

The Eclipsing X-Ray Binary System Centaurus X-3

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Abstract: Problem statement: We present new physical and geometrical elements for the eclipsing X-ray binary system Krzemenski's star (Centaurus X-3). **Approach:** In this study, the procedure depended on getting the best fit between the observational photometric light curves and synthetic ones built up in accordance to the Roche model. **Results:** The estimated elements showed a good agreement with the early estimated ones. **Conclusion:** In building the synthetic light curves, we assumed that the optical component of the system is filling to Roche lobe, the system is rotationally synchronized and we neglecting the effect of the magnetic fields of both components.

Key words: Light curve, Centaurus X-3, X-ray binary stars, the physical and geometrical elements, compact object

INTRODUCTION

A binary stellar system is simply one in which two stars orbit around a common center of mass, that is they are gravitationally bound to each other. Almost 50 percent of the stars in the sky are part of a binary or multiple stellar systems.

A sub-class of binary systems are X-ray binaries, the systems in which a compact object (a white dwarf, neutron star or a black hole formed after 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 (10^6 - 10^8 K), releasing the energy it acquired through gravitational infill in the form of X-ray radiation.

In 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. Figure 1 shows a sketch of an X-ray binary system as it would be seen by a nearby observer.

X-ray binary stars are usually subdivided into two categories:

- High Mass X-ray Binaries (HMXB) where the companion's mass is greater than several solar masses, which enable it to eject matter through the stellar wind
- Low Mass X-ray Binaries (LMXB) where the companion's mass is around one solar mass and it

provides matter through the inner Lagrangian point-the point where gravitational forces of the two stars and centrifugal force cancel

The first X-ray Source (Sco X-1) was discovered in 1962 during a rocket flight by a group led by Giacconi *et al.* (1964) Giacconi and Gursky (1974) who won the Nobel Prize for Physics in 2002 for his pioneering studies in X-ray astronomy.

The actual study of the X-ray binary stars began in the 1970s with the use of satellites equipped with X-ray detectors. The first one, UHURU, was launched in 1970 (Giacconi *et al.*, 1972). It mapped the X-ray sky in the energy range 2-6 keV. The Einstein observatory was launched in November 1978, It provided high-resolution images and accurate locations for thousands of X-ray sources (Harris *et al.*, 1993).

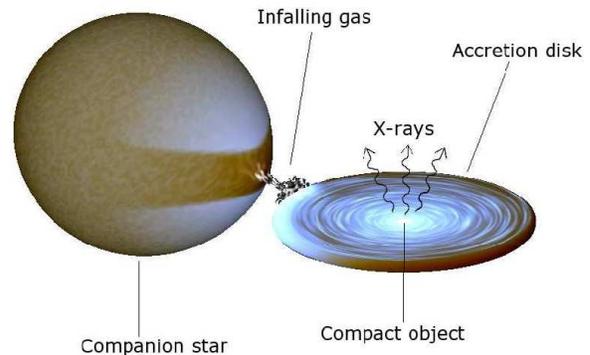


Fig. 1: A schematic view of an X-ray binary. Gas is pulled off the normal star by the gravity of the compact object

Table 1: The physical and geometrical elements of the system as given by earlier studies

