The correlation of X-ray binaries between X-ray and Optical light with MAXI and TESS

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We searched for the correlation between X-ray and optical variabilities of X-ray binaries by comparing the light curves observed by MAXI and TESS at the same time. First, from MAXI public light curves of more than 400 X-ray sources, We chose 33 sources which show appreciable modulations in X-ray and are observed in TESS (at Nov 2019). Then we obtained light curves of these 33 sources from TESS Full-frame images using 'eleanor'. Among them, Cen X-3 and SMC X-1 have been observed by both satellites at the same time for 54 days and showed clear modulations in both X-ray and optical light. We performed the modeling of optical light curves for these X-ray binaries based on a simple geometric model. In our model, tidal and rotational distortion, limb-darkening and gravity darkening effects are taken into account. In addition, the effect of the presence of a disk is also included. We'll discuss light curves of SMC X-1 and Cen X-3 using this model and give constraints on their parameters.

1.Introduction

High mass x-ray binary (HXMB)
Binary consists of massive star and X-ray source

Eclipsing X-ray binary
In some high inclination X-ray binary, the apparent brightness of X-ray drops when the companion star interrupts between the X-ray source and the observer as it orbits around the common center of gravity.

Ellipsoidal modulation
Light curve modulation due to star's asymmetrical shape. The shape distortion is caused by tidal and rotational effect.

SMC X-1 and Cen X-3

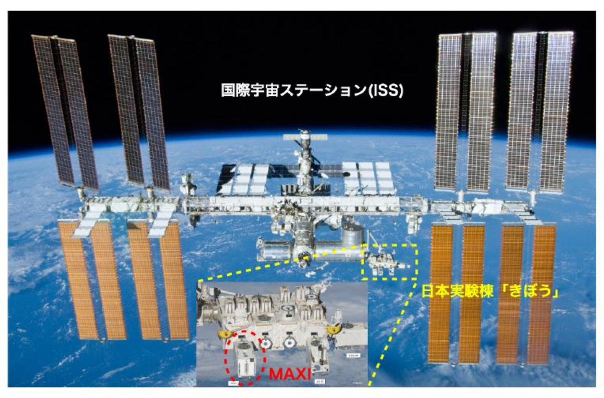
They are X-ray binary pulsars with some similar properties.
- Companions are massive stars with O or early B supergiants
- The X-ray sources are pulsars.
- They are eclipsing binary

	SMC X-1	Cen X-3
Star radius	$16.4 \pm 1.0 R_{\odot}$	$12.1 \pm 0.5 R_{\odot}$
Star mass	$15.7 \pm 1.5 M_{\odot}$	$20.2 \pm 1.5 M_{\odot}$
NS mass	$1.06 \pm 0.11 M_{\odot}$	$1.34 \pm 0.15 M_{\odot}$

