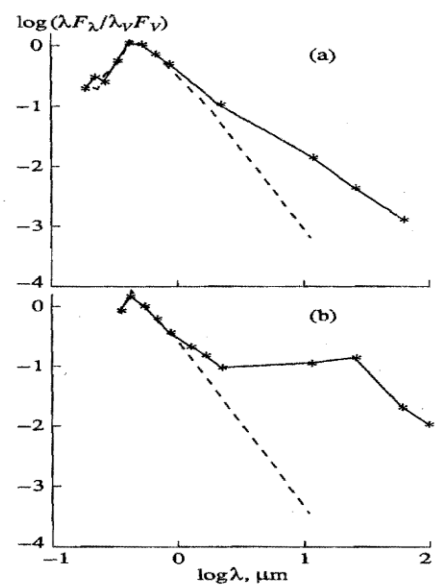

Fig. 2. (a) The energy distribution in the spectrum of HD 35929 (solid lines); the model of Kurucz (1979) for $T_* =$ 8000 K and $\log g = 4.0$ (dashed line). (b) The energy distribution in the spectrum of HD 203024 (solid line); the model of Kurucz (1979) for $T_* = 11000$ K and $\log g = 4.0$ (dashed line).

While performing photographic photometry of a large sky region in Orion, Strajzhys (1963) measured the visual magnitude of the star, $V_{pg} = 8^m.12$, and noted variations in its magnitude B_{pg} in the range $8^m.48$-$8^m.97$ on four plates taken at different times. Based on these data, Kukarkin *et al.* (1982) included this object in the catalog of suspected variable stars (NSV 2002). Our observations revealed optical variability of HD 35 929 in the range $0^m.2$, which is considerably greater than the accuracy of the measurements even with allowance for the uncertainties in passing to the standard Johnson system. Thus, the suspected variability of the star has been confirmed, although its amplitude was found to be somewhat smaller.

We carried out near-infrared *(K)* observations of HD 35 929 on January 17-18 and 22-23, 1995 simultaneously with the optical observations. The mean magnitude is $K = 6^m.8 \pm 0^m.2$. Thus, excess emission, which should probably be attributed to the circumstellar dust shell, is observed even in the near infrared. The circum-stellar gas cannot make an appreciable contribution to this excess, because the emission lines appear to be very weak, while its contribution to the continuum rarely exceeds $0^m.5$ at 2.2 μm even in the presence of strong emission features. The analysis of infrared excesses in a large group of A-type stars, which was performed by Miroshnichenko *et al.* (1996), shows that the excess in HD 35929 is rather small, suggesting that the star is very close to the main sequence. Assuming that the visual magnitude corrected for the interstellar extinction is $V_0 = 7^m.65$ and that the absolute visual magnitude is $M_V = 2^m.8$ for type A8 corresponding to the zero-age main sequence (Strajzhys and Kurilene 1981), we find the distance to the star to be slightly less than 100 pc. Thus, HD 35929 is one of the intermediate-mass stars nearest the Sun which are in the pre-main-sequence stage or which have reached the main sequence very recently.

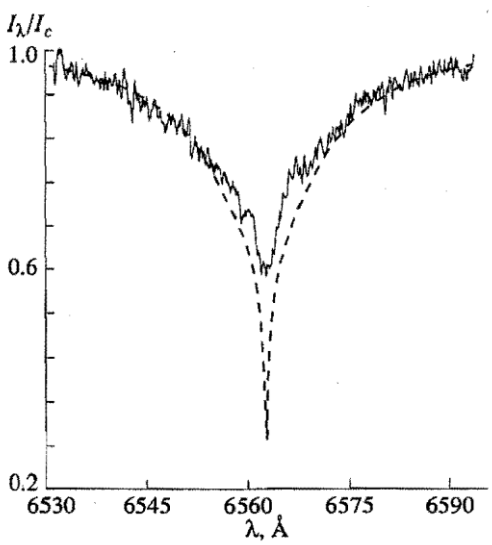

Fig. 3. The spectrum of HD 203024 in the Hα region in units of the continuum (solid line) and the model profile (Kurucz 1979) for $T_* = 11000$ K and $\log g = 4.0$ (dashed line).

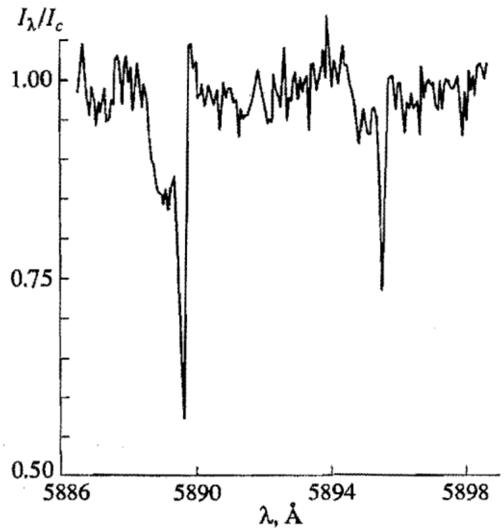

Fig. 4. The spectrum of HD 203024 in the region of the Hα and Na $D_{1,2}$ lines in units of the continuum.

