Super-Eddington accretion disks in Ultraluminous X-ray sources

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Abstract The origin of Ultraluminous X-ray sources (ULXs) in external galaxies whose X-ray luminosities exceed those of the brightest black holes in our Galaxy hundreds and thousands times is mysterious. The most popular models for the ULXs involve either intermediate mass black holes (IMBHs) or stellar-mass black holes accreting at super-Eddington rates. Here we review the ULX properties, their X-ray spectra indicate the presence of hot winds in their accretion disks supposing the supercritical accretion. However, the strongest evidences come from optical spectroscopy. The spectra of the ULX counterparts are very similar to that of SS433, the only known supercritical accretor in our Galaxy. The spectra are apparently of WNL type (late nitrogen Wolf-Rayet stars) or LBV (luminous blue variables) in their hot state, which are very scarce stellar objects. We find that the spectra do not originate from WNL/LBV type donors but from very hot winds from the accretion disks, whose physical conditions are similar to those in stellar winds from these stars. The results suggest that bona-fide ULXs must constitute a homogeneous class of objects, which most likely have supercritical accretion disks.

Keywords: Ultraluminous X-Ray Sources, Super-Eddington Accretion Disks

1. Introduction

Ultraluminous X-ray sources (ULXs) are X-ray sources with luminosities exceeding the Eddington limit for a typical stellar-mass black hole $\sim 2 \cdot 10^{39}$ erg s^{-1}. Despite their importance in understanding the origin of supermassive black holes that reside in most of present galaxies, the basic nature of ULXs remains unsolved [1]. The most popular models for the ULXs involve either intermediate mass black holes (IMBH, 10^3–$10^4 M_\odot$) [2] with standard accretion disks or stellar-mass black holes ($\sim 10 M_\odot$) accreting at super-Eddington rates. The last idea has been suggested [3] by analogy with SS433, the only known super-accretor in the Galaxy [4], and developed in [5], [6]. It was proposed that SS433 supercritical disk's funnel being observed nearly face-on will appear as an extremely bright X-ray source. Both scenarios, however, require a massive donor in a close binary.

Most of ULXs are associated with the star-forming regions and surrounded by nebulae of a complex shape, indicating a dynamical influence of the black hole [7]. They are not distributed throughout galaxies as it would be expected for IMBHs originating from low-metallicity Population III stars. The IMBHs may be produced in a runaway merging in a core of young clusters. In this case, they should stay within the clusters. It has been found [8] that all brightest X-ray sources in Antennae galaxies are located near very young stellar clusters. It was concluded that the sources were ejected in the process of formation of stellar clusters in the dynamical few-body encounters and that the majority of ULXs are massive X-ray binaries with the progenitor masses larger than $50 M_\odot$.

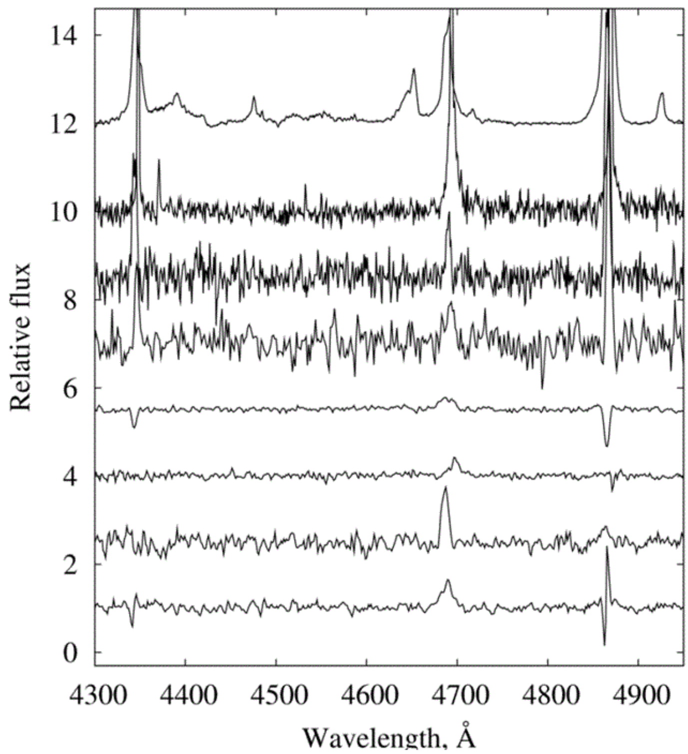

Fig1. *Normalized optical spectra of ULX counterparts. From top to bottom: SS 433 (1), NGC 5408 X-1 (2), NGC 4395 X-1 (3), NGC 1313 X-2 (2), NGC 5204 X-1, NGC 4559 X-7, Holmberg IX X-1 and Holmberg II X-1 (1). The numbers in brackets mean optical telescopes: 1 – the Subaru telescope, 2 – VLT (ESO), 3 – the Russian BTA telescope. The spectra are very similar in appearance, they may represent a rare type of massive stars WNL [10] or LBV stars in their hot states [11], [12]. All spectra are also similar to SS 433 [13]. This means that the spectra of the ULX counterparts are formed in hot winds.*

X-ray spectra of ULXs often show a high-energy curvature with a downturn between ∼4 and ∼7keV. It was called “an ultraluminous state” [9]. The curvature hints that the ULX accretion disks are not standard. Inner parts of the disks may be covered with a hot outflow or optically thick corona, which Comptonizes the inner disk photons.

