Spectral and timing analysis of BeXRB eRASSU J050810.4-660653 recently discovered in the Large Magellanic Cloud (LMC)

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ABSTRACT
We have studied the Be/X-ray binary (BeXRB) pulsar eRASSU J050810.4-660653 recently discovered in the Large Magellanic Cloud (LMC). Timing and spectral features of the source have been discussed in detail using NuSTAR & XMM-Newton observations. Coherent pulsation of the source was detected at $\sim 40.578 \pm 0.001$ s using NuSTAR observation. We analyzed pulse profiles of the source in different energy bands using NuSTAR & XMM-Newton data. The pulse-profile evolved with time but was generally suggestive of a pencil-beam dominated pattern, which combined with the measured luminosity, indicates that the source may be accreting in the sub-critical regime. The pulse fraction follows a linearly increasing trend with photon energy and is anti-correlated with luminosity. In the 1 year interval between the XMM and NuSTAR observations the pulse period shortened by 0.021 s which could be consistent with spin-up or orbital Doppler effect. The average flux of the source in (3-50) keV energy range is found to be $\sim 5.56 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and the corresponding luminosity is $\sim 1.66 \times 10^{37}$ erg s$^{-1}$. The variation of spectral parameters with pulse phase is studied using phase resolved spectroscopy which reveals that the observed photon index becomes harder with increasing flux.

Key words: accretion, accretion discs-stars: neutron-pulsars: individual: eRASSU J050810.4-660653 – X-rays: binaries.

1 INTRODUCTION
The Magellanic clouds are known for hosting large number of X-ray binaries particularly High Mass X-ray Binaries (HMXBs). The total number of HMXBs present in the Large Magellanic Cloud (LMC) is relatively lower as compared to Small Magellanic Cloud (SMC). Understanding the evolution of star formation and past histories of LMC (Antoniou & Zeza 2016), & SMC (Antoniou 2010) can account for the large number of HMXBs that is known today. On the basis of mass of X-ray binaries, they are classified into two categories viz. High Mass X-ray Binaries (HXMBs) and Low Mass X-ray Binaries (LMXBs). HMXBs with neutron star (NS) are further categorized into Be/X-ray binaries (BeXRBs) & Super Giant X-ray Binaries (Reig et al. 2011). The optical companion of a BeXRB is a Be star which is a non-supergiant fast-rotating B-type belonging to luminosity class III-V stars. Be stars are associated with spectral line emission (primarily the Balmer series) and hence the letter "e" in their spectral Type (Porter & Revinius 2003). In addition to their defining hydrogen lines, Be stars can also show He & Fe lines (see e.g Hanuschik (1996)). Be stars are also known to exhibit extra long-wavelength emission, relative to normal B type stars, this emission is termed as infrared excess. The companion Be star in a BeXRB system rotates rapidly which results in an expulsion of photospheric matter along its equatorial plane thereby resulting in the formation of circumstellar disk around it. The circumstellar disk which is also referred as decretion disc (Carciofi 2011) evolves continuously (Okazaki and Negueruela 2001) allowing the neutron star to capture matter at certain times. The accretion phenomenon is enhanced significantly at periastron passage (when the NS makes its closest approach to the Be star) resulting in enhanced X-ray emission by several orders of magnitude for several days. However, when a NS moves away from periastron, accretion from the circumstellar disk ceases which implies that the source returns to the quiescent state. These type of compact objects show transient character and are studied during bright outbursts by various observatories as the count rate is significantly enhanced. However, Type-II (giant) outburst activity are associated with a higher luminosity (1-2 orders of magnitude more luminous than type I outbursts). Such outbursts are uncorrelated with the orbital phase and can last longer than one orbital period whereas type I outbursts are connected to the binary orbital phase. Type-II outbursts are less frequent and hence rarely detected. LXP 38.55 (Vasilopoulos et al. 2016a), GX 304-1 (Jaisawal et al. 2016) are examples of sources which were reported to undergo type-I outburst while EXO 2030+375 (Wilson, Finger & Camero-Arranz 2008), GRO J2058+42 (Molkov et al. 2019) are examples of sources associated with type-II outbursts.

