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Spectral energy distributions and model atmosphere parameters of the quadruple system ADS11061

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Abstract. The spectral energy distribution between λ 3700 Å and λ 8100 Å of the two subsystems 41Dra and 40Dra of the multiple system ADS11061 has been introduced with a description of methodology of getting the spectra on Carl-Zeiss-Jena 1 m telescope of Special Astrophysical Observatory. The spectral type and luminosity class for each of them have been deduced and compared with earlier investigations, the B, V, and R magnitudes and $B-V$ colour indices have been computed, the interstellar reddening of both subsystems have been calculated and an envelope around 40Dra has been suggested, model atmosphere parameters of the subsystem 40Dra' components have been derived: $T_{eff}^{Ba} = 6100°$ K, $T_{eff}^{Bb} = 6100°$ K, lg g_{Ba}=4.03, lg g_{Bb}=4.20, $R_{Ba} = 1.82R_{\odot}$, $R_{Bb} = 1.44R_{\odot}$, and finally the formation and evolution of the system have been discussed depending on the filament fragmentation process.

Key words: stars: spectrophotometry — stars: binaries — binaries: individual: 40Dra, 41Dra — stars: atmospheric modeling

1. Introduction

The visual double star ADS11061 was known to be a quadruple hierarchical system consisting of two double-lined spectroscopic binaries separated by 19″ (Tokovinin, 1995), those are: ADS11061A(= 41Dra = Hip88136 = HR6810 = HD166866) and ADS11061B (= 40Dra = Hip88127 = HR6809 = HD166865). Table 1 contains the Bright Star Catalogue's data of the system (Hoffleit & Jachek, 1982), and Table 2 contains data from Hipparcos and Tycho Catalogues (ESA, 1997).

In addition to the discovery of duplicity of subsystem A (41Dra), Tokovinin in 1995 also improved the spectroscopic orbit of 40Dra, and estimated the physical and geometrical elements of the system (Table 3), and by his work he raised the importance of studying such system in solving the problem of multiple-star system formation.

Because it is a too close binary, the short-period subsystem Bab (40Dra) was not resolved by Balega et al. (1997) with the 6 m telescope of the Special Astrophysical Observatory, while Aab (41Dra) was resolved by means of diffraction-limited visible and infrared speckle interferometry, and with observations started in 1993 they obtained the following:

$$P = 3.4146\text{years}, T = 1994.5988, e = 0.9754,$$

$$a = 70\text{mas}, i = 50°, \Omega = 358°, \omega = 130°,$$

$$M_{Aa} = (1.26 \pm 0.20)M_{\odot}, M_{Ab} = (1.18 \pm 0.20)M_{\odot},$$

$$M_{bol}^{a} = 2^{m}.92 \pm 0^{m}.32, M_{bol}^{b} = 3^{m}.30 \pm 0^{m}.32.$$

Table 1: *Data from BS Catalogue*

	ADS11061A	ADS11061B
α_{2000}	$18^h00^m09^s$	$18^h00^m03^s$
δ_{2000}	+80°00′15″	+80°00′03″
HR	6810.41Dra	6809.40Dra
HD	166866	166865
V	$5^m.68$	$6^m.04$
$B-V$	$0^m.50$	$0^m.51$
$U-B$	$-0^m.01$	$-0^m.01$
Spectral type	F7	F7

Table 2: *Data from Hipparcos and Tycho Catalogues*

	ADS11061A	ADS11061B
$V_J(Hipp)$	$5^m.74$	$6^m.11$
$(B-V)_J(Hipp)$	$0^m.516$	$0^m.521$
B_T	$6^m.274$	$6^m.622$
V_T	$5^m.731$	$6^m.072$
$V_J(Tycho)$	$5^m.68$	$6^m.01$
$(B-V)_J(Tycho)$	$0^m.505$	$0^m.511$

Table 4: *Log of observations*

Night	ADU	No. of exposures for each star	Exposure time (sec.)	Seeing ($''$)
22 July 2001	3	12 for 41Dra and 10 for 40Dra	10-20	2
9 August 2001	3	5 for 41Dra and 3 for 40Dra	5-10	1.5
25 September 2001	3	6 for 41Dra and 3 for 40Dra	5-10	1.5
10 October 2001	15	6 for 41Dra and 3 for 40Dra	10-30	1
23 January 2002	15	10 for 41Dra and 7 for 40Dra	10-30	1.2
25 January 2002	15	6 for 41Dra and 7 for 40Dra	10-30	1 .5