2. Results

Spectra of almost all optical counterparts of studied ULXs (with SS433 included) are shown in Fig.1. All spectra were reduced by us. The main features in all spectra are the bright HeIIλ4686, hydrogen Hα and Hβ emission lines. The lines are obviously broad; the widths range from 500 to 1500km s^{-1}.

Calibrated spectra of the ULX optical counterparts taken with the Subaru telescope [14] are given in Fig.2. We conclude that all ULX counterparts ever spectrally observed have the same feature in their spectra, namely, the broad HeII emission line. We also clearly detect the broad Hα, Hβ lines and HeIλ6678, 5876 lines (Fig.2). There are also some hints on the Bowen CIII/NIII blend (4640 - 4650 Å). Although the Hβ line (Figs.1, 2) is affected by nebular emission in spite of our careful extraction, its broad wings are clearly detected. It is obvious that the emission lines are formed in stellar winds or disk winds.

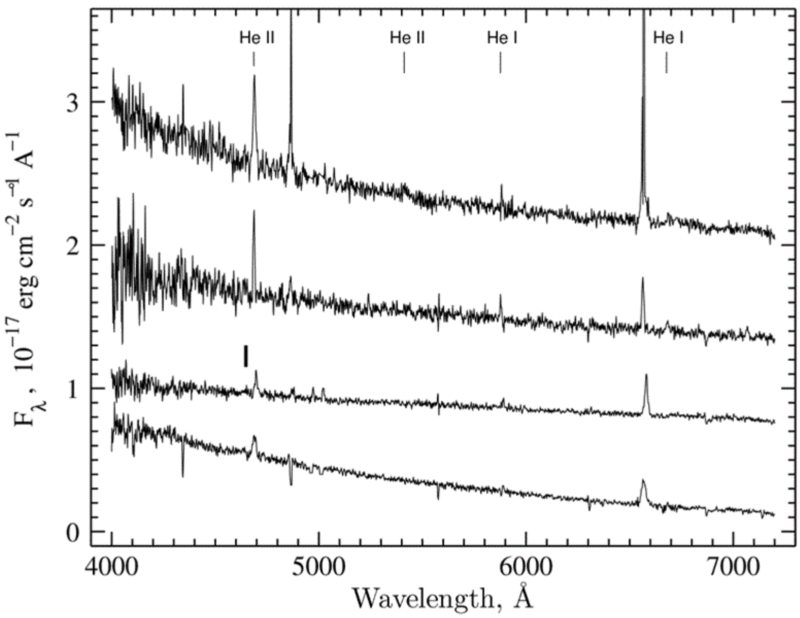

Fig2. *Calibrated spectra of the ULX optical counterparts taken with the Subaru telescope [14]. From top to bottom: the ULX in Holmberg II, Holmberg IX, NGC4559, and NGC5204. The two upper spectra were obtained on February 28, while the rest are the summed spectra from three nights. For better visualization we add the flux offsets of 1.8, 1.2 and 0.6 (10^{-17}erg/cm^{2}sÅ) for the Holmberg II, Holmberg IX, and NGC4559 ULXs, respectively. Besides the obvious hydrogen lines we mark HeII lines (λ4686 and λ5412) and HeI lines (λ5876 and λ6678). The thick bar indicates the position of the Bowen blend CIII/NIII λλ4640 − 4650.*

All spectra of the ULXs are surprisingly similar to each other. The optical spectra are also similar to that of SS 433, although the ULX spectra indicate a higher wind temperature. It was suggested in [14] that the ULXs must constitute a homogeneous class of objects, which most likely have supercritical accretion disks.

Among stellar spectra, such a strong HeII line with a nearly normal hydrogen abundance can be found only in stars recently classified as O2–3.5If*/WN5–7 [10]. Hereafter we omit index * which means a stronger ionization as indicated by NIV/NV lines. They are the hottest transition stars, whose classification is based on the Hβ profile, tracing the increasing wind density (i.e., the mass loss rate) from O2–3.5If, O2–3.5If/WN5–7, and to WN5–7.