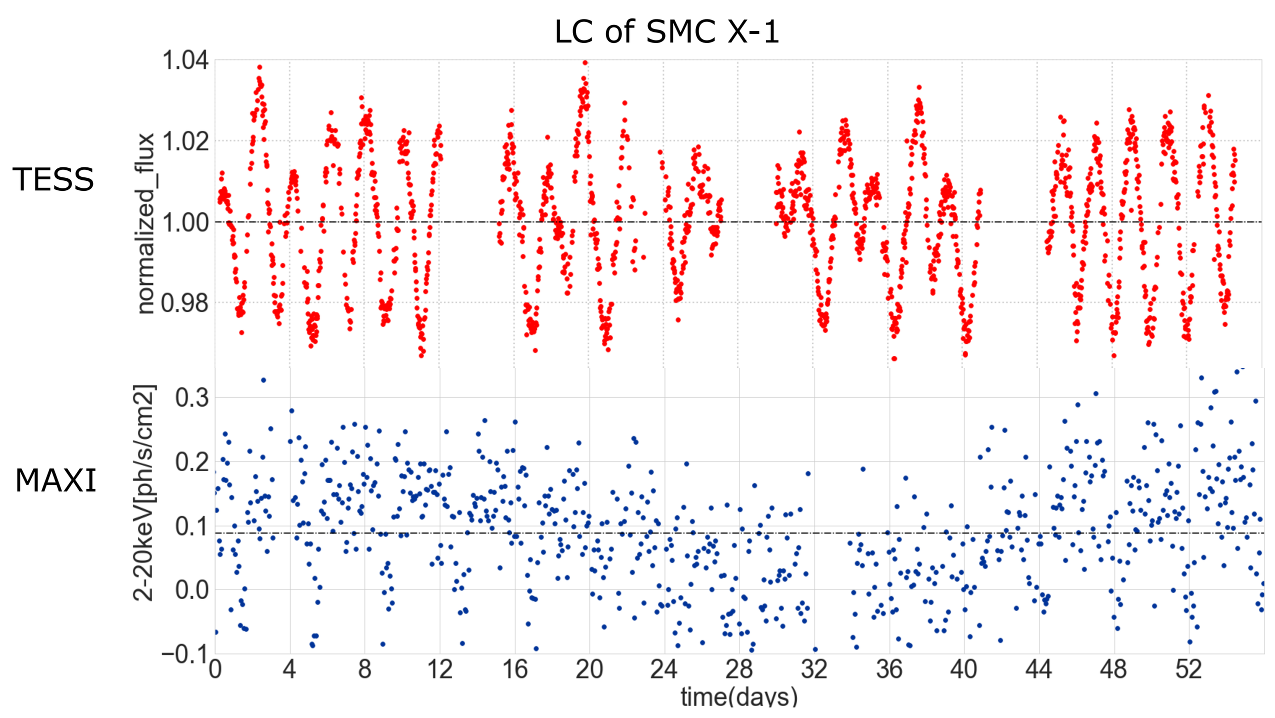
[1]

