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Research Note

On the Mass Limit of the X-ray Source in Cygnus X – 1

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Summary. Limiting values for the mass of the X-ray emitting source in Cygnus X-1 are derived without an initial assumption on the mass of the primary of HDE 226868. It is shown that the model of Trimble *et al.* (1973) with a low mass, low surface gravity B 0 I star is in contradiction to the observations. The heating effect on the facing hemisphere of the OB star by the X-rays of the secondary is shown to be negligible in accordance to the observations. The mass function and the Roche geometry set lower and upper limits, respectively, on the mass of the secondary. According to these restrictions the mass of the X-ray source most probably is $6.0 \leqq M_X/M_\odot \leqq 7.3$, thus giving evidence for the existence of a black hole in Cygnus X-1.

Key words: X-ray binaries – black hole

Introduction

The binary system HDE 226868 is assumed to be the optical counterpart of Cygnus X-1. Strong evidence for this identification was summarized for instance by Bolton (1972) and by Smith *et al.* (1973). According to Bolton (1972) and Brucato and Kristian (1973) the spectroscopically derived mass function leads to a minimum mass of about 5 $M_\odot$ for the X-ray emitting secondary star. This value exceeds remarkably the upper limit for neutron star masses thus making Cygnus X-1 an interesting canditate for a black hole in a binary system. This conclusion is essentially based on the assumption, that the primary star of HDE 226868 is a normal B0 Iab supergiant of more than 20 $M_\odot$, according to the spectral characteristics given for instance by Walborn (1973). Paczynski (1972) and Trimble *et al.* (1973) critizised this assumption. Indeed a spectrum gives only information on the effective temperature $T_{\rm eff}$ and the surface gravity g of a star. Trimble *et al.* (1973) gave a model of a low mass star which is in full agreement with the observed spectral type. Paczynski (1972) pointed out that the strong X-ray flux from the secondary might alter the appearance of the observable spectrum of the OB star. However, in both cases there is strong disagreement with other observed characteristics of the system, as will be shown below. In the following discussion limiting values for the system are derived which are not dependent on an assumed mass or luminosity of the OB star.

Observed Features

Careful spectroscopic observations of HDE 226868 by Walborn (1973) and by Brucato and Kristian (1973) confirmed and refined the earlier results showing that the spectrum is of the type O 9.7 Iab. This classification was done by Walborn (1973) by comparing the spectrum of HDE 226868 with the spectra of ε Ori B0 Ia and 19 Cep O 9.5 Ib. According to the same criteria ζ Ori is classified as spectral type O 0.7 Ib. Recent non-LTE model atmosphere calculations yielded $T_{\rm eff} = 29000$ °K, $\log g = 3.1$ for ε Ori and $T_{\rm eff} = 31000$ °K, $\log g = 3.2$ for ζ Ori, see Auer and Mihalas (1972). It should be mentioned that the non-LTE calculations give good agreement of the theoretical H_β and H_γ line profiles with the observed ones while earlier LTE models failed to do so. This is especially important since the H lines are good surface gravity indicators in this region of the $\log T_{\rm eff} - \log g$ diagramm. Unfortunately the lowest surface gravity in the models of Auer and Mihalas (1972) is $\log g = 3.3$. Some extrapolation was necessary, therefore, to obtain the solutions of ε Ori and ζ Ori. Plotting the lines of constant equivalent widths in the $\log T_{\rm eff} - \log g$ plane for the observed H and He lines, according to the procedure of Mihalas (1964), gives some idea of the accuracy which can be obtained. In the case of ε Ori and ζ Ori the uncertainty of $\log g$ can be roughly estimated to be ± 0.1 while the uncertainty of $\log T_{\rm eff}$ should not exceed ± 0.01. For HDE 226868, therefore, the values $\log T_{\rm eff} = 4.48$ and $\log g = 3.2$ can be regarded as well observed quantities. From radial velocity measurements Brucato and Kristian (1973) obtained $a_1 \sin i = 8.08 R_\odot$ and $f(M) = (M_X \sin i)^3/(M_{\rm OB} + M_X)^2 = 0.2256\, M_\odot$. Bolton (1972) found $a_1 \sin i = 7.5 R_\odot$ and $f(M) = 0.182 M_\odot$, where M_X is the mass of the X-ray emitting secondary and $M_{\rm OB}$ the mass of the OB star. Besides of the absorption lines of the OB star emission lines of H and He are seen. It is not clear where these lines originate and whether they really are exactly in antiphase to the absorption lines. Therefore in this paper no use is made of the emission lines velocities. For discussion of these features see Smith *et al.* (1973). Earlier photoelectric observations by Hiltner (1956) yielded $V=8^m.89$, $B\text{-}V=+0^m.85$, $U\text{-}B=-0^m.24$. The star is remarkably reddened, $E_{(B-V)}=1^m.09$, and therefore an absorption in V of $A_V=3^m.3$ is derived. It is unimportant for the moment to decide whether this absorption is due to interstellar matter or to a circumstellar envelope. In any case the absolute visual magnitude of the OB star is consequently $M_V=10^m.6-6\log r$, where r is the distance in pc. Photoelectric observations by Lester *et al.* (1973) showed light variations of an amplitude of $0^m.07$ in blue light. From the spectroscopical observations the orbital period is known to be $5^d.6$. The light curve shows a double wave with the minima at the conjunctions of the radial velocity curve. This is exactly the type of light curve one would expect from the light changes of a tidally distorted star. Similar light variations are reported for instance by Cherepashchuk *et al.* (1973). From the absence of X-ray eclipses it can be concluded that there are no eclipsing effects in the light curve. It is essential to note that there is no evidence for the so called reflexion effect which would be present if the hemisphere of the OB star facing the X-ray source would be substantially heated by the X-rays. Therefore the OB star is either altered in its appearance as a whole which may cause theoretical difficulties or the heating influence of the X-rays is small compared to the total luminosity of the OB star.

