The study of ultraluminous X-ray source UGC 6456 ULX

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Abstract We present preliminary results of a study of the ultraluminous X-ray source UGC 6456 ULX. The object is highly variable in both the X-ray (more 100 times, 0.3-10 keV) and optical (more 2 times, V band) ranges. The peak X-ray luminosity of UGC 6456 ULX exceeds $10^{40}$ erg s$^{-1}$, the absolute magnitude in the bright state exceeds $M_V = -7.6$, which makes it one of the brightest ULXs in the optical range. We found a correlation between the optical and X-ray fluxes, which may indicate that the optical emission is produced by re-processing of the X-rays in outer parts of the optically-thick wind coming from the supercritical accretion disk. Optical spectra of UGC6456 ULX show broad and variable hydrogen and helium emission lines, which also confirms the presence of the strong wind.

Key words: accretion, accretion disks — X-rays: binaries — X-rays: individual: UGC 6456 ULX

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are variable objects whose luminosity exceeds the Eddington limit for stellar mass black holes ($\gtrsim 10^{39}$ erg s$^{-1}$), assuming isotropic emission. These objects are located outside the centers of galaxies, that is, they are not super-massive black holes. Early papers on ULXs suggested intermediate mass black holes (IMBHs; $10^2 - 10^4 M_\odot$) as accretors in these systems (e.g., Colbert & Mushotzky 1999). However, studies of the last decade (Gladstone et al. 2009; Sutton et al. 2013; Fabrika et al. 2015; Pinto et al. 2016; Walton et al. 2018) have shown that observational properties of most ULXs can be explained by supercritical gas accretion onto black holes of stellar masses (from a few to several tens masses of the Sun), or even onto neutron stars. The last possibility has been convincingly confirmed by detection of coherent X-ray pulsations in six ULXs (Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2016; Carpano et al. 2018; Sathyaprakash et al. 2019; Rodríguez Castillo et al. 2019).

In contrast to the X-ray range, in the optical one ULXs are studied much more poorly. Only $\gtrsim 20$ ULXs have been unequivocally identified using Hubble Space Telescope (HST) data. All of them are faint sources with the visual magnitudes of $m_V = 21 - 26$ (Tao et al. 2011; Gladstone et al. 2013). Moreover, most ULXs are associated with star-forming regions (e.g., Poutanen et al. 2013) and located in crowded regions, which makes it difficult to study them with ground-based telescopes.

Here we present an identification of the optical counterpart of the ULX in the galaxy UGC 6456 (VII Zw 403), which is one of the closest blue compact dwarf galaxies ($D = 4.54$ Mpc, Tully et al. 2013). UGC 6456 ULX is a transient source: its luminosity changes by more than two orders of magnitude with a peak value of $1.7 \times 10^{40}$ erg s$^{-1}$ in the 0.3–8 keV energy range (Brorby et al. 2015). In the bright state,
the sources have a very hard power-law spectrum with a photon index of $\Gamma \sim 1$. We report the presence of a correlation between the long-term X-ray and optical variability of UGC 6456 ULX and present preliminary results of its optical spectroscopy.

2 ASTROMETRY

To identify an optical counterpart of UGC 6456 ULX, we used archival images from *Chandra X-Ray Observatory* and *HST*. *Chandra* observed the source only once, on 2000 January 7 (ObsID 871). The source was located on the S3 chip of the Advanced CCD Imaging Spectrometer (ACIS) with a very small offset from the optical axis ($< 0'.1$). The ULX position derived from the ACIS image using the Wavdetect task of CIAO 4.11 is R.A.(J2000) = 11$^h$28$^m$03$^s$.000, Decl.(J2000) = +78$^\circ$59$'$53$''$.41 with a statistic error of $\sim 0'.1$ and an absolute astrometric uncertainty of 0'8 at 90% confidence level

In the optical range, we have chosen the HST observation taken on 1994 February 16 with the Wide Field and Planetary Camera 2 (WFPC2) in the F555W filter. To apply astrometric corrections to the HST image, we used four reference stars from the Gaia Data Release 2 (Gaia Collaboration 2018). After accounting for the shifts, derived standard deviation of the difference between Gaia and corrected HST positions of the reference stars became less than 0'.03, and the resultant absolute astrometric uncertainty about 0'.02 at the 90% confidence level.

There is only one relatively bright object in the WFPC2/F555W image within the *Chandra* 0'8 error circle of UGC 6456 ULX (left panel of Figure 1). It is a point-like source with a visual magnitude of $m_{F555W} = 21.59 \pm 0.06 \ (m_V = 21.58)$ in the Vegamag system. At the galaxy distance this corresponds to an absolute magnitude of $M_V = -6.9$ after correction for reddening of $A_V = 0.2 \ \text{mag}$ (see Section 4).

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1 http://cxc.harvard.edu/cal/ASPECT/celmon/
2 Photometry was performed on c0f image in HSTPHOT 1.1 (Dolphin 2000)
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3 X-RAY AND OPTICAL VARIABILITY

The ULX was observed 17 times with the Swift X-ray telescope (XRT) since January 2011. From 2014 March 16 through 2014 April 6 the observations were made every few days. To extract a light curve we utilized preprocessed event files provided by the UK Swift data centre\(^3\). The source events were extracted from a circular region of 30 arcsec radius using task XSELECT of HEASOFT 6.26.1. The background was taken from an annulus with inner and outer radii of 80 and 130 arcsec respectively centered on the source. The resulting light curve is shown in Fig. 2.

