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Evolutionary Constraints on the Masses of the Components of HDE 226868/Cyg X-1 Binary System

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Abstract Calculations carried out to model the evolution of HDE 226868, under different assumptions about the stellar wind mass loss rate, provide robust limits on the present mass of the star. It has to be in the range 40±5 $M_\odot$ if the distance to the system is in the range 1.95 to 2.35 kpc and the effective temperature of HDE 226868 in the range 30000 to 31000 K. Including into the analysis observational properties such as the profiles of the emission lines, rotational broadening of the absorption lines and the ellipsoidal light variations, one can estimate also the mass of the compact component. This estimate leads to the result 20±5 $M_\odot$. The same analysis (using the evolutionary models and the observational properties listed above) yields lower limit to the distance to the system of $\sim$ 2.0 kpc, if the effective temperature of HDE 22868 is higher than 30000 K. This limit to the distance does not depend on any photometric or astrometric considerations.

Key words: black holes: individual (Cyg X-1) — stars: — evolution — stars: individual (HDE 226868) — X-rays: binaries — X-rays: individual (Cyg X-1)

1 OBSERVATIONAL DATA

After thorough analysis, I have chosen the following values for the observational parameters of the binary system HDE 226868/Cyg X-1 (I present no justification, because of the lack of space).

The mass function $f(M_{\rm x}) = 0.251{\pm}0.007 M_\odot$ (Gies et al. 2003). The effective temperature of HDE 226868 $T_{\rm e}$ = 30700 K (calibration for spectral type O9.7 I by Markova et al., 2004), which corresponds to the bolometric correction $B.C.$ = -3.06 (Vacca et al. 1996) and the unreddened colour index $(B-V)_{\rm o} = -0.26$ (Schmidt-Kaler 1982). The photometric data V = 8.81 and $B-V$ = 0.83 (Massey et al. 1995), which leads to the reddening $E_{\rm B-V}$ = 1.09 and the unreddened V magnitude $V_{\rm o}$ = 5.43. Rate of the stellar wind mass outflow from HDE 226868 $\dot{M} = -2.6\times10^{-6}$ $M_\odot$ yr^{-1} (Gies et al. 2003). The distance to the system d = 2.15 ±0.07 (1σ error) or ±0.2 (3σ error) kpc (Massey et al. 1995). I should stress, that the distance to the system is not definitely established (the values quoted in the more recent literature range from 1.8 (Malysheva 1997) to 2.3 kpc (Dambis et al. 2001)) and, therefore, most of my analysis will be carried out assuming the distance d to be a free parameter in the range 1.8$\sim$2.35 kpc.

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2 THE EVOLUTIONARY CALCULATIONS FOR HDE 226868

It is relatively straightforward to argue that HDE 226868 must be a core hydrogen burning star. To obtain a more precise estimate of its evolutionary status (and its parameters such as the mass), I computed the evolutionary tracks for core hydrogen burning phase of stars with the initial masses in the range $40 \sim 80\ M_\odot$. The Warsaw evolutionary code developed by Bohdan Paczyński, Maciek Kozłowski and Ryszard Sienkiewicz was used. The stellar wind mass loss rate was calculated according to the formula derived by Hurley et al. (1999, hereafter HPT). To take into account the fact that the formula gives the mass loss rate estimate with the accuracy that is probably not better than within a factor of two, I calculated three evolutionary sequences for each initial mass of the star: one with the mass loss rate given by HPT, one with the rate by a factor of two smaller and one with the rate by a factor of two greater. Some of the obtained evolutionary tracks in the H-R diagram are shown in Fig. 1. The parameters of some of the evolutionary models of HDE 226868 are given in Table 1.

The results of the evolutionary calculations are very robust and may be summarized as follows: HDE 226868 has to be fairly massive, simply, because it is very luminous. The estimate of its mass depends mainly on the distance to the system and has to be in the range $40{\pm}5\ M_\odot$ if the distance to the system is in the range 1.95 to 2.35 kpc and the effective temperature of HDE 226868 in the range 30000 to 31000 K. This estimate practically does not depend on the assumptions about the stellar wind mass loss rate.

The main reason why my estimate differs from most of the earlier estimates is due to the fact that their authors ignored the luminosity of HDE 226868 (which is an important observational parameter). E.g. Herrero et al. (1995) did not notice in their Table 1 that hydrogen burning star of $20\ M_\odot$ at effective temperature 32000 K cannot produce luminosity $\log(L/L_\odot) \sim 5.7$. Similarly star of $16 \sim 17\ M_\odot$ cannot produce luminosity $\log(L/L_\odot) \sim 5.4$ (both facts are obvious from Fig.1 in the present paper). On the other hand, my estimates are roughly consistent with the model of Gies and Bolton (1986a), based on an extensive analysis of the large and diversified collection of the observational data.

The more detailed description of my calculations and the analysis of the results will be given elsewhere.