Parameter		Reference
Mass of the optical star	$M_{opt} = (17 \pm 2) M_{\odot}$ $= (18.25 \pm 1.75) M_{\odot}$	(Hutchings <i>et al.</i> , 1979) (Bahcall, 1978)
Mass of the neutron star	$M_n = (1.2 \pm 0.6) M_{\odot}$ $= (1 \pm 0.3) M_{\odot}$ $= (0.85 \pm 0.25) M_{\odot}$	(Bahcall, 1978) (Hutchings <i>et al.</i> , 1979) (Avni and Bahcall, 1975; Krzemenski, 1974)
Eccentricity of the orbit	$e < 0.002$	(Hutchings, 1974)
Inclination of the system	$i = 90^\circ$	(Giacconi and Ruffini, 1978)
Orbital period	$P_{orb} = 2.087d$ $= 2.08712d$	(Schreier <i>et al.</i> , 1972) (Bagot, 1996)
Orbital period change	$= -1.6C10^{-6} \text{ sec year}^{-1} P_{orb}^* / P_{orb}$	(Van den Heuvel, 1978)
X-ray luminosity	$L \sim 7.7C10^{37} \text{ erg/s}$	(Bahcall, 1978)
Optical to X-ray luminosity ratio	$L_{opt}/L_x = 100$	(Schreier <i>et al.</i> , 1972) (Bahcall, 1978)
Pulsation period	$P_p = 4.84s$	(Bahcall, 1978)
Distance from earth	5-10 kpc	(Krzemenski, 1974)
Visual magnitude	$m_v = 13.4 \text{ mag}$ $\Delta m = 0.7 \text{ mag}$ $\Delta m = 0.8 \text{ mag}$	(Hutchings, 1974) (Avni, 1978b) (Al-Wardat <i>et al.</i> , 1998)
Duration of X-ray eclipse	$J_e = 39 \pm 2^\circ$	(Al-Wardat <i>et al.</i> , 1998)
Mass ratio of the system	$q = 0.06 \pm 0.002$	(Al-Wardat <i>et al.</i> , 1998)
Radius of the optical component	$r = 0.625 \pm 0.003$	(Al-Wardat <i>et al.</i> , 1998)
Limb darkening coefficient	$u = 0.8 \pm 0.02$	(Al-Wardat <i>et al.</i> , 1998)
Gravity darkening coefficient	$t_g = 0.4 \pm 0.02$	(Al-Wardat <i>et al.</i> , 1998)
Efficiency of absorption and re-emission	$\eta = 0.1 \pm 0.05$	(Al-Wardat <i>et al.</i> , 1998)
Optical to X-ray luminosity ratio	$L_{opt}/L_x = 100 \pm 5$	(Al-Wardat <i>et al.</i> , 1998)
Effective temperature of the optical star	$T_{eff} = 38000 \text{ K} \pm 1000$	

The European X-Ray Observatory Satellite (EXOSAT) operated from May 1983 to April 1986 allowed to perform continuous observations of X-ray sources lasting several days without the interference of Earth occultation's. These and later missions (Chandra, XMM-Newton, Rossi XTE, BeppoSAX, INTEGRAL and others) observed X-ray radiation from different sources.

As a result of this development by a number of scientists to the set of results shown in Table 1, which represents the previous studies of this system Centaurus X-3.

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 systems that show periodic light variations with time, known as the light curves.

Many contributions have been made to study and analyze the light curves of the X-ray eclipsing binaries, such as (Hutchings, 1978; Avni, 1978a; Antokhina and Cherpashchuk, 1987; 1994; Al-Wardat *et al.*, 1998; Sabat *et al.*, 1998) and others. The present study focuses on the analysis of one such binary, Centaurus X-3, in a step to derive more reliable physical and geometrical elements.

Specifications of the system Centaurus X-3 (Krzemenski's star): The eclipsing X-ray binary

system Krzemenski's star (Centaurus X-3) is known as a high-mass X-ray binary system consists of $18 M_{\odot}$ O6.5V-III giant optical star and a $1.2 M_{\odot}$ neutron star (Bahcall, 1978).

The X-ray star Cen X-3 was discovered from the UHURU observation by Giacconi *et al.* (1971) where it has been distinguished as 4.84 Second X-ray pulsar with a 2.087 day eclipse period. Krzemenski (1974) declared that the X-ray star Cen X-3 is a component of an eclipsing binary system consists of the star Cen X-3 and a giant optical star of the spectral type B0, with optical magnitude 13.4 mag at a distance of 10 kpc.

There are other issued values of the spectral type of the star, these are:

- O6.5II-Ve (Van den Heuvel, 1981)
- O6.5V-III (Hoffmeister *et al.*, 1985)
- O6f (Hutchings, 1978)

The light curve of this system characterized by two maximums at phases (0.25 and 0.75) because the observer faces the maximum area of the system and two minimums at phases (0.0 and 0.5), one results from the eclipse of the compact object to the optical star and the other the deeper results from the cold hemisphere of the optical star.

MATERIALS AND METHODS

Our method of determining the elements of eclipsing X-ray binaries depends on iterated attempts of getting the best fitting between the optical observational light curve and a synthetic one. The standard model of X-ray binaries was used in synthesizing light-curves of the system. The synthetic light curves were built in accordance to Roche model and taking into account the X-ray reflection and heating of the opposite side of the optical companion. We followed Sabat *et al.* (1998) in their solution to the Roche Model's basic equation, where they used Newton-Raphson method to solve it, after changing it into an eighth-degree polynomial equation, which proved to be more precise and yet, more efficient than the series solutions developed by Kopal (1959).

We considered the input elements of the best fit as the elements of the system. These elements are; mass ratio of the system q , fractional radius of the optical component r , limb darkening coefficient u , gravity darkening coefficient τ , efficiency of absorption and re-emission η , optical X-ray luminosity ratio L_{opt}/L_x and the effective temperature of the optical star T_{eff} .