We study the spectra of ULX counterparts in the HeII diagram ([15], [14]), where the relation between the line width and equivalent width of the HeIIλ4686 line is plotted (Fig.3). Here the line width represents the terminal velocity of a stellar wind, while the equivalent width reflects its photosphere temperature and mass loss rate.

In Fig.3, we show the classification diagram of WN stars [15] for LMC and Galactic objects. We supplement the diagram with additional stars recently classified [10]. The diagram plots stars in accordance with their wind velocity (FWHM) and photosphere temperature plus mass loss rate (EW). Three known LBV transitions (LBV–WNL) between their hot and cool states in AGCar, V532 in M33, and HD5980 in SMC are also shown in the figure. Consequent states in each LBV transition are connected by the lines. In their hotter state where the HeII line becomes stronger, the LBVs fit well the classical WNL stars [11].

In the figure, we also present two recently discovered extragalactic black holes NGC300X-1 and IC10X-1 together with the soft ULX transient M101ULX-1. The black holes in NGC300X-1 and IC10 have luminosities $L_X \sim 3 \times 10^{38}$erg s^{-1}, almost identical to that of CygX-3, which certainly contains a

WN-type donor star [22]. The comparable luminosities with that of CygX-3, short orbital periods, and the location in the diagram around the WN6–7 region confirm that their optical spectra come from WN donors. The same may be supposed for M101ULX-1 on the basis of its location in the diagram. It has been recently found that this source indeed contains a WN8 type donor [23], although its orbital period is ~40 times longer than in CygX-3 and ~6 times longer than in two other WR X-ray binaries.

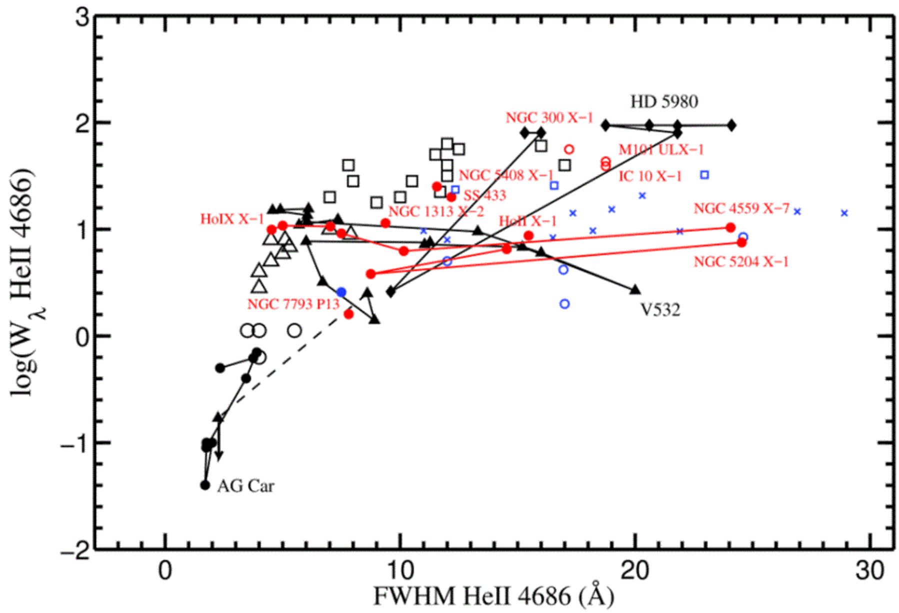

Fig3. *Classification diagram of WNL stars in the LMC and our Galaxy [15]. The black open squares, triangles, and circles mark WN8, WN9–10m, and WN11 stars, respectively. The blue filled circle denotes ζPup. Other Galactic and LMC stars [10] are O2If and O3If (open blue circles), O2If/WN5, O2.5If/WN6, O3If/WN6, and O3.5If/WN7 (blue crosses), and WN6ha and WN7ha stars (open blue squares). There are three known LBV–WNL transitions (AGCar, V532, and HD5980) in this diagram [11]. Consequent states of each LBV star are connected by the lines. Positions of our four ULX counterparts are also shown (connected by lines to show variability from night to night), together with those of NGC1313X-2, NGC5408X-1, NGC7793P13, SS433, NGC300X-1, M101ULX-1, and IC10X-1([13], [16]-[21]).*

Thus, the ULX counterparts and SS433 occupy a region at this diagram between O2–3.5If and WN5–7. This is also a region of the "intermediate temperature LBV" V532 and the "LBV excursion" of HD5980. Variability of the HeII lines of our counterparts in three consequent nights is shown by the points connected by the lines. However, their behavior in the HeII diagram is not similar to stars. They exhibit night-to-night variability both in the line width and equivalent width by a factor of 2–3. Variability in the radial velocity of the line is also detected with amplitudes ranging from 100 km s^{-1} in Holmberg IX to 350 km s^{-1} in NGC5204.