Table 3: *Spectroscopic elements of orbits and physical parameters of the system estimated by Tokovinin (1995)*

	41Dra	40Dra
P, days	1247.2	10.52785
T, JDH	49571.047	48000.008
e	0.9754	0.374
ω, °	127.6	246.2
K_1, km s^{-1}	44.79	39.14
K_2, km s^{-1}	0.17	42.91
γ, km s^{-1}	5.84	5.76
χ^2, N	62.5 82	63.2 59
$\sigma_1 2$, km s^{-1}	1.06	0.80
$q = M_2/M_1$	0.912	0.935
$(M_1 + M_2)\sin^3 i, M_\odot$	1.100	0.480
i	50°	35°
a, AU	3.040	0.125
α,$''$	0.085	0.003
$a(1-e)$, AU	0.0748	0.0747

This work is a contribution to the study of multiple systems through the quadruple system ADS11061 from a moderate resolution spectrophotometrical scope represented by the spectral energy distribution (SED) of both subsystems 40Dra (ADS11061B) and 41Dra (ADS11061A).

The importance of such observational contribution arises from the need of an accurate determination of spectral type and luminosity class of each of the four components of the system, since there was a large difference in spectral type determination between Tokovinin (1995), who estimated F7V for each of the four components, and the Hipparcos Input Catalogue, which gives K2V (Turon et al., 1992). This is in addition to the important role of the SED in determination of physical parameters for each of the four components by atmospheric modeling each of the subsystems on the basis of Kurucz model atmospheres.

Another important point of such work arises from the need of understanding the nature of formation and evolution of high eccentric orbit binary systems, in which the dynamical interaction can be changed following the state of the components on the orbit, where the system ADS11061 forms a unique case of such systems since it contains the eccentric orbit subsystem 41Dra .

2. Observations and data analysis

Spectra were obtained using a low resolution grating (325/4° grooves/mm, 5.9 Å/px reciprocal dispersion) within the UAGS spectrograph at the Cassegrain focus of the Carl Zeiss Jena (Zeiss-1000) 1 m telescope of SAO RAS during several observational nights listed in Table 4.

The instrument has an ISD015 Å 530×580 px CCD detector, where either ADU 7 or 15 was applied in clear nights instead of ADU 3 to avoid overexposed spectra of such a bright star. A 0.75 mm slit width was used to encompass all light from the star at a seeing of 1.5$''$, and it was rotated (by changing the angle of the instrument's table) to a suitable direction to prevent the effect of nearby stars on the spectra.

Two positional angles for the grating were used to cover the spectral range between 3700Å and 8100Å, 29° for the blue part and 30°30$'$ for the red part. This was done for two reasons, first, because of small dimensions of the detector which does not cover this spectral range and, second, in order to overcome the falling sensitivity of the detector in the blue part of the spectrum by applying longer integration times in this part, and there were at least 500Å of overlap between the two regions, allowing us further checks on our internal agreement.

HD217086 and HD192281 (Massey et al., 1988) were used as standard stars for the calibration of the detector. All frames of the standard stars and objects were flat-fielded, sky subtracted, and wavelength calibrated. Then the average spectral sensitivity curve of the CCD, which was derived using the standard star spectra for each angle, was used for flux calibration of the objects' spectra. All steps were made using routines within ESO-MIDAS[1], and wavelength calibration was performed using the emission spectra of a He-Ne-Ar lamp.

After the data reductions, the two individual observations were joined to form a single spectrum. The

[1] Munich Image Data Analysis System, developed, maintained and distributed by the European Southern Observatory.