Table 2: New elements of Centaurus X-3

Mass ratio of the system	$q = 0.062 \pm 0.001$
Radius of the optical component	$r = 0.63 \pm 0.002$
Limb darkening coefficient	$u = 0.82 \pm 0.02$
Gravity darkening coefficient	$\tau = 0.42 \pm 0.01$
Efficiency of absorption and re-emission	$\eta = 0.12 \pm 0.04$
Optical to X-ray luminosity ratio	$L_{opt}/L_x = 103 \pm 4$

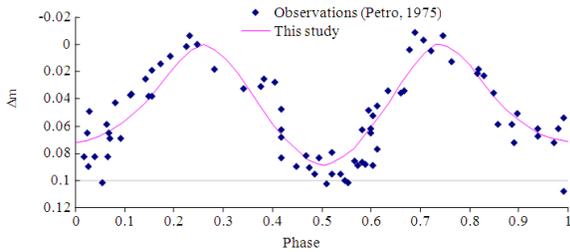


Fig. 2: The estimated synthetic light curve against the observations of Petro (1975)

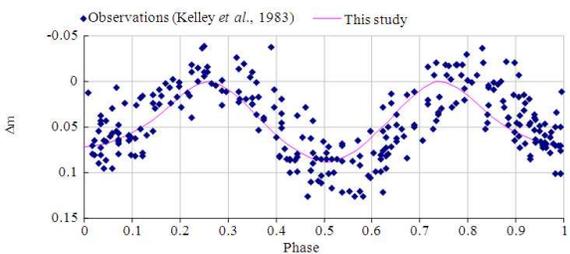


Fig. 3: The estimated synthetic light curve against the observations of Kelley *et al.* (1983)

Many attempts were performed to get the best fit. As an observational reference and guide, we used the observational light curves of Petro (1975) and (Kelley *et al.*, 1983).

RESULTS

The best fit was achieved using a synthetic light curve represented by the new physical and geometrical elements listed in Table 2.

The achieved best between different observation light curve and our synthetic one are represented by Fig. 2 and 3. Where Fig. 2 shows our synthetic light curve against the observations of Petro (1975), Fig. 3 shows it against the observations of Kelley *et al.* (1983).

DISCUSSION

The importance of this research required obtaining the values of elements of physical and geometrical required to verify compliance with other observational as well as it gives a clearer image and explains this dual system Centaurus X-3.

CONCLUSION

New physical and geometrical elements of the X-ray eclipsing binary system Centaurus X-3 (Krzeminski's star) were found. The procedure depended on getting the best fit between the observational photometric light curves, which measured using ground based telescopes and a synthetic light curve built up in accordance to the Roche model.

In building the synthetic light curves, we assumed that the optical component of the system is filling to Roche lobe, the system is rotationally synchronized and we neglecting the effect of the magnetic fields of both components.

REFERENCES

- Al-Wardat, M.A.S., H.M. Al-Naimiy, I.A. Barghouthi and H.A. Sabat, 1998. New elements for three eclipsing X-Ray binary systems: HZ Herculis, Centaurus X-3 and VELA X-1. *Astrophys. Space Sci.*, 260: 335-345. DOI: 10.1023/A:1001714812242
- Antokhina, E.A. and A.M. Cherepashchuk, 1994. Synthesizing of radial velocity curves of close binary systems. *Astronomicheskij Zhurnal*, 71: 420-430. <http://adsabs.harvard.edu/abs/1994AZh....71..420A>