BeXRBs encompass the majority of accreting HMXB pulsars (Reig et al. 2011). The typical magnetic fields of HMXB pulsars are of the order of $10^{12}$ G or more (Ikhsanov & Mereghetti 2015).

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The correlation between the orbital period and the spin period stands out to be one of the significant features of BeXRB systems (Corbet 1984). Furthermore, the spin period distribution of these class of binary system follows a bimodal distribution. Such distribution has been proposed as a result of two different types of supernovae viz. iron-core-collapse and electron-capture which produces majority of NS (Kniige, Coe & Podsiaiowski 2011). Other possible linkage between bimodal distribution & different accretion schemes have been proposed in previous studies (Cheng, Shao & Li 2014). The later proposed schemes have been supported by different long-term X-ray variability of compact objects having both short & long periods (Haberl & Sturm 2016). BeXRBs may undergo type-I & type-II outbursts.

The X-ray source eRASSU J050810.4-660653 was discovered in the LMC (Haberl et al. 2020) during the first all-sky survey monitoring by the instrument eROSITA on board Russian/German Spectrum-Roentgen-Gamma (SRG) mission. eROSITA accumulated a total exposure of 1.6 ks. The spectrum provided by eROSITA in the (0.2-8) keV range can be well described by an absorbed powerlaw with a photon index of ~1.2 & hydrogen column density of $2.1 \times 10^{21}$ cm$^{-2}$. The source flux and its corresponding luminosity in the energy range (0.2-10) keV were $3.4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ & $1.2 \times 10^{36}$ erg s$^{-1}$, assuming a distance of 50 kpc (Haberl et al. 2020).

Over the seven days of scan of the sky, the background subtracted light curve shows an increasing trend from 0.24 to 1.14 ct sec$^{-1}$ in the energy range (0.2-10) keV. Under the SALT transient followup program, the optical spectroscopy using the Robert Stobie Spectrograph on the Southern African Large Telescope (SALT) further confirmed the source as BeXRB (Maitra C. et al. 2020).

The motivation of this paper is to probe detailed coverage of spectral & timing analysis using data from NuSTAR and XMM-Newton observations. The observation IDs of the source under consideration are 90701342002 (NuSTAR) and 0860800301 (XMM-Newton).

2 OBSERVATION AND DATA REDUCTION

The BeXRB eRASSU J050810.4-660653 was observed by Nuclear Spectroscopic Telescope Array (NuSTAR) mission on Dec. 20, 2021. The mission consists of two co-aligned telescopes each having its own focal plane module (FPMA & FPMB) consisting of a pixellated solid-state CdZnTe detector (Harrison et al. 2013). Both telescopes FPMA & FPMB operate in the energy range (3-79) keV. However, due to background contamination above 50 keV, spectral analysis has been carried out in the energy range (3-50) keV. The data reduction was carried out using latest HEASOFT v6.29². Using the mission specific NUPIPELINE, we created clean event files for analysis. The obtained clean event files are then studied for timing and spectral analysis. The XSELECT tool was used for reading clean event files and hence we extracted counts/sec for FITS light curve, spectra and image. The image was observed using astronomical imaging and data visualization application DS9. We considered 70 arcsec region around the source for creating source region file. The background region file was also created of the same size by selecting a region far away from the source. Using the above two files, we run the command line NUPRODUCTS for getting necessary light curve FITS file and the spectral PHA file. The background correction for light curve was carried out using FTOOL LCMATH. Barycentric correction was then applied for orbit correction using FTOOL BARYCORR. The spectra obtained were fitted in XSPEC version 12.12.0. We have also analysed the XMM-Newton archival data observed on Dec.17, 2020. The data processing and extraction were done in XMM-SAS (v20.0.0). Circular source and background regions of 20 arcsec radius respectively were considered for extraction. The events collected by XMM-NEWTON (EPIC-pn detector) provide enough number of counts for period search. The EPIC data were reprocessed using the SAS task EPCHAIN. Event times have been converted to the barycentre of the solar system using the SAS task BARYCEN. We have created a light curve for EPIC-pn with a binning of 0.08 s to estimate the pulse period.

