Multiwavelength analysis of nearby ultraluminous x-ray sources (ULXs) and their environment

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Abstract. Ultraluminous X-ray sources (ULXs) are known as extragalactic point-like X-ray sources with luminosities considerably in excess of the maximum luminosity of a 10 solar mass accreting black hole. X-ray spectra of ULXs have been investigated in many previous studies. However, sparse observations render it more difficult to convincingly distinguish between two competing scenarios, i.e. sub-critical accreting intermediate-mass black hole and super-critical accreting stellar remnant black hole. Here, we report our investigation of a sample of nearby ULXs, as well as their host galaxies, in order to get a more complete understanding of their nature. Multiwavelength analysis was applied to study these ULXs. From X-ray study, we found that most ULXs in our sample do exhibit spectral variability in which higher energy X-ray predominates the spectra as the source becomes brighter. We also compiled some properties of the host galaxies, as a proxy of ULX environment. We found that ULXs in our sample can neither be exclusively associated with a certain type of morphology, nor with high nuclear activity. We also found that 12 out of 19 ULXs reside in host galaxies with star formation rate of less than 1 solar mass per year.

1. Introduction

Ultraluminous X-ray Sources (ULXs) were discovered from X-ray observations of nearby galaxies in the late 1970s by using Einstein satellite [1]. They share some general X-ray properties, despite possessing some individual characteristics, one of which is their being bright point-like sources which are not located in the nuclear region of a galaxy. It means that their high luminosity, which is considerably in excess of the maximum luminosity of 10$M_\odot$ black hole, cannot be associated with supermassive black hole (SMBH) activities. Currently, there is no clear evidence of the presence of any ULX in our Galaxy. Some X-ray studies have shown that general X-ray properties of ULXs resemble those of Galactic black hole binaries (GBHBs) so that we may in general assume the same energy generation mechanism as that of GBHBs for ULXs, namely accretion flows onto a black hole (see [2] for a review). Mass accretion rate is a key information since it determines the physical processes that happened in the accretion disk which in turns govern the produced radiation, in terms of both the spectral shape and the luminosity. However, it cannot be easily derived from observation. Fortunately, both luminosity and black hole mass can be derived from observation which in turns can be used to constrain mass accretion rate. For a fixed luminosity, higher black hole mass implies lower mass accretion rate, and vice versa. Therefore, ULXs can either be explained with higher black hole mass or higher mass accretion rate.
The well-known standard model of accretion disk [3] has been widely used to model soft X-ray thermal spectra of GBHBs in which the disk is assumed to be geometrically thin and optically thick so that the produced radiation in each radius can be approximated with blackbody radiation. The total spectrum can be obtained from the integration of blackbody spectra from all radii of the disk. The standard model has a number of drawbacks when applied to ULXs. Observationally, many ULX spectra deviate from that of the standard model. Those that can be fitted with the standard spectra usually require very high (> 2 keV) or very low (< 0.5 keV) inner disk temperature. Theoretically, the assumptions made for the standard model will eventually break down as one extends the value of mass accretion rate into a higher or lower regime. Different spectral features are expected to emerge due to different radiation processes in the disk as the assumptions of the standard model broke down. Therefore, X-ray spectral study is very important to understand the nature of ULXs. Many previous X-ray spectral studies focused on individual ULXs (e.g. [4],[5],[6]). Several attempts have also been made to study multiple ULXs using high quality, but sparse, XMM-Newton data to get insight into the spectral variability of ULXs (e.g. [7],[8]). However, sparse observations render it more difficult to convincingly distinguish between two competing scenarios, i.e. sub-critical accreting intermediate-mass black hole (IMBH) and super-critical accreting stellar remnant black hole. Here, we report our investigation of a sample of nearby ULXs, using long term monitoring data of Swift XRT, in order to investigate the general X-ray spectral variability of ULXs in our sample. Previous studies on X-ray spectral variability using Swift XRT data have been successful despite focusing on individual ULXs (e.g. [9],[10]). To get a more complete understanding of their nature, multiwavelength study was also conducted to these ULXs. We briefly describe our data and method in section 2 and we present our results and discussion in section 3. We finally conclude our work in section 4.