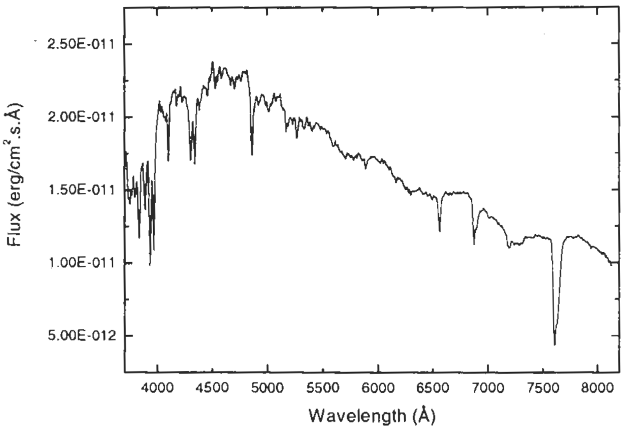

Figure 1: *Spectral energy distribution of 41Dra.*

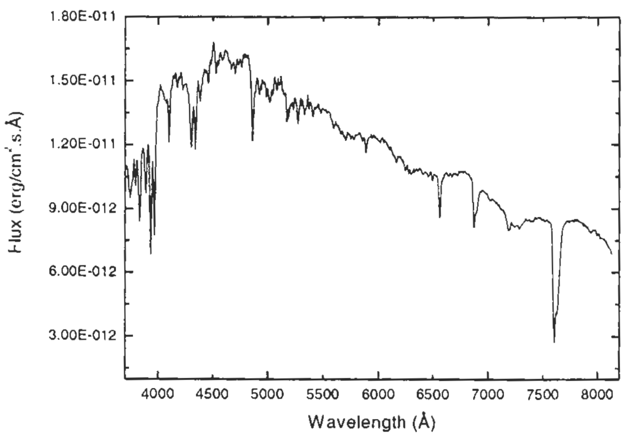

Figure 2: *Spectral energy distribution of 40Dra.*

segments were not averaged in the overlap region but rather were connected together at a common wavelength which has been chosen to avoid strong lines and variations near the edges of the spectrum segments.

3. Results and discussion

3.1. Spectral energy distributions and magnitudes

The final spectrum of each star has been taken as the average of all spectra (although there were no differences between the spectra of different exposures). Fig. 1 shows the final result of spectral energy distribution of 41Dra and Fig. 2 shows the spectral energy distribution for 40Dra, where we can see that they are identical except for the amount of the flux which refers to the magnitude difference between the two subsystems. The Balmer series and Balmer jump are clear in both spectra. Note that some of the strong lines and depressions, especially in the red part of the spectrum (around $\lambda 6867$Å, $\lambda 7200$Å, and $\lambda 7605$Å), are H_2O and O_2 telluric lines and depressions.

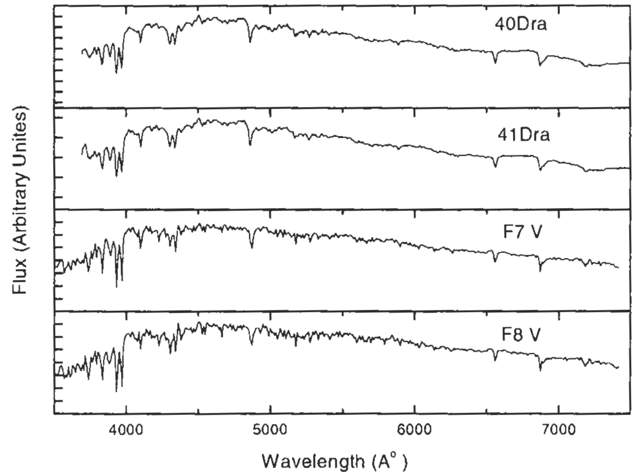

Figure 3: *Comparison of 40Dra and 41Dra with F7V and F8 stars from the library of stellar spectra of Jacoby et al. (1984).*

By making a comparison with the library of stellar spectra of Jacoby et al. (1984) (Fig. 3), we can conclude that these two systems are either F7 or F8 spectral type and V luminosity class which is almost consistent with the results of Tokovinin (1995).

