Modiﬁed Physical and Geometric Parameters of the Eclipsing X-Ray Binary System Centaurus X-3∗

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Abstract—Modiﬁed physical and geometric parameters for the eclipsing x-ray binary system Cen X-3 are presented. The parameters were estimated by comparing synthetic photometric light curves with the observed ones in an iterative method until the best ﬁt was achieved. The synthetic light curves were constructed in accordance with the Roche model, since Cen X-3 is likely to be powered by Roche-lobe ﬂow. We focused on the phenomenon of x-ray heating of the side of the optical component facing the compact object. The parameters and present status of this work are brieﬂy discussed.

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1. INTRODUCTION

The importance of the study of binary star systems arises from the fact that more than 50% of galactic stellar systems are binaries. They play an important role in determining several key stellar parameters, which is a bit complicated in the case of x-ray binary systems. In these systems a compact object (a white dwarf, neutron star, or a black hole formed after the collapse of an ordinary star) and a stellar companion orbit each other at a distance small enough to enable mass transfer from the companion star to the compact object. The transferred matter spirals towards the compact object and forms an accretion disk around it. The accreted gaseous matter is heated to very high temperatures (10⁶ to 10⁸ K), releasing the energy it acquired through gravitational infall in the form of x-ray radiation. In the case of a neutron star or a white dwarf, the emission originates from both the accretion disk and the surface of the compact star, while in black hole binaries the only source of x-rays is the accretion disk.

X-ray binary stars are usually subdivided into two categories: High Mass X-Ray Binaries (HMXB), where the mass of the companion is greater than several solar masses, enabling it to eject matter through stellar wind, and Low Mass X-Ray Binaries (LMXB), where the mass of the companion is about one solar mass, it provides matter through the inner Lagrangian point (the point where the gravitational forces of the two stars and the centrifugal force cancel each other out).

The ﬁrst x-ray source (Sco X-1) was discovered in 1962 during a rocket ﬂight by a group led by Riccardo Giacconi [1, 2], who won the Nobel Prize in Physics in 2002 for his pioneering studies in x-ray astronomy. Since then, x-ray sources have been observed by different space missions: UHURU, which was launched in 1970 [3, 4] and which mapped the x-ray sky in the 2–6 keV energy range; the Einstein observatory, which was launched in November 1978 and provided high-resolution images and accurate locations for thousands of x-ray sources [5]; the European X-Ray Observatory Satellite (EXOSAT), which operated from May 1983 to April 1986 and allowed to perform continuous observations of x-ray sources lasting for several days without interruption.
due to Earth occultation; Chandra; XMM-Newton; Rossi XTE; BeppoSAX; INTEGRAL; and others.

On the other hand, ground-based observations with optical telescopes have demonstrated that x-ray sources are often members of binary systems. A fraction of these sources are eclipsing binaries that show periodic light variations with time, and thus the x-rays are periodically cut off from the observer. In order to specify the physical and geometric parameters of an eclipsing binary system, we need to model and simulate its light variations, or what is termed as synthetic light curves. These methods are especially important in the study of eclipsing x-ray binaries, since they help determine the mass of the compact object and thus specify its nature as a neutron star or a black hole.

Many contributions have been made to the study and analysis of the light curves of eclipsing x-ray binaries, such as [6–11] and others. This work focuses on the analysis of one such binary, Cen X-3, in an attempt to derive more reliable physical and geometric parameters by emphasizing on the phenomenological model of x-ray reflection and heating of the primary star.

2. SPECIFICATIONS OF THE SYSTEM

The eclipsing x-ray binary system CenX-3 is known as a high-mass x-ray binary system that consists of an 18 $M_\odot$ O6.5 V–III giant optical star and a 1.2 $M_\odot$ neutron star [12] with a spin period of 4.8 s and an orbital period of 2411 (see [13] for a review).

The x-ray star Cen X-3 was discovered from the UHURU observation by [14], where it was distinguished as a 4.84 second x-ray pulsar with a 2^4087 eclipse period. Krzemiński [15] declared that the x-ray star Cen X-3 is a component of an eclipsing binary system consisting of the star Cen X-3 and a giant optical star of the B0 spectral type with an optical magnitude of 13^m.4 at a distance of 10 kpc. There are other spectral types published for this star: O6.5 II–Ve [16], O6.5 V–III [17], and O6 VI [18].

The light curve of this system is characterized by two maxima at the phases 0.25 and 0.75, and two minima at the phases 0.0 and 0.5. One results from the eclipse of the compact object by the optical star, and the other (the deeper)—from the cold hemisphere of the optical star.