HD 203024. This object lies at an angular distance of 2.5 degrees from the compact star-forming region 1 Cep (Shevchenko 1989), which harbors one of the brightest Herbig Ae/Be stars—HD 200775. Based on the Strömgren photometry, Pfau *et al.* (1987) estimated the reddening, spectral type, and distance to the star: $E_{b-y} = 0^m.14$, B9, and 346 pc, respectively. As in the case of HD 35929, the continuum energy distribution derived from these data is in good agreement with our results (Fig, 2b). Our averaged color indices of the star in the *UBVRI* system, corrected for interstellar reddening, lead us to conclude that they are in best agreement with the spectral type B9.5 V (Strajzhys 1977) for the color excess $E_{B-V} = 0^m.20$. For $M_V = 1^m.5$ for type B9.5 of the zero-age main sequence (Strajzhys and Kurilene 1981) and $V_0 = 8^m.3$, we estimated the distance to be 250 pc, a value that is rather close to the distance of 300 pc obtained for the star-forming region 1 Cep (Shevchenko 1989). The disagreement with the distance estimate of Pfau *et al.* (1987) is probably attributable to the use of different values for the luminosity of the star. If we consider the data available for HD 200775 [$\bar{V} = 7^m.4$, $E_{B-V}= 0^m.59$, and spectral type B3 V (Shevchenko 1989)], then using the same calibration for the luminosities of ZAMS stars ($M_V = -1^m.0$), we find for B3 V that the distance moduli of the two stars are essentially identical. Thus, within the accuracy of all the estimates obtained, it can be assumed that HD 203024 belongs to 1 Cep. If the distance to this star-forming region is 300 pc, the separation between the stars will be ~10 pc.

We observed optical light variations in the star at a level of $0^m.10$ in the *UBV* bands and 0'715 in the *RI* bands. The infrared brightness of the object proved to be close to the sensitivity threshold of the instrument, resulting in large uncertainties in the flux measurements. The infrared observations that we carried out on six nights between August 12 and 27, 1995 simultaneously with the optical observations yielded the following averaged estimates: $J = 8^m.25 \pm 0^m.20$, $H = 7^m.95 \pm 0^m.25$, and $K = 7^m.7 \pm 0^m.3$, Thus, the near-infra-red excess is very small; in particular, it is scarcely noticeable in the *J* band, while in the *H* and *K* bands its magnitude does not exceed the accuracy of our measurements. Nevertheless, the rather large excess at longer wavelengths is comparable to the excesses in such Herbig Ae/Be stars as HD 31 648 and HD 36 112 (Miroshnichenko *et al*, 1996).

The region of the spectrum that contains the Hα line shows no distinct emission feature. However, a comparison with model profiles (Kurucz 1979) reveals a weak emission component (Fig. 3). We compared the observed profile with the theoretical profile calculated for a star with effective temperatures in the range 10000-12000 K (log g = 4.0). In our comparison, we introduced a scaling factor into the observed profile (because of the narrowness of the spectral region in which it was obtained, the continuum of the star was not covered), trying to best fit the line wings, in which there was virtually no emission feature. The best fit was obtained for a temperature of 11 000 K. The line equivalent width, which was found by subtracting the model profile from the observed profile, turned out to be 1.24 Å.

The second region of the spectrum that contains the Na I $D_{1,2}$ lines exhibits narrow interstellar components with equivalent widths of 0.11 Å (the D_2 line) and 0.06 Å (the D_1 line) and with centroid velocities of-18.8 and -17.8 km s^{-1}, respectively, as well as broader, probably circumstellar components (Fig. 4). The latter have equivalent widths of 0.08 Å (D_2) and 0.03 Å (D_1) and centroid velocities of -50.4 and -46.8 km s^{-1}, respectively. In turn, each component consists of several sub-components. There is also the He I λ5876 Å line in this region of the spectrum. The photospheric spectrum of a star with this effective temperature must exhibit a weak absorption feature here [with a depth of ~0.05 of the continuum level (Böhm and Catala 1995)] The observed noise prevents a reliable identification of the line, but the small intensity dip near λ5876 Å suggests that the observed profile of this line appears to differ only slightly from the photospheric profile.