2.1 Light curves, pulse profiles and pulse fraction

We consider NuSTAR light curves with binning 0.01 s for analysis of pulse period and pulse profile. Light curves were plotted using FTOOL LCURVE. Using Fast Fourier Transform (FFT) of the light curve as shown in Figure 1, the approximate estimation of the pulse period was made. Next, we performed the epoch-folding technique (Davies 1990); (Larsson 1996). This method is based on $\chi^2$ maximization technique and hence we estimated the best period at 40.578 s as shown in Figure 2. In order to estimate the uncertainty in the measurement of pulsations we employed the method described in Boldin et al. (2013). For this purpose, we generated 500 simulated light curves in which the count rate for each time bin is computed using the expression $r_n = r_0 + \gamma \tau r_n$, where $r_n$ is the count rate of the new light curve at the $n^{th}$ point, $r_0$ is the count rate corresponding to the original light curve, $\gamma$ represents the quantity uniformly distributed in the interval (-1: 1) & $\tau r_n$ represents the measurement error of flux for the $n^{th}$ point. We obtained corresponding best period for the derived light curves using the epoch folding technique.

We found the best period for each of the 500 samples, then took the mean and standard deviation of these results to arrive at $P_{\text{spin}} = 40.5786 \pm 0.0011$ s. The FFT of the NuSTAR data revealed a significant harmonic peak at half the fundamental pulse period $i.e.$ 20.366 s (see Fig. 1). The XMM-Newton light curve was analyzed in the same way (refer to Fig. 2 which is the periodogram of the XMM data) giving a pulse period $P_{\text{spin}} = 40.5997 \pm 0.0014$ s. The FFT and periodogram corresponding to the XMM-Newton observation has been presented in Figure 1 (right) and Figure 2 (blue) respectively. Since these observations as shown in Table 1 were carried out almost exactly one year apart, it appears the pulsar has spun up by $-0.021 \pm 0.002$ s yr$^{-1}$.

Pulse profiles of the source were then obtained by resolving light curve in the energy range (3-50) keV into several energy bands of (3-7) keV, (7-12) keV, (12-18) keV, (18-24) keV, (24-30) keV, (30-35) keV, & (35-50) keV. Pulse profiles for NuSTAR and XMM-Newton shown in Figure 3 & 4 have been folded with a chosen time zero-point $T_0$ (or folding epoch) such that the minimum flux bin lies at phase = 0.0. The NuSTAR pulse profile does not show much variation with energy. In general, the NuSTAR pulse profile is single peaked and it is asymmetric. It has a sawtooth shape at all energies, with the peak emission lying close to phase 0.75. The lowest NuSTan energy band (3-7 keV) is different though, it has an additional emission component beginning at phase 0.1. It is difficult to compare the strength of the modulation seen in different energy bands because of the change in count rate. In order to understand the evolution of pulse profile, we have obtained the pulse profile using XMM-Newton observation as well, the two observations being one year apart. The energy resolved profile were generated in the energy bands (0.5-3) keV, (3-7) keV & (0.5-10) keV. The XMM pulse contains a single broad pulse,

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¹ https://www.salt.ac.za/
² https://heasarc.gsfc.nasa.gov/docs/software/heasoft/download.html
³ https://sites.google.com/cfa.harvard.edu/sacimaged9

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Table 1. NuSTAR & XMM-Newton observations indicated by their observation IDs along with the date of observation and exposure.

| Observatory | Observation ID | Date of Observation (DD-MM-YEE Y) | Exposure (ks) |
|-------------|----------------|------------------------------------|---------------|
| NuSTAR      | 90701342002    | 20-12-2021                         | 55.8          |
| XMM-Newton  | 860800301      | 17-12-2020                         | 34.2          |

Figure 1. FFT of the NuSTAR (left) & XMM-Newton (right) light curve of the source revealing the presence of harmonic along with the fundamental signal. The x-axis has been plotted in log scale.