B, V, and R magnitudes were computed using $UBVRI$ Bessel (1990) passbands, then normalizing to Vega. In practice we compute the integrals:

$$X = -2.5 \log \frac{\int S_x(\lambda) F_\lambda d\lambda}{\int S_x(\lambda) d\lambda}$$

where $S_x(\lambda)$ is the transmission function for passband X, after interpolating $S_x(\lambda)$ to the wavelength spacing of F_λ which is 5.98 Å. The results (Table 5) show a good correspondence with BS catalogue (Table 1) and Hipparcos and Tycho catalogues (Table 2).

Table 5: *B, V, and R magnitudes and B-V colour indices*

	41Dra	40Dra
B	$6^m25 \pm 0.06$	$6^m63 \pm 0.06$
V	$5^m73 \pm 0.06$	$6^m10 \pm 0.06$
R	$5^m45 \pm 0.07$	$5^m81 \pm 0.07$
$B-V$	$0^m52 \pm 0.08$	$0^m53 \pm 0.08$

3.2. Interstellar reddening

The system ADS11061 is a nearby star lying at a distance of about 45 pc from the Sun (Turon et al., 1992; Kiselev et al., 1997; Balega et al., 1997; Al-Wardat et al., 2002), so the interstellar reddening of the flux will be small as it is clear from the following:

$$A_{V41Dra} = 3.2E(B-V)$$

$$= 3.2 \times 0.02 = 0\overset{m}{.}064,$$

and

$$A_{V40Dra} = 3.2E(B-V)$$
$$= 3.2 \times 0.03$$
$$= 0\overset{m}{.}096,$$

where:

$$E(B-V) = (B-V)_{obs} - (B-V)_0.$$

Here we used the FitzGerald (1970) F7V $(B-V)_0$ intrinsic colour which is equal to $0\overset{m}{.}5$ and Schiled's (1977) interstellar reddening law.

If we take into account these results in spite of the fact that it lies within the error values of $B-V$ and since the two subsystems are located within one binary system, there will be only one way to explain the difference between A_{V40Dra} and A_{V41Dra}, that is, the binary subsystem 40Dra is surrounded by an envelope which absorbs a small part of the outgoing flux.

3.3. Model atmospheres

The model atmospheres of the 41Dra components and the energy distribution in the continuous spectrum were calculated in the previous papers (Balega et al., 2001; Al-Wardat et al., 2002), and they were compared with the observed ones. Herein model atmospheres of the 40Dra components will be introduced.

The determination of the spectral type as F7 or F8 yields an effective temperature between 6100 and 6400° K, and the colour index (B-V=0.53) also yields $T_{eff} \approx 6200°$ K which lies within the same limits.

Since 40Dra has not been resolved by speckle interferometric techniques, there was only one way to detect the magnitude difference between its components, which is the relative residual intensity of lines of components from high resolution echelle spectra; the result was $\Delta m = 0\overset{m}{.}51 \pm 0.03$ (Fig. 4). For comparison it was $\Delta m = 0\overset{m}{.}42 \pm 0.02$ for 41Dra (Fig. 5), which is close to the result of speckle interferometry $\Delta m = 0\overset{m}{.}426 \pm 0.028$ (Balega et al., 2001).

The distance to the system ADS11061 has been estimated as 43.276 ± 3 pc (Al-Wardat et al., 2002), which yields luminosities of the components of the subsystem 40Dra: $L_a = 4.13 \pm 0.54 L_{\odot}$ and $L_b = 2.58 \pm 0.34 L_{\odot}$. In a first approximation these values along with 6200° K effective temperatures permit estimation of the radii:

$$\lg(R/R_{\odot}) = 0.5\lg(L/L_{\odot}) - 2\lg(T/T_{\odot}),$$

which gives: $R_{Ba} = 1.77 R_{\odot}$ and $R_{Bb} = 1.40 R_{\odot}$. These values together with the masses which can be estimate from Tokovinin's results (Table 3) enable

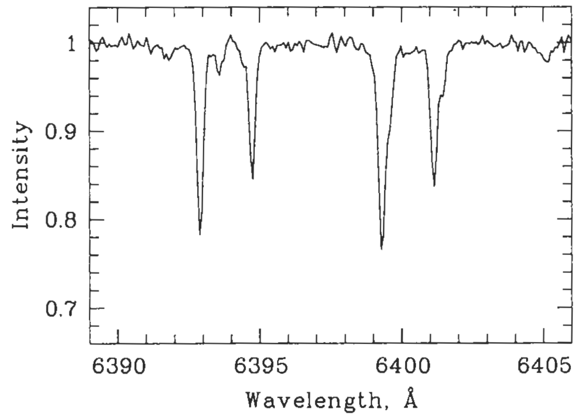

Figure 4: *A part of the high resolution (echelle) spectrum of 41Dra taken on the 1st of July 2001.*