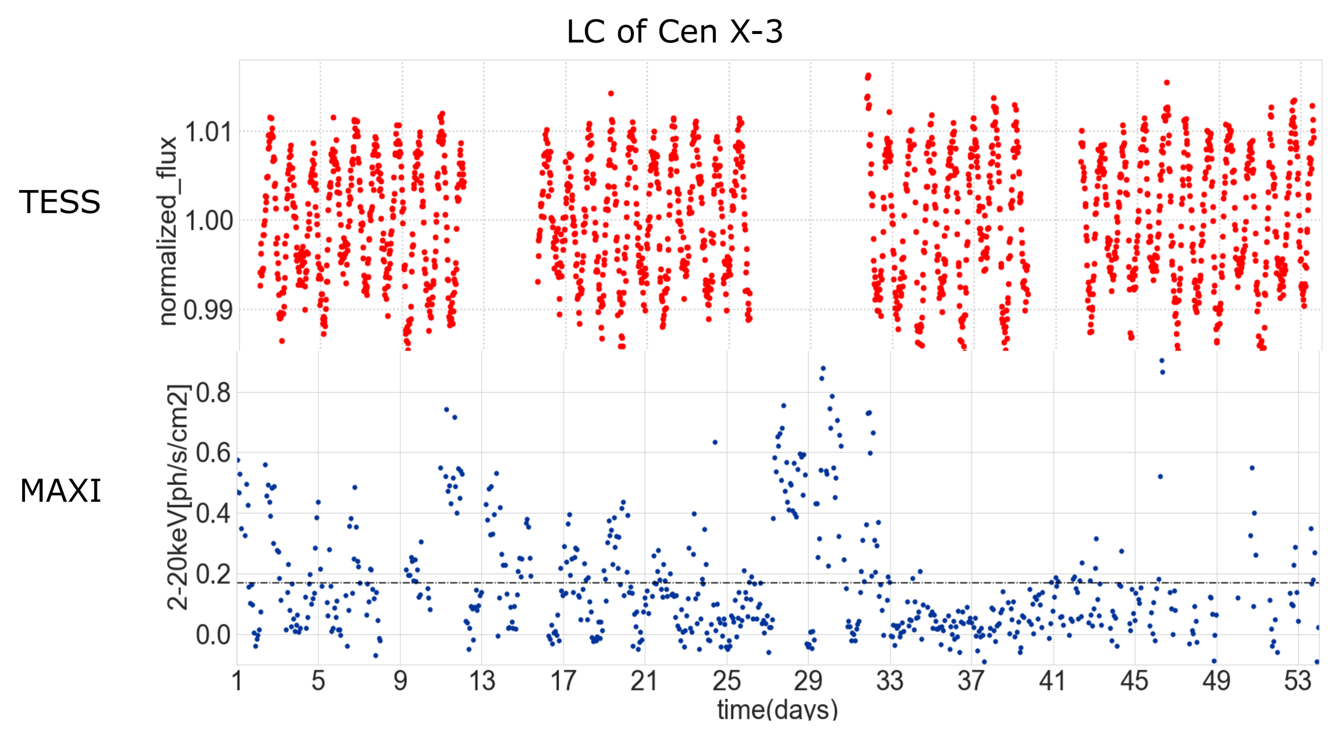
MAXI

All-sky X-ray monitoring instrument mounted on the International Space Station.(ISS) It monitors X-ray sources in the entire sky once every 90 minutes. Light curves of about 400 X-ray sources are available from the official MAXI page. (http://maxi.riken.jp/top/lc.html)



2.Datasets





◆Light curves of SMC X-1 and Cen X-3

SMC X-1 and Cen X-3 were observed by TESS and MAXI at the same time for about 53 days.

- TESS : To obtain the light curve from the TESS full frame images (FFI), we used the photometry program eleanor[2]
- MAXI : The X-ray light curves were obtained from the official website of MAXI (http://maxi.riken.jp/top/lc.html)

	SMC X-1	Cen X-3
Start time (MJD)	58325.2	58571.0
End time (MJD)	58379.6	58622.6
TESS Sectors	1, 2	10, 11

3.Analysis and discussions

◆Estimating orbital period

First, we estimated the orbital period by performing a folding analysis of the TESS data. The results are 3.895 days for SMC X-1 and 2.086 days for Cen X-3. Fig. 3 is the folded light curves with these periods. The optical data shows two maxima and two minima, while the X-ray "eclipse" coincides with one of those minima, and we set the phase to 0.
Hence, at phase 0, the neutron star is far

◆Modeling of optical light curves

Ellipsoidal modulation and some other effects of neutron star and accretion disk

(i) Companion star geometry with effect of tidal and rotational distortion. In our model, it is assumed that the optical sphere coincides with the Roche lobe Limb-darkening.

(ii) Gravity darkening. According to von Zeipel's law, the relation between surface temperature (T) and surface gravity(g) of companion star is $g \propto T^{\beta}$ [3] and since SMC X-1 and Cen X-3 are massive stars, β is set to 0.25

(iii) Limb darkening. It is calculated as a function of the surface gravity (log g), and the edge attenuation coefficients are calculated based on Claret 2017 [4], which is limb darkening coefficients for TESS band. Since the coefficients are functions of surface gravity, metallicity(Z) and micro turburent(Mt), we obtained Z=-1.00, Mt=2.0 for SMC X-1 and Cen X-3 Z=0.00, Mt=2.0 from it's table and calculated interpolation to make the limb dark coefficients as a function of log g.

(iv) Accretion disk. In our model, it is assumed that the shape of disk is circular, its radius is equal to the average radii of the Rochelobe of neutron star and it is optically thick.

(v) X-ray irradiation heating. When a star or an accretion disk is illuminated by X-rays from a X-ray source, its temperature rises and distribution changes.