Figure 2. Periodogram of the source, for both NuSTAR (black) and XMM-Newton (blue) observation. A coherent signal is clearly detected at ~ 40.578 s for NuSTAR and ~40.599 s for XMM-Newton.

However, the sawtooth shape is reversed compared to the NuSTAR profile. XMM sees the peak emission occurring before phase 0.5, in contrast to the NuSTAR profile which peaked after phase 0.5. Perhaps the component seen (only) in the lowest energy NuSTAR profile has increased in strength. We also note that this component is stronger still at the lowest energies (0.5-3 keV) seen by XMM. The evolution of the pulse profiles observed using NuSTAR and XMM-Newton data depicts a changing activity in the accretion geometry. This is also revealed by comparing the common energy resolved profile (3-7) keV of the system corresponding to NuSTAR & XMM-Newton observations.

The Pulse Fraction (PF) is defined as, $PF = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}$, where $P_{\text{max}}$ & $P_{\text{min}}$ represents maximum and minimum intensities of pulse profile. The variation of PF is found to be linear revealing a very striking correlation with energy which is shown in Figure 5 which is typical for majority of X-ray pulsars (Lutovinov & Tsygankov 2009).

We have also examined the variation of PF with the luminosity as shown in Figure 6. For this purpose, we have considered the PF of the NuSTAR and XMM-Newton observations in the common energy band (3-7) keV which are associated with different luminosities. Interestingly, the PF was found to be anti-correlated with the luminosity of the source.

3 SPECTRAL ANALYSIS

The NuSTAR (FPMA & FPMB) X-ray spectra of the source eRASSU J050810.4-660653 were fitted in the (3-50) keV energy range which is presented in Figure 7. We ignored the fitting of the source in the energy range above 50 keV due to background count domination. For spectral fitting, we grouped the data using GRPPHA tool to achieve a minimum of 20 counts per spectral bin. The spectra were optimally binned based on the study of Kaastra & Bleeker (2016). The relative normalization factors between the two modules were ensured by fixing the constant factor for instrument FPMA as unity without constraining the instrument FPMB to match the average count rate as that in FPMA. This factor corresponding to FPMB was found out to be $1.02 \pm 0.01$ from the relevant statistical data. This represents an uncertainty of ~2% which is in good agreement with Madsen et al. (2015). The spectral fitting posed a challenge in constraining the $n_H$ value. Therefore, we fixed the absorption column ($n_H$) at a value of $1.18 \times 10^{22}$ cm$^{-2}$ which has been obtained using the HEASARC estimator tool$^4$ for the source location in the sky. The spectra was then fitted by using a single continuum model CONSTANT*PHABS*CUTOFFPL. The spectral fitting with the given model estimates the cutoff energy at 20.10 keV & photon index at 0.84. The applied model reduces the fit statistics i.e $\chi^2$ per degrees of freedom to about ~ 1.04. Though weak residuals are seen in the fitted spectra, however, these residuals are insignificant.

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$^4$ https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
Figure 3. Energy-resolved Pulse profile for NuSTAR observation of BeXRB eRASSU J050810.4-660653

Figure 4. Pulse profiles for XMM-Newton observation of BeXRB eRASSU J050810.4-660653 in the low energy band.
and do not contribute to emission or absorption components. The average flux was then calculated in the energy range (3-50) keV. The estimated value of the flux turns out to be $\sim 5.56 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$, and hence the luminosity being $\sim 1.66 \times 10^{37} \text{erg s}^{-1}$ assuming the source to be at a distance of 50 kpc (Haberl et al. 2020).

In the low energy range, the spectra was suitably fitted by considering the XMM-Newton observation using the absorbed power-law model. The single continuum model CONSTANT*PHABS*POWERLAW generated the best fit results in the soft energy band (0.5-10) keV. The fitted spectra has been presented in Figure 8 and the corresponding statistical data has been presented in Table 2. The absorbed flux of the system in the said energy range was found to be $\sim 5.62 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$ which is equivalent to a luminosity of $\sim 1.7 \times 10^{36} \text{erg s}^{-1}$.