- Antokhina, E.A. and A.M. Cherpashchuk, 1987. SS 433-the parameters of the eclipsing system with a processing thick accretion disk. *Astronomicheskii Zhurnal*, 64: 562-585.
- Avni, Y. and J.N. Bahcall, 1975. Ellipsoidal light variations and masses of X-ray binaries. *Astrophys. J.*, 197: 675-688. DOI: 10.1086/153558
- Avni, Y., 1978a. Mass Estimates from Optical Light Curves for Binary X-Ray Sources. In: *Physics and Astrophysics of Neutron Stars and Black Holes*, Giacconi, R. and R. Ruffini (Eds.). North-Holland Publishing Company, Amsterdam, pp: 43-62.
- Avni, Y., 1978b. On the contribution of active galactic nuclei to the diffuse X-ray background. *Astron. Astrophys.*, 63: 13-16. <http://articles.adsabs.harvard.edu/full/1978A%26A....63L..13A/L00013.000.html>
- Bagot, P., 1996. Boost of the orbital motion in high mass X-ray binaries. *Astron. Astrophys.*, 314: 576-584. <http://adsabs.harvard.edu/full/1996A%26A...314..576B>
- Bahcall, J.N., 1978. Optical Properties of Binary X-Ray Sources. In: *Physics and Astrophysics of Neutron Stars and Black Holes*, Giacconi, R. and R. Ruffini (Eds.). North-Holland Publishing Company, Amsterdam, pp: 63-110.
- Giacconi, R. and H. Gursky, 1974. *X-Ray Astronomy*. 1st Edn., Springer, Holland, ISBN: 9027702950, pp: 460.
- Giacconi, R. and R. Ruffini, 1978. *Physics and Astrophysics of Neutron Stars and Black Holes*. 1st Edn., North-Holland Pub. Co., New York, pp: 866.
- Giacconi, R., H. Gursky, J.R. Waters, G. Clark and B. Rossi, 1964. Two sources of cosmic X-rays in Scorpius and Sagittarius. *Nature*, 204: 981-982. DOI: 10.1038/204981a0
- Giacconi, R., H. Gursky and E. Kellogg, E. Schreier and H. Tananbaum. 1971. Discovery of periodic X-ray pulsations in centaurus X-3 from HURU. *Astrophys. J.*, 167: 67-73. DOI: 10.1086/180762
- Giacconi, R., S. Murray, H. Gursky, E. Kellogg and E. Schreier *et al.*, 1972. The Uhuru catalog of X-ray sources. *Astrophys. J.*, 178: 281-308. <http://adsabs.harvard.edu/full/1972ApJ...178..281G>
- Harris, M.J., G.H. Share, M.D. Leising and J.E. Grove, 1993. SMM observations of gamma-ray transients. I. A search for variable emission at MeV energies from five galactic and extragalactic sources. *Astrophys. J.*, 416: 601-619. DOI: 10.1086/173262
- Hoffmeister, C., G. Richter and W. Wenzel, 1985. *Variable Stars*. 1st Edn., Springer-Verlag, Berlin, ISBN: 3540134034, pp: 328.
- Hutchings, J.B., A.P. Cowely, D. Crampton, J. van Paradijs and N.E. White, 1979. Centaurus X-3. *Astrophys. J.*, 229: 1079-1084. DOI: 10.1086/157042
- Hutchings, J.B., 1974. The synthesis of close-binary light curves. VI. X-ray and collapse binaries. *Astrophys. J.*, 188: 341-348. DOI: 10.1086/152722
- Hutchings, J.B., 1978. Optical Observations of X-Ray Sources. In: *Physics and Astrophysics of Neutron Stars and Black Hole*. Giacconi, R. and R. Ruffini (Eds.). North Holland Publishing Co., Amsterdam, pp: 202-215.
- Kelley, R.L., S. Rappaport, G.W. Clark and L.D. Petro, 1983. Orbital period changes in Centaurus X-3. *Astrophysical J.*, 268: 790-799. DOI: 10.1086/161001
- Kopal, Z., 1959. *Close Binary Systems*. 1st Edn., Wiley, New York, ISBN: 0471503258, pp: 558.
- Krzeminski, W., 1974. The identification and UBV photometry of the visible component of the Centaurus X-3 binary system. *Astrophys. J.*, 192: L135-L138. DOI: 10.1086/181609
- Petro, L.D., 1975. Photoelectric observations of Krzeminski's star, the companion of Centaurus X-3. *Astrophys. J.*, 195: 709-713. DOI: 10.1086/153372
- Sabat, H.A., H.M. Al-Naimiy, I.A. Barghouthi and M.A. Al-Wardat, 1998. Synthetic light-curves of some eclipsing X-ray binary systems. *Astrophys. Space Sci.*, 260: 347-357. DOI: 10.1023/A:1001766829080
- Schreier, E., R. Levinson, H. Gursky, E. Kellogg and H. Tananbaum *et al.*, 1972. Evidence for the Binary nature of Centaurus X-3 from UHURU X-ray observations. *Astrophys. J.*, 172: L79-L89. DOI: 10.1086/180896
- Van den Heuvel, E.P.J., 1978. Evolution of Close Binaries, with Possible Applications to Massive X-Ray Binaries. In: *Physics and Astrophysics of Neutron Stars and Black Holes*, Giacconi, R. and R. Ruffini (Eds.). North Holland Publishing Co., Amsterdam, pp: 828-871.
- Van den Heuvel, E.P.J., 1981. X-Ray Binaries and Stellar Evolution. In: *X-Ray Astronomy, Space Science Reviews*, Anderson, R.D. (Ed.). D Reidel Publishing Company, Dordrecht, pp: 309-309.