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Long-term X-ray/UV observations of the ultraluminous X-ray source Holmberg II X-1

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Ultraluminous X-ray sources (ULXs) are point-like extra-galactic sources with luminosities exceeding the Eddington limit for stellar-mass black holes. The results of our recent observations of one of these sources – Holmberg II X-1 – with the Astrosat observatory prompted us to look at the long-term brightness and spectral variability of this source using the Swift/XRT observations. We found that after being in the state of low variability ($\lesssim 2$ times) and hard spectrum ($\Gamma \sim 1.8$) for about ten years, the source returned to the state with high variability ($\gtrsim 10$ times) and a soft spectrum ($\Gamma \sim 2.5$). Thus, during the time of the Swift monitoring of more than 15 years, the ULX experienced state transitions at least 3 times. Also we found that the period of 27 days observed in the variable state and vanished in the steady state appeared again as the source returned to the variable state. Further analysis and modeling are necessary to shed light on the possible mechanisms of the observed state transitions of Holmberg II X-1.

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1. Introduction

According to modern views, ultraluminous X-ray sources (ULXs) are neutron stars and stellar-mass black holes accreting at super-Eddington rates [1, 2]. Despite significant progress in our understanding of these systems in recent years, many aspects remain unclear, such as details of the geometry and structure of super-critical accretion disks and their winds, reasons for the high variability of ULXs, evolutionary status and binary system-progenitors of ULXs, etc. Answers to these questions are most actively sought in the X-ray and optical ranges.

We have observed the ultraluminous X-ray source Holmberg II X-1 (hereafter, Ho II X-1) with the AstroSat observatory, the first Indian X-ray mission. Besides the X-ray detectors, it is also equipped with two 37.5-cm telescopes capable of obtaining images in the far- and near-UV ranges simultaneously with the X-ray data. Ho II X-1 was chosen as the target for these observations because it is a bona fide ULX with an X-ray luminosity of $\gtrsim 10^{40}$ erg/s, high variability in X-rays and high brightness in the UV/optical bands [3, 4]. The source is located in an irregular gas-rich dwarf galaxy at 3.39 Mpc [5].

The source was observed with AstroSat three times in the autumn of 2016, two times only in X-rays in November 2019 and 5 more times from December 2019 to February 2020. Thus we have obtained 8 simultaneous X-ray (0.7 – 7 keV) and UV (F148W filter with the mean $\lambda = 148.1$ nm) observations covering a time range of 3.5 years. The details of the analysis of the AstroSat data are described in the paper [6].

Unfortunately, all the AstroSat observations fell on the epoch when the source showed extremely low activity in the X-ray range, the full amplitude of its variability was only about a factor of 1.5 (black points in the upper panel of Fig. 1). In the UV range, due to the low accuracy of the measurements, we have obtained only the upper limit on the object's variability which is about 25% of the minimum value measured in those observations [6]. The Hubble Space Telescope (HST) UV data obtained on November 27, 2006 with the ACS/SBC camera in the F165LP filter and on August 24, 2013 with the WFC3/UVIS camera in the F275W filter also did not allow us to reveal significant variability. All the measurements were carried out using the aperture photometry method, the results are shown in Table 3 of paper [6]. The obtained flux densities were then converted from the HST filters to the AstroSat F148W one using a model of the object's spectral energy distribution (a black body with the effective temperature 35.5 ± 2.9 kK). The resulting light curve is shown in the bottom panel of Fig. 1.

Besides the very low variability, Ho II X-1 has also displayed relatively hard spectra with $\Gamma \simeq 1.8$ in our AstroSat observations [6] despite the fact that this source was thought to be a typical soft ULX ($\Gamma \approx 2.4$, [7]) based on a series of early observations carried out with XMM-Newton in 2002–2010. State transitions of Ho II X-1 consisting of both spectral and variability pattern changes are reported by Gúrpide et al. [8] who analysed the Swift observations of 2006–2019. Since about 60 new Swift observations have appeared so far, we decided to carry out similar analysis involving these new data.