3 THE PARAMETERS OF THE BINARY SYSTEM

Using the values of the observational parameters quoted in the first section, we can express the radius and luminosity of HDE 226868 as functions of the distance:

$$R_{\rm opt}/R_\odot = 10.59\, d, \tag{1}$$

$$L_{\rm opt}/L_\odot = 8.95 \times 10^4\, d^2, \tag{2}$$

where d is the distance in kpc.

The knowledge of the mass function and of the radius of the orbit of HDE 226868 (Gies et al. 2003) gives us two more equations:

$$M_{\rm opt}\sin^3 i/[q(1+q)^2] = 0.251\,, \tag{3}$$

$$R_{\rm opt} = f_{\rm RL}(0.38 + 0.2\log\, q)(1+q) \times 8.36/\sin i\,, \tag{4}$$

where $q = M_{\rm opt}/M_{\rm x}$ is the ratio of the masses of the optical and compact components, i is the inclination of the orbit and $f_{\rm RL}$ is the Roche lobe fill-out factor (the ratio of the radius of HDE 226868 to the radius of the Roche lobe around it).

Table 1 Parameters of the selected evolutionary models of the binary system HDE 226868/Cyg X-1.

T_e [10^3 K]	M_{opt} [$M_\odot$]	d [kpc]	M_0 [$M_\odot$]	f_{SW}	R_{opt} [$R_\odot$]	log$L$ [$L_\odot$]	$-\dot{M}$ [10^{-6} $M_\odot$ yr^{-1}]	f_{RL}	i [°]	M_x [$M_\odot$]
Observational parameters										
30.7 -2.7,+1.3		2.15 ±0.2			22.77 ±2.3	5.617 ±0.13	2.60 -1.3,+2.6	$\geq$ 0.95	33 ±5	
Acceptable models										
30	36.74	1.98	40	1	21.10	5.511	1.68	0.95	30.0	18.3
								0.96	27.0	20.7
30	39.53	2.15	44.3	1.17	22.88	5.581	2.60	0.99	33.9	16.6
								1.00	30.7	18.5
30.7	39.67	2.04	43.5	1	21.63	5.572	2.07	0.95	28.9	19.9
30.7	**41.67**	**2.15**	**46.3**	**1.05**	**22.77**	**5.617**	**2.60**	**0.96**	**36.1**	**16.0**
								0.97	**32.5**	**17.9**
								0.98	**29.4**	**20.1**
								0.99	**26.6**	**22.6**
								1.00	**24.1**	**25.6**
30.7	43.18	2.22	48	1	23.56	5.647	2.78	0.99	328	18.1
								1.00	29.7	20.3
31	40.84	2.12	50	2	22.37	5.618	4.88	0.95	36.1	15.8
								0.96	32.5	17.7
								0.97	29.4	19.9
								0.98	26.6	22.4
								0.99	24.0	25.4
31	44.80	2.27	50	1	23.88	5.675	3.07	0.99	32.7	18.6
								1.00	29.6	20.8

NOTES:

(1) M_0 denotes the initial (ZAMS) mass of the optical component, f_{SW} denotes the multiplying factor applied to HPT formula; other symbols have their usual meanings.
(2) The bold face entries correspond to the "best fit" models (with parameters of the optical component closest to the observational estimates — compare the first part of the table).

Once a given evolutionary model of HDE 226868 is selected from the grid of the models discussed in section 2 and a value of the parameter f_{RL} is assumed, the Eqs. (3)–(4) can be solved for i and q. Knowing q we can immediately calculate also the mass of compact component M_x. In principle, this procedure can be applied to any combination of the evolutionary model and of the value of f_{RL}. In fact, however, not every evolutionary model of HDE 226868 (acceptable if we consider the optical component alone) permits the construction of a consistent model of the