3.1 Phase Resolved Spectral Analysis

Phase resolved analysis was carried out for understanding the variation of spectral parameters with pulse phase. For this purpose, we have divided the pulse period into 10 segments. For each segment, we created good time interval (GTI) files using tool XSELECT and then merged them with tool MGTIME. After successfully creating merged GTI files, the required spectra files were generated using the NUPRODUCTS package.

The spectra corresponding to all the phase bins have been fitted using the continuum model CONSTANT*PHABS*POWERLAW. The hydrogen column density in phase resolved spectral study has been fixed at $1.18 \times 10^{22} \text{cm}^{-2}$. For each phase bin, flux has been estimated in the (3-50) keV energy range. The nature of flux variation is analogous to the pulse profile. The flux varied between the peak value of $7.95 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$ in the phase interval (0.6-0.7) & (0.7-0.8) and minimum value of $2.68 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$ in the phase interval between (0.9-1). The variation of photon index with phase also varies between maximum value of 1.16 in the phase interval (0.1-0.2) and minimum value of 0.67 in the phase interval (0.6-0.7) & (0.7-0.8). The minimum value of $E_C$ with phase lies in the phase interval (0-0.1) at 10.92 keV while the maximum value corresponds to phase interval (0.3-0.4) at 31.02 keV. The flux is anticorrelated with the power-law photon index which is evident from phase-resolved spectral study represented in Figure 9.
Table 2. The above table lists the fit parameters of eRASSU J050810.4-660653 using model combination CONSTANT*PHABS*CUTOFFPL for NuSTAR observation and CONSTANT*PHABS*POWERLAW for XMM-Newton observation. Photon Index ($\alpha$) & CUTOFF energy ($E_C$) are the spectral parameters of the CUTOFFPL model. Flux was calculated within energy range (3-50) keV for NuSTAR and within energy range (0.5-10) keV for XMM-Newton. $\chi^2$ represents reduced $\chi^2$. Errors quoted for each parameters are within 90% confidence interval.

![Figure 9](image)

4 DISCUSSION & CONCLUSION

The available NuSTAR and XMM-Newton data for the source have been used to analyze timing and spectral properties of this BeXRB system. Timing analysis of NuSTAR data detected the coherent pulsations at 40.5786 ± 0.0011 s. The same analysis of XMM-Newton data detected the pulsation to be 40.5997 ± 0.0014 s. Since, these observations have been made at different spans of time, it appears that the pulsar has spun-up by -0.021 s yr$^{-1}$. However, we are unaware of the effects of orbital Doppler shift on spin period as the source was discovered recently. Such effects may be explored in the long run with the availability of more observational data.

Transformation of pulse profiles from multi-peaks to single peak from lower energies to higher energies are commonly observed in many pulsars (Shaw et al. 2009). Such features have been observed in Her X-1 (Klochkov et al. 2008b), 4U 0115+63 and V 0332+63. This type of variations are typically observed in various X-ray pulsars especially bright ones (Lutovinov & Tsygankov (2009)). A qualitative interpretation of pulse-profile dependency has been proposed based on the results of (Mowlavi et al. 2006). The variation of pulse profile of X-ray pulsar V 0332+63 was interpreted in a purely geometric fashion. Among accretion-powered pulsars, pulse profile of BeXRBs are found to be complex during outbursts. The pulse profile in our timing analysis is characterised by single peaked feature throughout the observations. The observed pulse profiles corresponding to the source are asymmetric in nature which are typically observed in X-ray pulsars. Various theoretical models have been formulated to explain the asymmetric nature of the pulse profiles. The distorted magnetic dipole field, where the magnetic poles are not exactly opposite to one another, may be a probable reason for the asymmetric nature of the pulse profiles. The distorted accretion geometry can simply be visualised from the variations in the pulse profile observed in the two sets of data observed at different spans of time. The single peaked feature reflects a pencil beam pattern in the NS radiation. A pencil-beam pattern is also characterized by luminosities lower than the critical luminosity ($L_C$) of the source. $L_C$ marks the transition in the accretion regime of the source. If the luminosity of the source is lower than $L_C$, the accretion phenomena is known to occur in the sub-critical regime while for luminosities greater than $L_C$, the accretion phenomena occurs in the super-critical regime of the pulsar. Hence, the pencil-beamed pattern reveals the fact that the source may be accreting in the subcritical regime. In the case of a ‘pencil beam’ pattern, the accreted material reaches the surface of the NS through nuclear collisions with astrophysical protons or through coulomb collisions with thermal electrons (Harding et al. 1994). The emission phenomena take place from the top of the column (Burnard, Arons, & Klein 1991). Therefore, it is appropriate to express that the X-ray luminosity of the source is lower
than the critical luminosity. The luminosity dependence of the pulse profiles reflects an alteration in the physical state of the accretion column. In case of accretion in the sub-critical regime, the height of the accretion column is known to be anti-correlated with the accretion rate which may be a probable reason for the luminosity dependence of the pulse profiles (Becker et al. 2012).