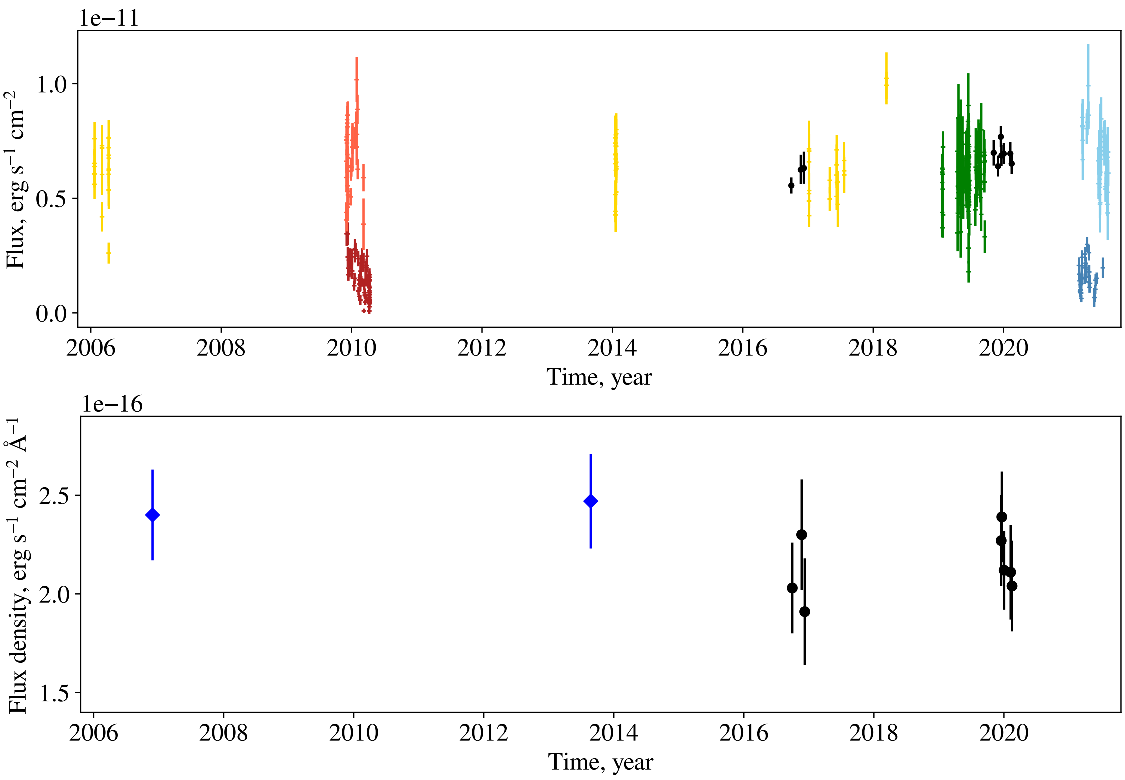

Figure 1: Light curves of Ho II X-1 in the X-ray (0.3–10.0 keV, *top panel*) and UV (flux density at 148.1 nm, *bottom panel*) ranges. The black circles in both panels mark the AstroSat data. The crosses of different colors denote the Swift/XRT observations split into four groups: G1, G2, G3 and G4 are shown in red, green, blue and yellow, respectively. For the groups G1 and G3, when the ULX was in the variable state, we analyzed separately the observations of the low and high source luminosity; these subgroups are marked by shades of the corresponding color. The HST observations are marked by diamonds.

2. Observations and results

Ongoing Swift/XRT monitoring of Ho II X-1 has been carried out since 2006. The data points fill this time interval unevenly, most of them are concentrated near 2010, 2019 and 2021. To construct a light curve we used preprocessed event files provided by the UK Swift data center[1]. The source aperture was 30″, the background counts were extracted from an annular aperture around the object free of other sources.

Inspection of the Swift light curve in count rates has shown that the ULX behavior is of two distinct types. The source can be caught either in the state of high variability (as in 2010, hereafter, *variable state*) with the X-ray luminosity rapidly changing from its upper values to 10–20 times lower or in the *steady state* with the luminosity just below the maximum (as in 2019). This behavior was studied by Gúrpide et al. [8], they also revealed that the source became much harder when it went into the steady state. However, that analysis did not cover the latest 2021 data, which show that the source returned to the variable state (Fig. 1).