2. Data and Method
A sample of nearby (< 10 Mpc) ULXs was constructed from a catalog of ULXs [11] which utilized Chandra ACIS Survey. This catalog was chosen due to high spatial resolution of Chandra X-ray mission. There are 56 ULXs in 36 host galaxies within a distance of 10 Mpc.

Swift XRT data were used to investigate X-ray spectral variability in our sample. We collected all available Swift XRT data in the archive since 2006 until July 2016. From the X-ray image, we found that about half of ULXs in our sample require special treatments in data reduction and analysis, which were finally excluded in our current study. These are ULXs which are located very close to the central region of the host galaxy, coincide with any diffuse sources, and/or located very close to other point sources. It reduces the number of ULXs in our sample to 19 ULXs in 17 host galaxies. For each ULX, light curves and spectra were extracted from a circular region with a radius of 47 arcseconds centered at the source position reported in [11]. Another nearby circular region three times a radius of the source region was chosen as the background.

We define hardness ratio as the count rate in 1.5 – 10 keV divided by that of 0.3 – 1.5 keV of background subtracted source with a signal-to-noise ratio > 5. Hardness intensity diagram (HID) was then made by plotting the hardness ratio versus the intensity in count/s. Due to short exposure time of Swift XRT observation of each ObsID, we did not analyse detail spectrum of each ObsID due to poor statistics. However, there are five ULXs with more frequent observations, compared to the rest, from which we can co-add the spectra and fit them with simple phenomenological models. Before we co-added the spectra, we first grouped observations with the same epoch of redistribution matrix file (RMF). For each RMF group, we further grouped the data based on their count rate to see how the spectra change with intensity. We also checked the hardness ratio of each count rate group to make sure that the co-added spectra have similar hardness ratio.

For the study of host galaxies of ULXs, in our current work we only consider three properties,
i.e. morphological classification, stellar mass, and star formation rate (SFR) of the host galaxies. Morphological classification was obtained from various databases (SIMBAD, HyperLEDA, NED and Subarcsecond mid-infrared atlas of local AGN). Stellar mass of a host galaxy was derived from the mass-to-luminosity ratio [12] which requires information of magnitude in B filter and (B-V) color which were collected from the Third Reference Catalogue of Bright Galaxies (RC3). As for the SFR, hydrogen recombination line (H$_\alpha$) was utilized except for PGC50779 and NGC5128 in which we used total infrared (TIR). Required information to calculate SFR was obtained from Catalog & Atlas of the LV galaxies [13] and IRAS archive for H$_\alpha$ and TIR, respectively. The SFR was calculated by following the method described in [14]. We also checked the radial distribution of each ULX within the host galaxy by utilizing information of inclination as well as position angle of the host galaxy to obtain deprojected radial distance of each ULX from the center of each host galaxy.

3. Results and Discussion

ULXs in our sample show variability in intensity with a factor of up to 5 with one exception, PGC23324 X-1, which shows flux variability with a factor of up to 15. For most ULXs we found that the fraction of higher energy photons increases with intensity as can be seen from figure 1 and 2 for more sparse and frequent observations, respectively. Note that we do not plot all ULXs in our sample for the clarity of those figures. PGC23324 X-1 is an example of ULXs in our sample in which soft photons predominate in all available observations. Based on this finding, the spectral energy distribution is expected to vary as a function of intensity. Therefore, we need to analyzed co-added spectra of ULXs in our sample to see how the spectra change with intensity.