Distance of HDE 226868

The absorption $A_V=3^m.3$ derived from the three colour photometry agrees with a distance of 2.2 kpc, see Neckel (1967), if it is due to interstellar absorption. Hiltner (1956) found a polarization $p=0^m.108$ for HDE 226868 which again is in agreement with the value $(p/A_V)=0.03$ for this region of the sky. Smith *et al.* (1973) were able to measure the equivalent width of the interstellar K line on spectra of HDE 226868 and obtained EW = 0.49 Å ±0.05. According to the calibration of Münch (1968) this is consistent with a distance of at least 2 kpc. Therefore, if a distance of less than 2 kpc is assumed for HDE 226868, at least a part of the absorption and the appearance of the interstellar line must be due to a circumstellar shell. It was pointed out by Bolton (1972) that in this case an abnormally bright infrared source would be observable at the position of Cygnus X-1. Therefore a distance of 1 kpc or less is impossible due to the absence of a sufficiently strong infrared source. This restriction completely rules out the model of Trimble *et al.* (1973) for Cygnus X-1. Even if the most luminous object of her sequence of B0 I stars of low mass is used, see Trimble (1972), with $M/M_\odot=0.5$ and $\log L/L_\odot=3.6$ and if the bolometric correction for B0 I atmospheres of $3^m.2$ is adopted, than the distance of Cygnus X-1 would be only 230 pc. The evolutionary timescale of this model is only some 10^3 years and would decrease rapidly if a more luminous star is used.

Since however a distance derived from the features of the interstellar medium is rather weak, the limiting properties of Cygnus X-1 are calculated for distances of 1 kpc, 1.5 kpc and 2 kpc, keeping in mind that a distance of 1 kpc or even less is hardly justified to be accepted.

Table 1. Distance dependent properties of Cygnus X-1

r(kpc)	M_{bol}	$M_{OB}/M_\odot$	$M_X/M_\odot$	q	$R_{OB}/R_\odot$
1.0	−7.6	6.3	≧2.6	≧0.41	10.7
1.5	−8.5	14.5	≧4.4	≧0.30	16.2
2.0	−9.1	25.1	≧6.0	≧0.22	21.3

Mass Limits for Cygnus X-1

For a star of $T_{eff}=4.48$ a bolometric correction of $3^m.2$ is assumed, according to Harris (1963). There is some uncertainty in this value due to the fact that the B.C. for hot stars must be derived from model atmosphere calculations. More recent investigations by Morton (1969) indicate a somewhat lower value of approximately $3^m.0$. An uncertainty of $0^m.2$ in B.C. should be taken into account. The distance dependent absolute magnitude of HDE 226868 is therefore $M_{bol}=7^m.4-5\log r$. Since

$$\log g=4.45+\log M/M_\odot-2\log R/R_\odot$$

and

$$M_{bol}=42.31-5\log R/R_\odot-10\log T_{eff}$$

are generally valid it is possible to get the mass of the OB star as a function of the distance. Table 1 gives the derived values M_{OB} together with the respective bolometric magnitudes. The limiting masses M_X of the secondary follow from the mass function. The value $f(M)=0.2256$ from Brucato and Kristian (1970) was used, the somewhat lower value 0.182 from Bolton (1972) would lead to limiting masses $M_X/M_\odot \geqq 2.4$, 4.0 and 5.5, respectively. The mass function gives also the lower limit for the mass ratio $q=M_X/M_{OB}$, and the radius R_{OB} is derived from the above formulae.