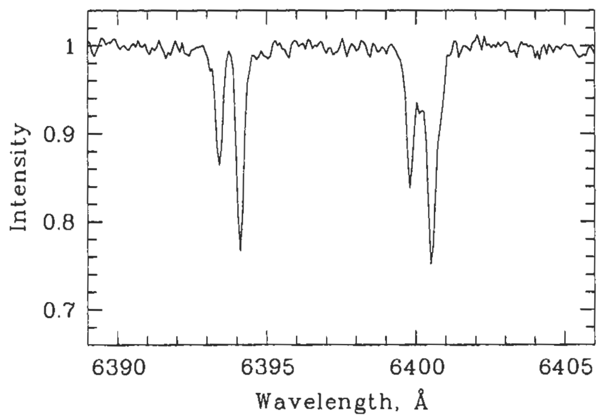

Figure 5: *A part of the high resolution (echelle) spectrum of 40Dra taken on the 1st of July 2001.*

obtaining the gravity acceleration at the surface of the components:

$$\lg g = \lg(M/M_{\odot}) - 2\lg(R/R_{\odot}) + 4.43.$$

The derived values $\lg g_{Ba}$=4.07 and $\lg g_{Bb}$=4.25 along with the effective temperatures allow construction of the model atmospheres of the components using the grid of the Kurucz (1994) blanketed models. Then, using the programme Sam1 modified for the programme KONTOUR (Leushin & Topilskaya, 1985), the energy distributions in the continuous spectrum H^a_{λ} and H^b_{λ} were computed.

The energy flux from 40Dra is created from the net luminosity of the components Ba and Bb located at a distance d from the Earth. So we can write:

$$F_{\lambda} \cdot d^2 = H^a_{\lambda} \cdot R^2_{Ba} + H^b_{\lambda} \cdot R^2_{Bb},$$

from which

$$F_{\lambda} = (R^2_{Ba}/d)^2 (H^a_{\lambda} + H^b_{\lambda} \cdot (R_{Bb}/R_{Ba})^2),$$