![Figure 1. HID for ULXs with sparse observations.](image1)

![Figure 2. HID for ULXs with frequent observations.](image2)

We managed to obtain co-added spectra of five ULXs (NGC7793 X-1, NGC1313 X-2, NGC3031 X-3, IC342 X-1, and PGC23324 X-1). We fitted those spectra with single power law model $P_0$ and single disk blackbody model $DISKBB$ by using $XSPEC$. We used $TBABS$ to model Galactic and extragalactic absorption. The Galactic HI column density for each ULX was adopted from [15] while the extragalactic absorption was treated as free parameter. Both single power law and disk blackbody models can in general fit the spectra of these five ULXs. Due to low statistics, especially at higher energy (> 5 keV), we did not attempt to add more sophisticated model, such as thermal comptonization, which are widely suggested to model curvature at higher energy in ULX spectra.

Figure 3 shows the spectra of IC342 X-1 fitted with single power law model. Black and
red colors represent spectra of similar count rates but different RMFs. These two spectra are very similar which implies that spectra of similar count rates do not change with time. Red, green, and blue colors represent spectra of the same RMF but of different count rate ranges, which increase from red to blue. The variability of the spectra is minimum at lower energy. The obtained values of photon index ($\Gamma$) are rather steep. The evolution of the photon index as a function of unabsorbed luminosity in $0.3 - 10$ keV range can be seen in figure 4 (upper panel). The photon index does not vary much with luminosity despite the apparent change in the spectral shape. The fitting result with single disk blackbody model is shown in figure 4 (lower panel). We can see that the obtained innermost disk temperature ($kT_{in}$) is rather high ($>1$ keV). The change in the spectral shape, together with the obtained values of the inner disk temperature and unabsorbed luminosity, can be interpreted as the evolution from the broadened disk spectra to those of the ultraluminous spectra with curvature at high energy, as the source becomes brighter (see [2] and references there in). The pattern of spectral variability found in this study is consistent with some earlier studies (e.g. [9],[16]). Similar to the evolution of the photon index, the innermost disk temperature does not vary much with luminosity. Similar results were obtained for the other ULXs except NGC7793 X-1, which shows rather flat power law spectra and extremely high innermost disk temperature ($>2$ keV).

In a small number of ULXs (not shown in figure 1 and 2), we see an opposite trend in their hardness intensity diagrams, in which the fraction of soft photons increases as the source becomes brighter. Unfortunately, these ULXs were not frequently observed that we could not get decent spectral information.

![X-ray spectra of IC342 X-1 fitted with single power law model](image1)

**Figure 3.** X-ray spectra of IC342 X-1 fitted with single power law model (see text for details).

![Photon index ($\Gamma$) and innermost disk temperature ($kT_{in}$) of IC342 X-1](image2)

**Figure 4.** Photon index ($\Gamma$) and innermost disk temperature ($kT_{in}$) of IC342 X-1.

From our study of the three properties of the host galaxies, we found that 37% of the host galaxies in our sample are having peculiar morphology, 26% are categorized as interacting, 37% are found to have starburst activity, and 47% are known as AGNs. ULXs in our sample are located in galaxies with stellar mass in the range of $10^8 - 10^{11} M_\odot$. In terms of SFR, we found that the SFR value of the host galaxies in our sample is rather low, with a range of $0.05 - 2 M_\odot$/yr. In fact, 12 out of 19 ULXs are located in host galaxies with SFR less than $< 1 M_\odot$/yr. We also confirmed that the deprojected position of all ULXs in our sample are located within two $R_{25}$ radii and most of them are located within one $R_{25}$ radii.

Based on the result of morphological classification, abnormal activities in the host galaxies are not a requirement for the existence of a ULX in a galaxy. The fact that we have not found any ULX in our own Galaxy remains puzzling. However, some ULXs are reported to be transient.
4. Conclusion
Based on our multiwavelength study, it appears that inhomogeneity exist even in a small sample of nearby ULXs, both in X-ray and host galaxy properties. However, majority of ULXs in the sample exhibit similar trend in X-ray spectral variability, in which the fraction of high energy photons increases with intensity. Based on the available spectra, we either obtained rather hot thermal spectra or rather steep non-thermal spectra, both of which are difficult to explain by using low mass accretion rate model.

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