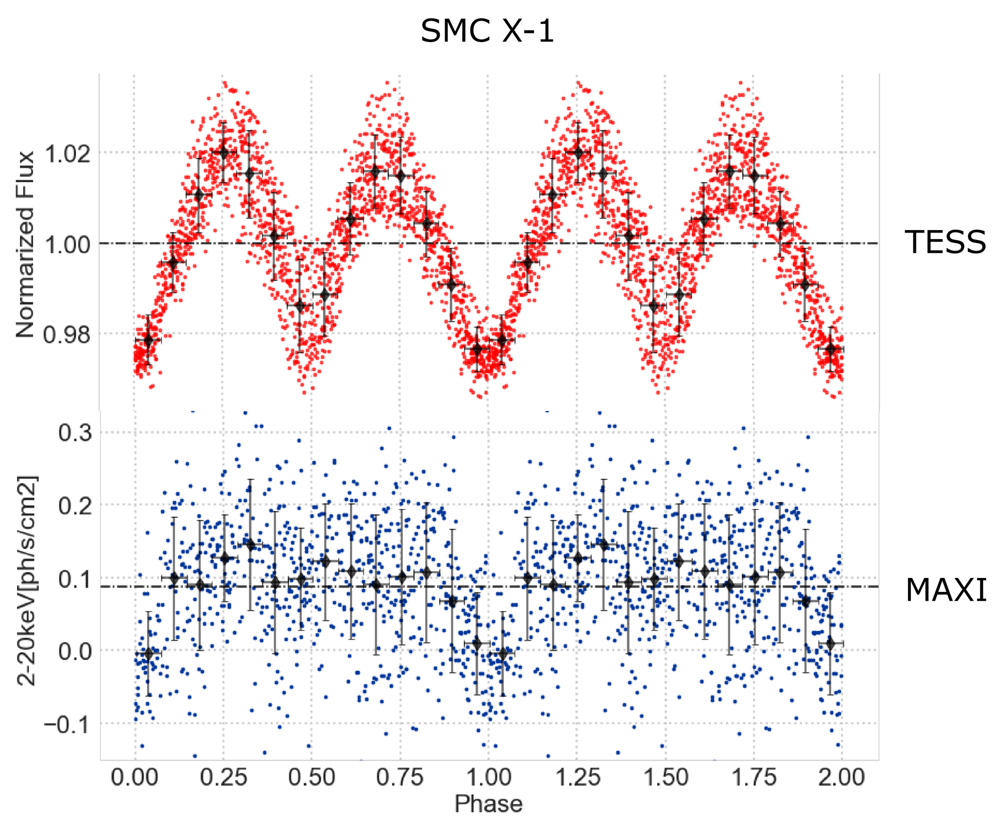
The results of fitting parameters are shown in table 3.1

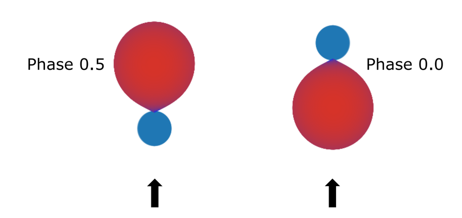
Table 3.1

parameter	Dependence	fix or fitting	SMC X-1	Cen X-3	ref
mass ratio	(i)	Fix	0.067	0.066	[1][5]
Effective temperature of companion (K)	(i)	Fix	28000	38000	[1][5]
Inclination angle (deg)	(i)~ (v)	Fix	63.9	59.4	[1][5]
X-ray luminosity of Neutron star (erg/s)	(v)	Fix	6.0×10^{38}	7.7×10^{37}	[6][7]
Separation ($R_{\odot}$)	(v)	Fitting	32.4 ± 1.9	12.6 ± 1.84	
Temperature of accretion disk (K)	(iv)	Fitting	$(3.46 \pm 0.23) \times 10^4$	$(2.26 \pm 0.29) \times 10^4$	
Surface gravity (log g)	(ii), (iii)	Fitting	3.14 ± 1.25	3.30 ± 1.43	

◆Super orbital modulation

The folded light curve shows that around phase (phase~0) when the accretion disk and neutron star are visible to the observer, the variance is large, while around the phase~0.5, when the X-ray source is nearest from the observer, the variance is small. This indicates that the super orbital modulation is due to the variation around the neutron stars. A possible origin of such variations is warped precession disk, which is discussed in some papers[8]. We'll create a model with precession disk and discuss whether the super orbital modulation in optical light is possible by the precession of accretion disk.