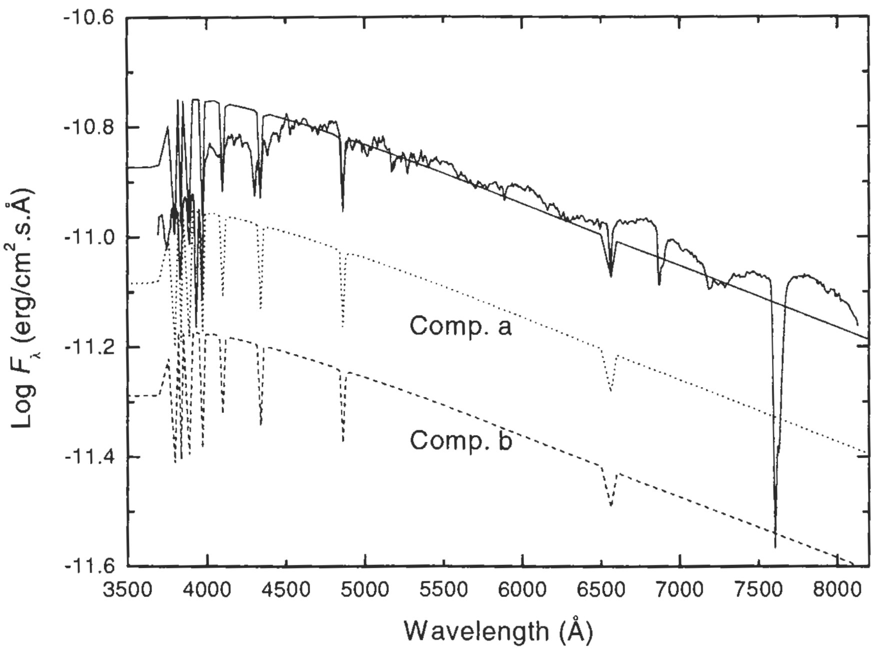

Figure 6: *The observed energy distribution in the continuous spectrum of 40Dra at the level of the Earth's atmosphere with the computed ones using the following parameters:* $T_{eff}^{Ba} = 6200°\mathrm{K}, T_{eff}^{Bb} = 6200°\mathrm{K}, \lg g_{Ba} = 4.07, \lg g_{Bb} = 4.25, R_{Ba} = 1.73R_\odot, R_{Bb} = 1.37R_\odot$, *and* $d = 43.276\,pc$.

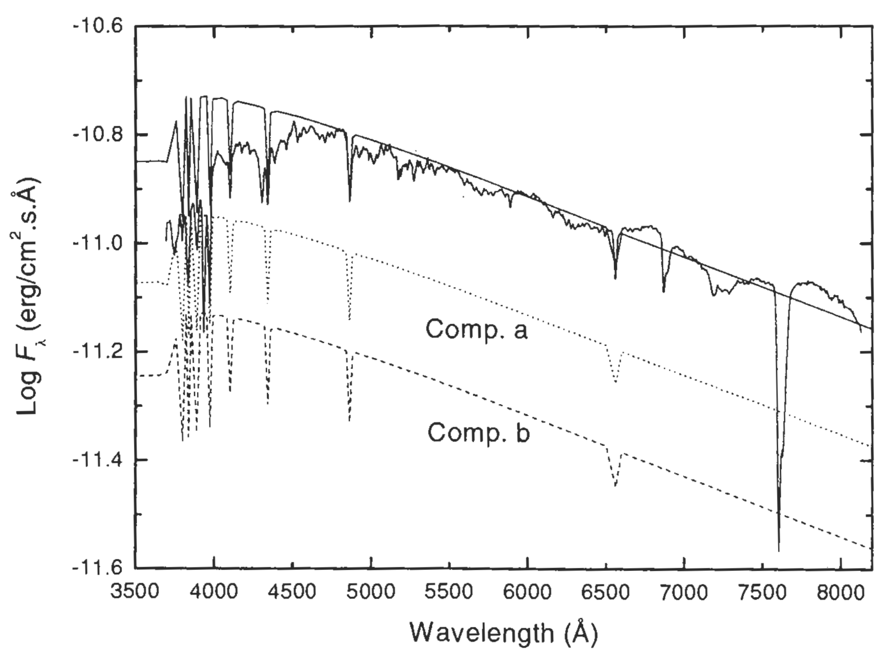

Figure 7: *The observed energy distribution in the continuous spectrum of 40Dra at the level of the Earth's atmosphere along with the computed ones. Solid line represents the total computed flux of the two components, dots represent the computed flux of the first component with* $T_{eff} = 6100°\ K$, $log\ g = 4.03$, $R = 1.82R_\odot$, *dashes represent the computed flux of the second component with* $T_{eff} = 6100°\ K$, $log\ g = 4.20$, $R = 1.44R_\odot$.

where H_λ^a and H_λ^b are the fluxes from a unit surface of the corresponding component. There was no good agreement between the observed flux and that computed using the following parameters:

$$T_{eff}^{Ba} = 6200°\mathrm{K}, T_{eff}^{Bb} = 6200°\mathrm{K},$$

$$\lg g_{Ba} = 4.07, \lg g_{Bb} = 4.25,$$

$$R_{Ba} = 1.73R_{\odot}, R_{Bb} = 1.37R_{\odot},$$

and $d = 43.276$ pc (Fig. 6). While a good agreement found using the following parameters:

$$T_{eff}^{Ba} = 6100°\mathrm{K}, T_{eff}^{Bb} = 6100°\mathrm{K},$$

$$\lg g_{Ba} = 4.03, \lg g_{Bb} = 4.20,$$

$$R_{Ba} = 1.82R_{\odot}, R_{Bb} = 1.44R_{\odot},$$

and $d = 43.276$ pc was taken as a postulate (Fig. 7). These elements represent adequately enough the parameters of 40Dra components. And gives a new spectral type for the components of the system as F8V, which is consistence with observational estimations.