### Table 1. Physical and geometric parameters of the system from the literature

| Parameter                        | Value                  | Ref. |
|----------------------------------|------------------------|------|
| $M_{\text{opt}}$                 | $17 \pm 2 M_\odot$    | [18] |
| $18.25 \pm 1.75 M_\odot$        |                        | [12] |
| $M_n$                            | $1.2 \pm 0.6 M_\odot$  | [12] |
| $1 \pm 0.3 M_\odot$             |                        | [18] |
| $0.85 \pm 0.25 M_\odot$         |                        | [20] |
| $e$                              | $< 0.002$              | [20] |
| $i$                              | $90^\circ$             | [15] |
| $P_{\text{orb}}$                | $2^d 087$              | [2]  |
| $2^d 08712$                      |                        | [21] |
| $\dot{P}_{\text{orb}}/P_{\text{orb}}$ | $-1.6 \times 10^{-6}$ s/yr | [22] |
| $L_x$                            | $7.7 \times 10^{37}$ erg/s | [22] |
| $L_{\text{opt}}/L_x$             | 100                    | [23] |
| Pulsation Period $P_p$           | 4.84 s                 | [24] |
| Distance, kpc                    | 5 to 10                | [24] |
| $m_V$                            | $13^m.4$               | [12] |
| $\Delta m_V$                    | $0^m.7$                | [22] |
| $0^m.8$                          |                        | [12] |
| Duration of x-ray eclipse $\vartheta_e$ | $39 \pm 2^\circ$    | [2, 15, 25] |
| Mass ratio $q$                   | $0.06 \pm 0.002$       | [10] |
| $R$ (optical component)          | $0.625 \pm 0.003 R_\odot$ | [10] |
| Limb darkening coefficient $u$   | $0.8 \pm 0.02$         | [10] |
| Gravity darkening coefficient $\tau_o$ | $0.4 \pm 0.02$     | [10] |
| Efficiency of re-emission $\eta$ | $0.1 \pm 0.05$         | [10] |
| $T_{\text{eff}}$ (optical companion) | $38\,000 \pm 1000$ K | [10] |
Figure 1 shows the best fit between our synthetic light curve represented by the parameters listed in Table 1 [10] and Petro’s observations [19].

3. METHOD AND PROCEDURES

To synthesize the light curves of the system, we used the standard model of x-ray binaries, which is based on the Roche model and the phenomenon of x-ray reflection and heating of the side of the optical companion facing the compact object. We followed [11] in their solution to the basic equation of the Roche Model, where they used the Newton–Raphson method to solve it after changing it into an eighth-degree polynomial equation which proved to be more precise and more efficient than the series solutions developed by [26].

An important role in the optical light variations of x-ray binaries is played by the effect of x-ray reflection and heating of the side of the optical companion facing the compact object which makes that side hotter and more luminous than the other one. Hence, more light comes out of it which is responsible for the peaks of the light curve.

The re-emitted intensity $J^*(x, y)$ as a function of the incident flux is:

$$J^*(x, y) = \sigma E A F_{in},$$  \hspace{1cm} (1)

where $E$ represents to some extent the re-distribution of the wavelengths of the incident flux which is re-emitted at the observed effective wavelengths. Many authors described and simplified this effect for the case of two optical components, starting with [26, 27]. But the case of x-ray binaries is a bit more complicated, because the secondary component (x-ray source) is a small compact object which makes its contribution to the optical light negligible, whereas it radiates effectively in the x-ray band. So, the reflected flux $F_{ref}$ can be described by the following equation:

$$F_{ref} = \tau_o \eta (L_x/L_{opt}) (R/r')^2 \cos \Gamma,$$  \hspace{1cm} (2)

where $\tau_o$ is the gravity darkening coefficient, $\eta$ is the efficiency of absorption, $L_x$ is the x-ray luminosity, $L_{opt}$ is the optical luminosity, $R$ is the radius of the
Table 2. Modified parameters of the system

| Parameter                              | Value                      |
|----------------------------------------|----------------------------|
| Mass Ratio $q$                         | $0.062 \pm 0.002$          |
| $R$ (optical component)                | $0.636 \pm 0.003 R_\odot$  |
| Optical to x-ray luminosity ratio $L_{\text{opt}}/L_x$ | $105 \pm 3$               |
| Limb darkening coefficient $u$         | $0.85 \pm 0.02$            |
| Gravity darkening coefficient $\tau_o$ | $0.37 \pm 0.02$            |
| Efficiency of re-emission $\eta$       | $0.6 \pm 0.05$             |
| $T_{\text{eff}}$ (optical component)  | $38000 \pm 1000$ K        |

optical star in $R_\odot$, $r'$ is the distance between the center of the compact object and the point at which we calculate $F$ on the surface of the optical star, and $\Gamma$ is the angle of incidence of x-rays on the primary star.

In addition to the efficiency of absorption and re-emission $\eta$, we considered another six input parameters which represent the physical and geometric characteristics of the system once the best fit has been achieved. These parameters are: mass ratio of the components $q$, fractional radius of the optical component $r$, limb darkening coefficient $u$, gravity darkening coefficient $\tau_o$, optical to x-ray luminosity ratio $L_{\text{opt}}/L_x$, and the effective temperature of the optical star $T_{\text{eff}}$.