The smoothness of the PF plot gives another interesting characteristic of the source. This is consistent with the absence of strong features such as CSRF in the energy spectrum of the source. The non-monotonic dependence of the PF on energy around the cyclotron feature has been reported for various X-ray pulsars (Tsygankov et al. (2006); Lutovinov & Tsygankov (2009); Ferrigno et al. (2009)). On examining the variation of PF with luminosity, it was observed that the PF follows an anti-correlated pattern with luminosity. This may have arisen due to an increment in the unpulsed component of the total emission or a net decrement of the pulsed component (Yang et al. 2018).

The NuSTAR spectrum was best-fitted by an absorbed CUT-OFFPL model revealing a photon index of 0.84 & cutoff energy of ~20 keV. The average flux of the source in (3-50) keV energy range was found to be ~ 5.56 × 10^{-11} erg cm^{-2} s^{-1} which corresponds to a luminosity of ~ 1.66 × 10^{37} erg s^{-1} assuming a distance of 50 kpc. Usually, residuals are seen in the spectral fit of many BeXRB systems when fitted with power-law, therefore an additional component like soft blackbody is generally required to obtain the best fit statistics (e.g. Bartlett, Coe & Ho (2013); La Palombara et al. (2013a,b); Vasilopoulos et al. (2013, 2014, 2016a); Sturm et al. (2014)). However, black body model was not required as the spectra was suitably fitted without its implementation as positive residuals in the soft energy band were not prominent. Various BeXRBs like 1A 0535+26, V 0332+53, Cep X-4, 4U 0115+63 and many more are known to exhibit significant CRSF feature (Staubert et al. (2019)). However, such characteristic features were not observed in the source. We do not find the presence of fluorescent lines of iron in the observed spectra. The absence of additional spectral features were also verified by phase resolved spectroscopy, as various sources are known in which the cyclotron line or its higher harmonics are prominent only at certain phases of rotation (e.g Molkov et al. 2019, 2021). It is evident from Figure 9 that the cut-off energy varies with pulse phases. The cut-off energy has no clear physical meaning although it may be related to the strength of the magnetic field (Makishima et al. 1990). An empirical relation between exponential cut-off energy and cyclotron line energy has been established by Makishima et al. (1990) which is beyond the scope of our study for this source. However, it has been observed that for cut-off energies in the range (8-12) keV, the cyclotron line energies are inferred to lie in the range (12-40) keV (Makishima et al. 1990). In the present study of the source, the cut-off energy is found to be about 20 keV which suggests that the cyclotron energy (if present) must be at higher energies (> 50 keV). Since, we have ignored the energy spectrum above 50 keV due to background domination, the absorption feature (if present) may be detected with the availability of more observational data. Interestingly, the power-law photon index was found to vary with the pulse phase of the system. It is evident from Figure 9 that when the source flux is high, the system becomes harder and when the source flux is low, the system becomes softer. The increase in luminosity is associated with an increase in optical depth. This in turn leads to an increase in the hardness of photons which is in agreement with hardening (decrease in photon index) of the spectrum with increase in flux of the system (Reig & Nespoli 2013).

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DATA AVAILABILITY

The observational data used in this study can be accessed from the HEASARC data archive and is publicly available for carrying out research work.

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