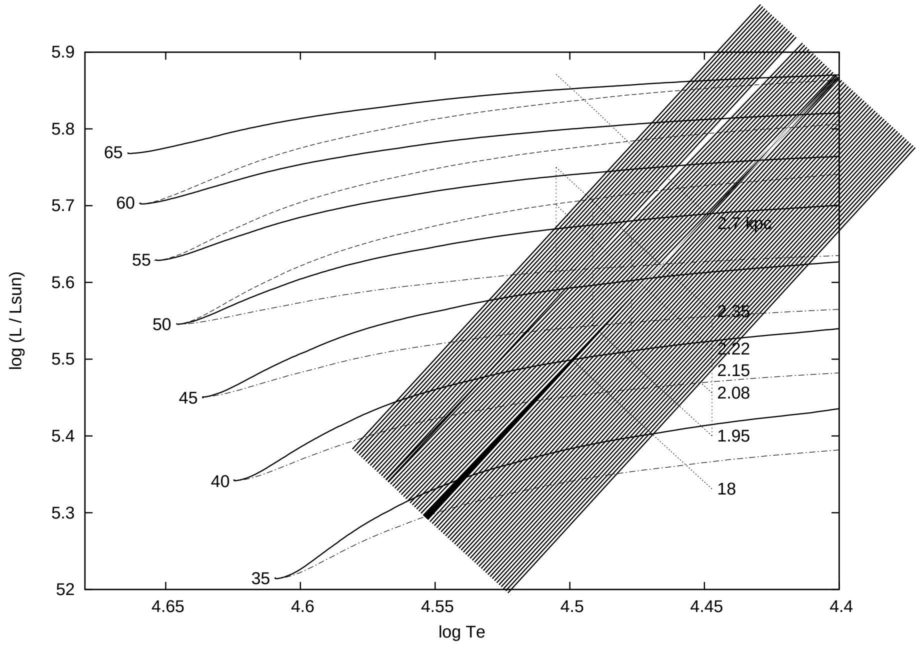

Fig. 1 The evolutionary tracks in the H-R diagram. The tracks are labeled with the initial mass of the star (in solar units). The solid lines describe the tracks computed with the stellar wind mass loss rates according to HPT (Hurley et al., 2000) formula. The broken lines and the dash-dotted lines describe the tracks computed with the mass loss rates smaller by a factor of two and larger by a factor of two, respectively. The slanted dotted lines correspond to the position of HDE 226868 for different assumed values of its distance (the assumed value of the distance in kpc is given at the right end of each line). The vertical dotted lines correspond to the effective temperatures of HDE 226868 equal (from left to right) to 32, 31, 30 and 28 $\times 10^3$K. The most likely position of HDE 226868 lies within the parallelogram corresponding to the values of the effective temperatures in the range 30000 to 31000 K and values of the distance in the range 1.95 to 2.35 kpc.

binary system. This is because of the observational constraints on the value of the inclination i and, especially, because of the strong observational constraints on the value of the fill-out factor $f_{\rm RL}$. As demonstrated by Gies and Bolton (1986a,b), in order to explain quantitatively the He emission lines produced in the stellar wind from HDE 226868, the fill-out factor $f_{\rm RL}$ has to be larger than 0.9 and, most likely, not smaller than 0.95 (perhaps the best value would be around 0.98). On the other hand, Gies and Bolton demonstrated that observed rotational broadening of the photospheric absorption lines of HDE 226868 and the observed amplitude of the ellipsoidal light variations impose substantial constraints on the values of the mass ratio, the fill-out factor and the inclination. In particular, the observed amplitude of the ellipsoidal light variations (which is determined mainly by the fill-out factor and the inclination) strongly constrains the inclination. For the assumed values of $f_{\rm RL}$ equal 0.9, 095 and 1, the resulting inclination is $\sim 38^\circ$, $\sim 33^\circ$ and $\sim 28^\circ$, respectively.

Constructing models of the binary system, to be consistent with observations, I assumed that for any adopted value of $f_{\rm RL}$, the calculated inclination should be within $\pm 5^\circ$ from the corresponding values quoted above. I started with different models of the optical component, acceptable from the point of view of the stellar evolution, as described in section 2. Then, I assumed the value of $f_{\rm RL}$ equal 0.95 and solved eqs. (3)–(4) to find q, i and $M_{\rm x}$. Subsequently, I tried higher values of $f_{\rm RL}$. These higher values produced the solutions with lower (in many cases unacceptably low) values of the inclination. The dependence of q, i and $M_{\rm x}$ on the assumed value of $f_{\rm RL}$ may be seen from two sequences of binary models (with $M_{\rm opt} = 41.67 M_{\odot}$ and $M_{\rm opt} = 40.84 M_{\odot}$), presented in Table 1.

I classified, as acceptable, the models satisfying the following criteria:

(1) $d = 1.8 \sim 2.35$ kpc;
(2) $T_{\rm e} = 30000 \sim 31000$ K;
(3) $-\dot{M} = 1.3 \sim 5.2 \times 10^{-6}\ M_{\odot}\ {\rm yr}^{-1}$;
(4) $f_{\rm RL} \geq 0.95$;
(5) $i = 28^{\circ} + (1 - f_{\rm RL}) \times 100^{\circ} \pm 5^{\circ}$ (this corresponds to $i \approx 28^{\circ} \sim 38^{\circ}$ for $f_{\rm RL} = 0.95$ and $i \approx 23^{\circ} \sim 33^{\circ}$ for $f_{\rm RL} = 1.00$, as advocated by Gies & Bolton (1986a)).

Parameters of selected acceptable models are given in the second part of Table 1.

There are several conclusions that can be drawn from Table 1. The first concerns the mass of the compact component From the acceptable models, its value must be in the range $20 \pm 5\, M_{\odot}$. The second conclusion is related to the distance to the binary system. It appears, that consistent models are possible only for distances $\gtrsim 2$ kpc. Smaller distances require unacceptably low values of the inclination. Finally, the third conclusion confirms the earlier results (based on the evolutionary calculations alone) limiting the present mass of HDE 226868 to the range 40 ± 5 $M_{\odot}$ and the initial mass to the range $43.5 \sim 50\ M_{\odot}$.

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