4. RESULTS AND DISCUSSION

Our method of determining the parameters of eclipsing x-ray binaries depends on iterative attempts to achieve the best fits between the observed optical light curves and the synthetic ones. Therefore, many iterations were performed to reach the best fit. As an observational reference and guide, we found in the literature three observed light curves reported by [19, 28, 29].

Figures 2, 3, and 4 show the best fit achieved between our synthetic light curve, represented by the parameters listed in Table 2, and the observed light curves of [19], [28], and [29] respectively, while Fig. 5 shows the combination of the three observed light curves fitted with our synthetic one.

The values of the best fit represent adequately enough the physical and geometric parameters of the system’s components within the errors of the observed photometry.

5. CONCLUSIONS

The modified physical and geometric parameters of the eclipsing x-ray binary system Cen X-3 were estimated based on the best fit between the observed photometric light curves, which were measured using ground based telescopes, and the synthetic light curves built in accordance with the Roche model. The modification of the system’s parameters was based mainly on increasing the influence of the phenomenon of x-ray heating of the side of the optical component facing the compact object. In constructing our synthetic light curves, we assumed that the optical component of the system fills its Roche lobe and that the system has synchronous rotation; we neglected the effect of the magnetic fields of both components.

REFERENCES

1. R. Giacconi, H. Gursky, and J. R. Waters, Nature 204, 981 (1964).
2. J. B. Hutchings, Astrophys. J. 188, 341 (1974).
3. E. M. Kellogg, Astrophys. J. 197, 689 (1975).
4. R. Giacconi, S. Murray, H. Gursky, et al., Astrophys. J. 178, 281 (1972).
5. M. J. Harris, G. H. Share, M. D. Leising, and J. E. Grove, Astrophys. J. 416, 601 (1993).
6. J. B. Hutchings, in Physics and Astrophysics of Neutron Stars and Black Holes, Ed. by R. Giacconi and R. Ruffini (North Holland Publ. Co., Amsterdam, 1978), pp. 202–215.
7. Y. Avni, in Physics and Astrophysics of Neutron Stars and Black Holes, Ed. by R. Giacconi and R. Ruffini (North Holland Publ. Co., Amsterdam, 1978), pp. 43–62.
8. E. A. Antokhina and A. M. Cherepashchuk, Sov. Astron. 31, 295 (1987).
9. E. A. Antokhina and A. M. Cherepashchuk, Astronomy Reports 38, 367 (1994).
10. M. A. S. Al-Wardat, H. M. Al-Naimiy, I. A. Barghouthi, and H. A. Sabat, Astrophys. and Space Sci. 260, 335 (1998).
11. H. A. Sabat, H. M. Al-Naimiy, I. A. Barghouhti, and M. A. S. Al-Wardat, Astrophys. and Space Sci. 260, 347 (1998).
12. J. N. Bahcall, in Physics and Astrophysics of Neutron Stars and Black Holes, Ed. by R. Giacconi and R. Ruffini (North Holland Publ. Co., Amsterdam, 1978), pp. 63–110.
13. F. Nagase, Publ. Astron. Soc. Japan 41, 1 (1989).
14. R. Giacconi, H. Gursky, E. Kellogg, et al., Astrophys. J. 167, L67 (1971).
15. W. Krzeminski, Astrophys. J. 192, L135 (1974).
16. E. P. J. van den Heuvel, Space Sci. Rev. 30, 309 (1981).
17. C. Hoffmeister and P. N. Kholopov, Sov. Astron. 29, 719 (1985).
18. J. B. Hutchings, A. P. Cowley, D. Crampton, et al., Astrophys. J. 229, 1079 (1979).
19. L. D. Petro, Astrophys. J. 195, 709 (1975).
20. Y. Avni, J. N. Bahcall, Astrophys. J. 197, 675 (1975).
21. R. Giacconi, in Physics and Astrophysics of Neutron Stars and Black Holes, Ed. by R. Giacconi and R. Ruffini (North Holland Publ. Co., Amsterdam, 1978), pp. 17–42.
22. E. Schreier, R. Levinson, H. Gursky, et. al., Astrophys. J. 172, L79 (1972).
23. P. Bagot, Astron. and Astrophys. 314, 576 (1996).
24. E. P. J. van den Heuvel, in Proc. Enrico Fermi School on Physics of Neutron Stars and Black Holes (North Holland Publ. Co., Amsterdam, 1978), pp. 828–871.
25. Y. Avni, Astron. and Astrophys. 63, L13 (1978).
26. Z. Kopal, Close Binary Systems (Chapman & Hall, London, 1959).
27. W. M. Napier, Astrophys. and Space Sci. 2, 61 (1968).
28. J. van Paradijs, J. Lub, J. W. Pel, et al., Astron. and Astrophys. 124, 294 (1983).
29. H. Mauder, Astrophys. J. 195, L27 (1975).