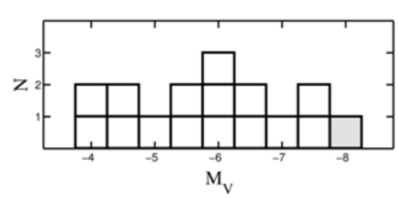

Fig4. *Absolute magnitudes of all well-studied ULXs and SS433 (shadowed). The data are from [16] with some updates from [25] and [6].*

If the ULX counterpart spectra were produced from donor stars, the variable surface gravity at about the same photospheric temperature would be required. Instead, the spectra may be formed in unstable and variable winds formed in accretion disks. This idea agrees with the fact that we do not find any regularities between the EW, FWHM, and radial velocity of the HeII line.

We can exclude the case where these ULXs actually have WNL donors and their stellar winds produce the observed optical spectra. It is difficult to explain the rapid variability of the HeII line-width, because the wind terminal velocity in stars is determined by the surface gravity.

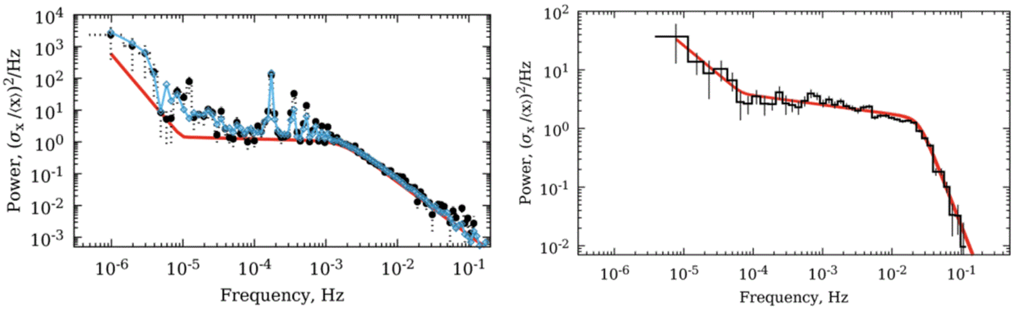

Fig5. *Power density spectra of SS433 (left) and the ULX NGC5548 X-1 (right). In SS433 we observe a flat portion [26] which may be considered as alpha-viscosity fluctuations appearing at the spherization radius as was originally proposed [27] for standard disks [24]. The power spectrum of SS433 has been obtained from a single ten-days ASCA observation. The circles and dotted line are the observed power spectra, the red (dark grey) solid line is the initial model of the accretion disk intrinsic variability. The blue (light grey) line and diamonds are the Monte Carlo model, which takes into account the gaps in observations and extra variability added by eclipse occurred during these observations. The power spectrum of SS433 has a flat part stretching from* $\sim 10^{-5}$ *to* $\sim 10^{-3}$ *Hz. The power spectrum of NGC5408 X-1 has been obtained by averaging six most long observations from XMM-Newton. A model with two breaks fitting the spectrum is shown by the solid line. This object also has a flat part in the power spectrum.*

The total luminosity of a supercritical disk is proportional to the Eddington luminosity with an additional logarithmical factor depending on the original mass accretion rate ([24], [5]), because the excess gas is expelled as a disk wind and the accreted gas is advected with the photon trapping, contributing little to the photon luminosity. However, the UV and optical luminosity in such disks may strongly depend on the original mass accretion rate, because these budgets are mainly produced by the reprocess of the strong irradiation from the wind (the excess gas). Optical spectra of SS433 and the ULX counterpart are nearly the same, but in X-rays they are drastically different because we cannot observe the funnel in SS433 directly. It was found [14] that the mass accretion rates in the ULXs may be by a factor of 1.5–6 smaller and their wind temperatures are by 1.4–4 times higher than those in SS433. In Fig.4 we show the absolute magnitude of all well-studied ULXs together with SS433. Thus, one may interpret that SS433 is intrinsically the same as ULXs but this is an extreme case with a particularly high mass accretion rate, which could explain the presence of its persistent jets [4].

In Fig.5 we present another evidence of the super–Eddington accretion in ULXs. The power density spectrum of SS433 exhibits a flat part in the $10^{-5} - 2 \cdot 10^{-3}$ Hz frequency range [26]. The presence of such a part is related to the abrupt change in the disk structure and the viscous time at the spherization radius. In this place the accretion disk becomes thick, which reduces drastically the time of passage of matter through the disk ([24], [27]). The same picture is observed in the well-studied ULX NGC5408 X-1. We need longer observations of the ULXs to study their power density spectra in more detail.

Acknowledgements

The research was supported by Russian Science Foundation grant N14-50-00043 (observations and analysis of variability) and Leading Scientific Schools of Russia. SF acknowledges support of the Russian Government Program of Competitive Growth of Kazan Federal University.

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