DISCUSSION

Our observations of two bright stars, which previously have not attracted the attention of astronomers, have revealed that they have small near-infrared excesses and light variations, reinforcing the belief that they belong to the group of pre-main-sequence objects. However, their positions on the evolutionary tracks appear to differ somewhat. According to Miroshnichenko *et al.* (1996), as Herbig Ae/Be stars with masses of ~2-4 M⊙ approach the main sequence, they primarily lose the near-infrared excess. At the same time, the range in which the excess is observed shifts longward. Stars that are closer to the main sequence exhibit progressively smaller excesses at progressively longer wavelengths. HD 35929 shows a very weak near-infrared excess (the observed light exceeds the photospheric light by $\sim 0^m.5$ in *K)* and a far-infrared excess that is considerably smaller than in most of the Herbig Ae/Be stars. HD 203024 has almost the same near-infrared excess, while its far-infrared excess is still great, although part of it may be due to the emission of matter in the star-forming region near which the star lies. The vanishingly weak emission component of the Ha line suggests that this star will apparently soon become a young main-sequence star. The same energy distribution is observed in such objects as TY CrA and HD 176386, which also lie near a star-forming region, do not exhibit emission lines at all, and are considered to be young main-sequence stars (Bibo *et al.* 1992), These stars show scarcely any variability, which is also the case for HD 203024. However, the latter requires a more thorough confirmation, because some of the young stars that have long exhibited very small light variations suddenly again turn out to be strongly variable, for example, V451 Ori (Shevchenko 1989; Koval'chuk 1990). On the one hand, this may be the effect of observational selection that results from the observations of the objects being nonregular. On the other hand, this may be a reflection of the properties of circumstellar shells: their geometric properties and the degree of inhomogeneity. Thus, it is quite probable that greater light variations may be detected in HD 35929. The probability is lower for HD 203024, because most of the Herbig Ae/Be stars of spectral types earlier than A0 are weakly variable (Bibo and Thé 1989).

A comparison of some of the observed properties of HD 200775 and HD 203024 is in order. "the former exhibits stronger emission lines and an infrared excess, suggesting a large amount of matter in its shell. This star is more massive and, hence, the time of its pre-main-sequence evolution is smaller. This leads us to conclude that the formation of HD 203024 began earlier than that of HD 200775. A comparison of the profiles of Na I lines in the spectra of these stars also leads to several conclusions. The shortward shifted absorption components of the lines in HD 203024 suggest that the matter moves along the line of sight away from the star, i.e., the stellar wind. Furthermore, the plane of the predominant concentration of matter in its shell appears to make a small angle with the line of sight, It thus follows that if the dust component of the shell is still fairly inhomogeneous, the star can show light variations. The spectrum of HD 200775 that contains the region with the D_2 line was obtained in November 1994 with the 6-m Special Astrophysical Observatory telescope (~0.2 Å resolution). Its profile contains only one narrow component with an equivalent width of 0.25 Å and velocity of -17.7 km s^{-1}, a value that matches the velocity determined for the components of this line in HD 203024. The great intensity of the line in HD 200775 is due to the stronger interstellar extinction, while the absence of circumstellar components suggests that the shell is oriented at a large angle to the line of sight.

CONCLUSION

We used our photometric and spectroscopic observations to study two early-type stars, the candidates for pre-main-sequence objects HD 35929 and HD 203024. Based on the photometric data, we classified HD 35929 and HD 203024 as A8 V and B9.5 V stars, respectively. Weak near-infrared excesses were detected in both stars. The spectrum of HD 203024 shows a weak emission component in the Hα line. The amplitude of the light variations in HD 203024 does not exceed $0^m.1$ in the optical photometric bands. The observed variability of HD 35 929 has an amplitude of about $0^m.2$. However, it may be larger, because the spectral type of the star is rather late; in addition, variability at a level of $0^m.5$ was noted previously (Strajzhys 1963). It follows from our analysis that HD 35 929 is in a somewhat more advanced evolutionary stage than HD 203 024. Both stars, however, are probably very close to the main sequence.

Infrared observations with higher signal-to-noise ratio should be made in order to refine the magnitudes of infrared excesses in both stars. Of particular interest are observations of HD 203 024 in the *LM* bands, because it is in this range that the excess in objects in this evolutionary stage begins to increase. Such observations will make it possible to study the evolution of circumstellar shells around Habig Ae/Be stars in more detail. Further spectroscopic observations are needed to study the dynamics of the shell around HD 203 024. High-resolution spectroscopic observations should also be performed for HD 35 929, whose possible emission component in the Hα line must be very weak or lacking. Of interest is to perform a photometric monitoring of both stars at optical wavelengths in order to establish the degree of inhomogeneity of the shells. Since HD 35 929 is an object of the HIPPARCOS input catalog (HIC 25 546), the luminosity and evolutionary status of this star can be refined by measuring its parallax.

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