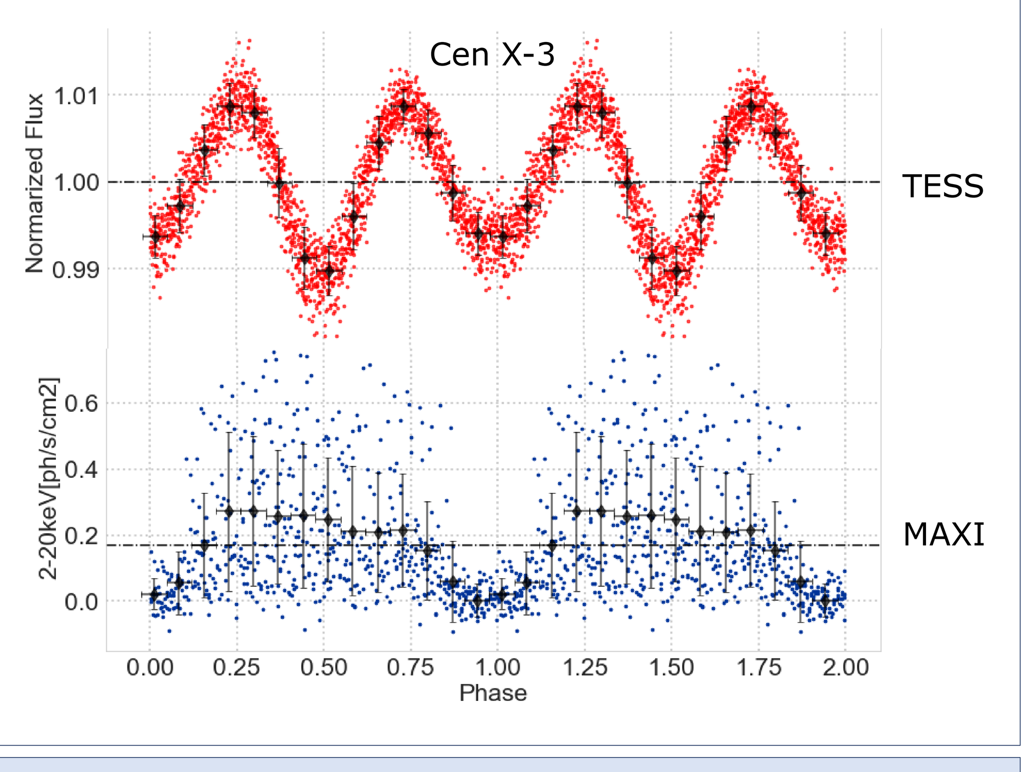


Fig 3.1

Folded data of visible and X-ray light curves (upper: SMC X-1, lower: Cen X-3). The folding period is 3.895 days for SMC X-1 and 2.086 days for Cen X-3. The schematic in the middle shows the binary stars at phase=0 and 0.5. Red object indicates the companion star, blue one indicates the neutron star and accretion disk, and the arrows indicate the direction of the observer's line of sight.

4.References

[1] van der Meer, A.; Kaper, L., et al 2007 Astronomy and Astrophysics, Volume 473, Issue2, October II 2007, pp.523-538
[2] Feinstein, et al.2019 Publications of the Astronomical Society of the Pacific, Volume 131, Issue 1003, pp. 094502 (2019).
[3] Orosz, Jerome A.; Bailyn, Charles D. 1997 The Astrophysical Journal, Volume 477, Issue 2, pp. 876-896.
[4] von Zeipel, H. 1924 Monthly Notices of the Royal Astronomical Society, Vol. 84, p.665-683
[5] Claret, A. 2017 Astronomy and Astrophysics, Volume 600, id.A30, 6 pp.
[6] Falanga, M.; Bozzo, E.; Lutovinov, A.; Bonnet-Bidaud, J. M.; Fetisova, Y.; Puls, J. 2015 Astronomy & Astrophysics, Volume 577, id.A130, 16 pp.
[7] Whelan, J. A. J.; Wickramasinghe, D. T. 1976 Monthly Notices of the Royal Astronomical Society, vol. 174, Jan. 1976, p. 29-45.
[8] Schreier, E.; Levinson, R.; Gursky, H.; Kellogg, E.; Tananbaum, H.; Giacconi, R. 1972 Astrophysical Journal, vol. 172, p.L79
[9] Pragati Pradhan, Chandreyee Maitra, and Biswajit Paul 2020 The Astrophysical Journal, Volume 895, Issue 1, id.10, 12 pp.