The ratio of the luminosity L_X of the X-ray star and L_{OB} of the OB star is of course independent of the distance. At a distance of 2 kpc an intrinsic X-ray luminosity of $1\cdot10^{37}$ erg/s was derived by Smith *et al.* (1973). The intrinsic luminosity of the OB star at the same distance would be $1.33\cdot10^{39}$ erg/s. Even if the OB star is filling its limiting Roche lobe not more than 6% of the radiation emitted by the X-ray source meets the facing hemisphere of the OB star. It is assumed that the emission form the X-ray emitter is isotropic. If all the energy is absorbed by the OB star and completely thermalized the facing hemisphere can radiate an excess energy of 0.0005 of its intrinsic luminosity. Therefore, the resulting reflexion effect cannot exceed $0^{m}.001$ which is indeed beyond the limits of observation if the light curve of Lester *et al.* (1973) is examined. It is obvious that in the case of Cygnus X-1 the spectral characteristics of the OB star cannot be altered by the influence of the X-ray source thus ruling out the argument by Paczyński (1972).

Geometrical Properties of Cygnus X—1

From the absence of X-ray eclipses and the luminosity ratio of the OB star and the X-ray source it is concluded that the light variations are entirely due to the light changes of the tidally distorted OB star. The formulae of Merrill (1970) together with the amplitude of the light curve of $0^{m}.07$ give a relation between $\sin i$, q and r_1 where r_1 is the radius of the OB star in units of the distance of the two stars. Taking the limb darkening coefficient $u_{OB}=0.36$ according to Grygar (1965) and the gravity darkening coefficient $\tau=0.45$ from Hosokawa (1957) one finds in first approximation

$$r_1^3 \cdot q \cdot \sin^2 i = 0.024 .$$

On the other hand, the distance a of the two stars is $a=a_1(1+1/q)$ and $a_1 \sin i = 8.08 R_\odot$ is known from the radial velocity curve. The OB star cannot exceed its Roche limiting surface, the relative radius r_1^* of the Roche limit is a function of q only. It is possible, therefore, to find a lower limit for i as a function of q, see Table 2, where the equality holds good if the OB star fills its Roche lobe. Combining this with $a \cdot \sin i$ gives an upper limit for the true radius R_{OB}, dependent on q, where again the equality is reached if the OB star fills its limiting surface.

Table 2. Limiting Inclination and Radius dependent on q

q	$a \cdot \sin i$	r_1^*	i	$R_{OB}/R_\odot$
0.2	48.5 $R_\odot$	0.53	$\geqq 64^\circ.2$	$\leqq 28.5$
0.3	35.0	0.49	$\geqq 55.7$	$\leqq 20.8$
0.4	28.3	0.46	$\geqq 51.3$	$\leqq 16.7$
0.5	24.2	0.44	$\geqq 48.7$	$\leqq 14.2$
0.6	21.6	0.42	$\geqq 46.9$	$\leqq 12.5$
0.7	19.6	0.41	$\geqq 45.1$	$\leqq 11.3$
0.8	18.2	0.40	$\geqq 44.3$	$\leqq 10.3$

Table 3. Distance dependent limits due to Roche geometry

r(kpc)	q	$\sin i$	$M_X/M_\odot$	$f(M)$
1.0	$\leqq 0.75$	$\geqq 0.71$	$\leqq 4.7$	0.309
1.5	$\leqq 0.42$	$\geqq 0.78$	$\leqq 6.1$	0.254
2.0	$\leqq 0.29$	$\geqq 0.83$	$\leqq 7.3$	0.212

Taking R_{OB} from Table 1 gives an upper limit for q since otherwise the OB star would exceed its limiting surface. The upper limit of q then yields an upper limit of M_X. The limiting values are given in Table 3. The resulting mass function $f(M)$ for the case of the OB star filling the lobe is given, too.

Conclusion

The only possibly weak assumption used in this paper is the identification of Cygnus X-1 with HDE 226868. If this basic assumption is accepted than it follows from the results in Table 1 that the X-ray emitting source has a mass remarkably in excess of the maximum mass for neutron stars. If a distance of only 1.5 kpc is postulated, $4.4 \leqq M_X/M_\odot \leqq 6.1$ will follow. In this case the OB star should be well below its Roche limiting lobe; otherwise a mass function clearly in excess of the observed value is received. A distance of 2 kpc yields a model consistent with all the observed properties of HDE 226868. In this case the OB star would be an entirely normal supergiant. The assumption of the OB star filling its limiting surface allows for the explanation of Cygnus X-1 by the model described by van den Heuvel (1973); in this case the mass function agrees very well with the observed one. It seems reasonable, therefore, to accept the existence of a compact object of 6—7 $M_\odot$ as the X-ray emitting source in Cygnus X-1.

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