However, it should be noted that the model is highly dependent on the precision of observations and is consistent with observations within the errors. It is also possible that there exists interstellar matter in the system, as was mentioned earlier, which can transform the short-wave radiation into a long-wave radiation and leads to changes in the slope of the continuum spectra and in the depth of the Balmer jump which is seen in the observed spectrum as a variance towards the low temperature. And this can be explained as a consequence of an abrupt rise of interstellar matter absorption for short wavelength radiation.

3.4. Formation and evolution of the system

Table 6 lists the final parameters of the system. It shows a good confirmation between the components of the systems as a whole. This leads us to adopt the filament fragmentation process for the formation of such hierarchical system, where Zinnecher (1989, 2001) pointed out that tumbling filaments, rotating end over end, would tend to fragment into binaries with high eccentricity, and this has also been confirmed by Bonnell and Bastien (1992) using numerical simulations. The positions of the system's components on the evolutionary tracks of Girardi et al. (2000) are shown in Fig. 8.

4. Conclusions

Thus on the basis of the spectrophotometric study and atmospheric modeling of the system ADS11061, the following main conclusions can be drawn.

1. A new spectral type for each of the components of the subsystem 40Dra as F8 was approved using model atmospheres. This differ slightly from the earlier estimations of Tokovinin (1995) and those given by BS catalogue as F7 (Table 1), while it contradict those given by Hipparcous input catalogue as K2.

Table 6: *Parameters of the system ADS11061.*

	41Dra		Ref.	40Dra		Ref.
P, days	1247.2		1,2	10.52785		2
e	0.9754		1,2	0.374		2
i	50°		1,2	35°		2
a, AU	3.040		1,2	0.125		2
$a(1-e)$,AU	0.0748		1,2	0.0747		2
Component	a	b		a	b	
Mass, $M_{\odot}$	1.24	1.17	3	1.315	1.229	2
Sp. Type	F8	F8	3,4	F8	F8	4
T_{eff}	6100	6100	3	6100	6100	4
Radius, $R_{\odot}$	2.15	1.76	3	1.82	1.44	4
log g	3.86	4.01	3	4.03	4.20	4

References: 1: Balega et al.,1997; 2: Tokovinin, 1995; 3: Al-Wardat et al., 2002; 4: This work.

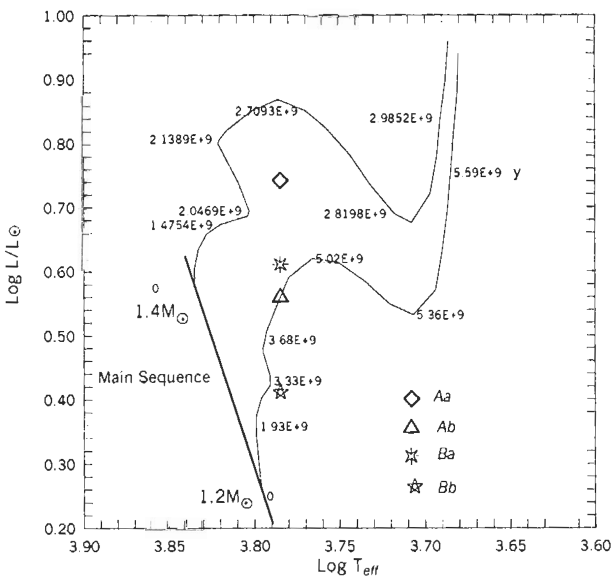

Figure 8: *The positions of system's components on the evolutionary tracks (without overshooting) of* $1.2M_{\odot}$ *of Girardi et al. (2000), with the age in years.*

2. The BVR magnitudes and $B - V$ colour indices of both subsystems were calculated, and showed a good agreement with BS and Hipparcos and Tycho catalogues.

3. An envelope around the subsystem 40Dra was proposed depending on the interstellar reddening calculations and on the comparison between observed and computed SED.

4. Model atmospheres for the subsystem 40Dra were built and the parameters of its components were subtracted.

5. Finally, filament fragmentation was proposed as the most likely process for the formation and evolution of the system.

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