We carried out a spectral analysis of the Swift data to convert count rates to physical fluxes.

[1] `https://www.swift.ac.uk/`

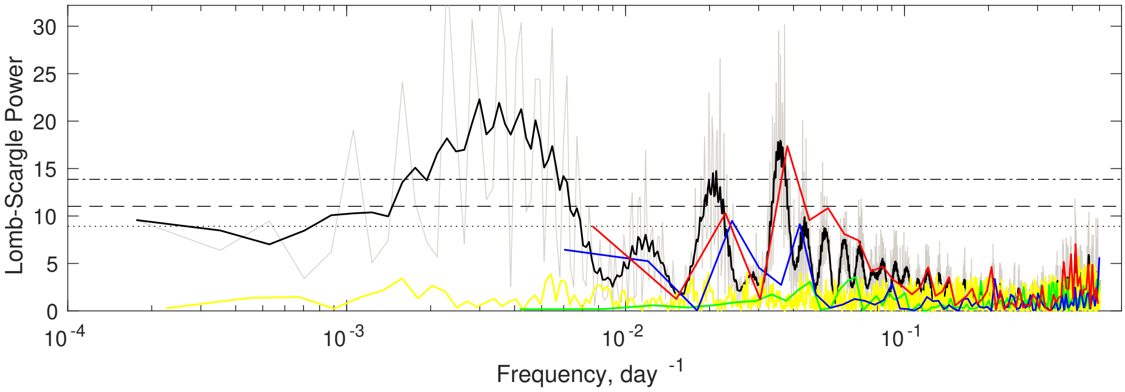

Figure 2: Lomb-Scargle spectra for the entire Swift/XRT light curve (grey) and for the light curves of individual groups (the group definition and colors are the same as in Fig. 1). The black curve is the grey spectrum smoothed with a moving average filter. Dotted, dashed and dash-dotted lines represent the 1σ, 2σ and 3σ significance levels for the grey spectrum computed according to [9]. The 3σ level for the LS-spectra of the groups G1, G2 and G3 is about 10.

Since the spectral shape depends on the object state, we split the data into four groups (see the caption of Fig. 1). The spectra were fitted with the model `tbabs*(diskbb+powerlaw)`. For the groups G1 and G3 corresponding to the variable state, we fitted independently the observations with low and high source brightness. Thus we have obtained an approximately the same index $\Gamma \approx 2.5$ for the G1-low and G1-high spectra; they differ only in the normalization of the power law, as was reported by Grisé et al. [3]. In the case of G3, the spectral index is found to depend on the ULX brightness: we obtained $\Gamma \approx 2.6$ and 2.3 for G3-low and G3-high, respectively. The G2 and G4 have very similar spectra, both with $\Gamma \approx 1.85$, close to what we see in the AstroSat data. The parameters of the `diskbb` model component (the disk inner temperature and normalization) turned out to be about the same in all the groups, $T_{\rm in} \sim 0.15$ keV. The light curves in flux units obtained with the corresponding models are shown in Fig. 1.

Additionally, we have constructed Lomb-Scargle spectra for each data group and for the entire light curve. The result is shown in Fig. 2. Excluding the rise of the power below 0.01 day^{-1} which is likely caused by gaps in the data, the strongest peak in the LS-spectrum of the entire light curve is located at 0.036 ± 0.005 day^{-1}. This frequency corresponds to the period $\simeq 28$ days found by Gúrpide et al. [8]. The same peak is also seen in the LS-spectra of G1 and G3 (the variable state) but not seen in G2 and G4 (the steady state). Also, one can suspect from the figure that the peak frequency slightly increases with time (the period becomes shorter), but more careful analysis is needed to confirm this.

The reasons that cause the object to change its variability pattern and spectral shape are not clear. They can be related to some physical processes, for example, instabilities in the accretion disk or changes in the incoming matter flow, or to purely geometric factors such as partial eclipses of the X-ray source by the donor stars (or by other gas structures) or precession of the disk. Further observations and analysis are necessary to reveal the nature of this behavior.

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