Starting from May 2017, we obtained several (five in the V band) quasi-simultaneous observations with Swift and optical telescopes of SAO RAS (the CCD photometer of Zeiss-1000 or multi-mode focal reducer SCORPIO (Afanasiev & Moiseev 2005) of the 6-m telescope BTA were used). The time intervals between the X-ray and optical observations were inside 1 day in the bright state of the ULX and in the range from 1.6 to \(\simeq 6\) days in the faint state. However, it should be noted that the ULX variability in the faint state is lower and slower than in the bright state (Vinokurov et al. 2020, in preparation), therefore the time delays of a few days are unlikely to introduce significant distortions into the observed pattern. On the contrary, in the bright state the object is highly variable on a timescale of 1 day, at least in X-rays (see the Swift light curve in Fig. 2 and Brorby et al. 2015).

An aperture photometry of the UGC 6456 ULX counterpart was done with the APPHOT package in IRAF. To check the object for variability we used four stars with colors similar to that of the object as reference sources. The seeing was from \(1''.0\) to \(2''.1\) in all the observations, that allowed us to avoid possible contamination from the neighboring stars and obtain reliable measurements. The obtained magnitudes were converted to the Vegamag system using three relatively bright isolated stars whose magnitudes were measured from the HST WFPC2/F555W data.

Variations of the object brightness in our observations reach \(\Delta m_V \approx 0.8\) mag (from \(M_V \approx -6.8\) to \(M_V \approx -7.6\)), whereas the Swift count rate changes by at least 6 times. A correlation between the X-ray flux and the V band magnitude is clearly seen in Fig. 2 (right panel).

4 OPTICAL SPECTROSCOPY

The optical spectra were obtained with the BTA/SCORPIO in 2015–2019; the 1'' slit and four grisms were used. One observation was conducted with the VPHG1200B grism (spectral range is 3600-5400 Å, resolution \(\approx 5.5\) Å), eight observations with VPHG1200G (4000-5700 Å, \(\approx 5.3\) Å), four with...
Fig. 3: Left panel: variations of the equivalent width (EW) of the He II λ4686 emission line. The arrows indicate an upper limit to the line EW. Right panel: radial velocity curve measured from the He II λ4686 emission line.

VPHG1200R (5700-7500 Å, ≈ 5.3 Å) and the remaining four observations with VPHG550G (3500-7200 Å, ≈ 12 Å). The seeing varied from 1″ to 2″. Data reduction was carried out with the LONG context in MIDAS using standard algorithm. An extraction of the spectra was done with the SPEXTRA package (Sarkisyan et al. 2017).

Two spectra with the best signal-to-noise ratio are shown in the right panel of Fig. 1. The spectra are not simultaneous. The first one taken with the VPHG1200R grism was obtained on 2015 February 23, whereas the second with VPHG1200G on 2015 September 7. A broad He II λ4686 line is clearly seen. Its width after correction for the spectral resolution is ≈ 900 km s⁻¹. The blue spectrum contains also a weak broad component of the Hβ emission line with the width comparable with the He II line and also possible contains Hγ emission and Hδ absorption lines. In the red spectrum, there are He I λλ5876, 6678, 7065 broad emission lines (with widths in the range of 200 – 300 km s⁻¹) and a very strong and asymmetric Hα line. Wings of this line extend over 90 Å. The narrow emission lines (narrow components of Hβ and Hα, [O III] λλ4959, 5007 and [S II] λλ6716, 6731) are formed in the nebula near the source.

All the wide lines are highly variable. In this work we have investigated a behavior of the He II λ4686 line, because it is not contaminated by the nebula emission. Its equivalent width (EW) vary from ≈ −7 to ≥ −1 Å (when the line is nearly undetectable, the left panel of Fig. 3) and the width from ≈ 500 to ≈ 900 km s⁻¹. We also found changes in the radial velocity up to 400 km s⁻¹ (the right panel of Fig. 3) but additional observations are required to distinguish whether the nature of these changes is periodic or stochastic. We note that for the VPHG1200B and G observations the accuracy of the radial velocity measurements is better than 15 km s⁻¹ and better than 30 km s⁻¹ for the VPHG550G ones.

Using observed ratios of the hydrogen lines in the nebula (Hγ/Hβ and Hα/Hβ), we determined the reddening value of $A_V = 0.2 \pm 0.1$ mag. In our calculation we assumed Case B of photoionization (Osterbrock & Ferland 2006).

5 CONCLUSIONS

In this work we have presented the preliminary results of the study of the UGC 6456 ULX. Discovered optical counterpart is one of the brightest among all identified ULXs. The object demonstrates high optical and X-ray variability, which has an amplitude similar to that observed in the well studied ULX with a neutron star NGC 7793 P13 (Fürt et al. 2018). The nature of the variability requires further research. The correlation between changes in optical and X-ray fluxes may indicate re-processing of the X-ray radiation in the outer parts of the strong wind of the supercritical disk. The existence of such a
wind is confirmed by the presence of the wide hydrogen and helium emission lines in the optical spectra, that are typical for the all spectroscopically studied ULXs (Fabrika et al. 2015).

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