Understanding the Nature of Ultra-Luminous X-ray Sources

Jifeng Liu

The ultra-luminous X-ray sources (ULXs) were observed as early as 1980s in a few nearby galaxies with the Einstein X-ray satellite, and later on studied with ROSAT and ASCA (for reviews, cf. Colbert & Mushotzky 1999; Miller & Colbert 2004). More and more ULXs are being observed with the advent of the Chandra and XMM-Newton X-ray observatories owing to their superior sensitivity, spatial resolution and positional accuracy as compared to previous X-ray missions. Now ULXs are firmly established as a new class of extragalactic nonnuclear X-ray point sources that shine with luminosities of 10^{39}–10^{41} erg/sec, about 10 - 1000 times the Eddington luminosity for a canonical neutron star. The nature of these sources is still a matter of debate, and current models center around two alternatives. First, they are the long-sought intermediate mass black holes (IMBHs) of 10^2–$10^5 M_\odot$ emitting at sub-Eddington levels as Galactic X-ray binaries, with timing and spectral properties scaled up by mass. The IMBHs may be formed through the merging of stellar mass black holes (e.g., Miller & Hamilton 2002), or stellar interaction in dense stellar fields (e.g., Portegies Zwart & McMillan 2002). Second, they are the ordinary stellar mass black holes whose apparent super-Eddington luminosities are due to various beaming effects, such as the geometric beaming in presence of slim disks (e.g., King et al. 2001), or the relativistic beaming as in microquasars (e.g., Kording et al. 2002).

Evidence has accumulated in the last few years that supports the IMBH interpretation and/or argues against beaming. **(1)** X-ray spectroscopy with high quality data obtained with XMM and Chandra has revealed very cool accretion disks ($\sim$0.1 keV) suggestive of IMBHs in some ULXs, e.g., NGC1313 X-1 and X-2 (Miller et al. 2003), NGC5408 X-1 (Kaaret et al. 2003), Holmberg IX X-1 (Miller et al. 2004), NGC4559 X-7 (Cropper et al. 2004), and M101 ULX-1 (Kong et al. 2004). **(2)** Quasi-periodic oscillations (QPO) with long quasi periods have been observed in a few ULXs (M74-ULX, Liu2005a; NGC5408-ULX, Soria et al. 2004), suggestive of IMBHs based on the $M_\bullet - f_b$ scaling relation that has been verified in Galactic X-ray binaries and active galactic nuclei (Belloni & Hasinger 1990). **(3)** For the ULX in M82, a narrow QPO and a broad Fe K_α emission line argue against beaming, which in turn reinforces the IMBH interpretation (Strohmayor & Mushotzky 2003). **(4)** Periodic modulations of the ULX fluxes have been found in the ULXs in IC342 (Sugiho et al. 2000), Circinus (Bauer et al. 2002), and M51 (Liu2002b). If the high amplitude modulations are attributable to orbital motions, an almost edge-on viewing geometry is suggested, which argues against beaming along the polar direction. **(5)** Another evidence against beaming is the general lack of radio counterparts for most ULXs (Mushotzky 2004), although radio counterparts exist for a few ULXs (e.g., NGC5408 X-1, Kaaret et al. 2003). **(6)** A beautiful case against beaming comes from the optical survey of 16 nearby ULXs with ground-based telescopes by Pakull & Mirioni (2002), which revealed an X-ray ionized nebula (XIN) surrounding the ULX in Holmberg II. The He II λ4686 emission line from the nebula, as confirmed by a follow-up HST study (Kaaret et al. 2004), has a high luminosity that requires an isotropic X-ray luminosity above 6×10^{39} erg/sec and rules out the beaming model for this source.

However, the above evidence, while encouraging, is not conclusive; there is still evidence that does not support, or require the IMBH interpretation. **(1)** The cool accretion disk components may not be the unique spectral fit in all ULXs (e.g., in NGC55-ULX, Stabbort et al. 2004). Also, the accretion disk components are not always cool, and are sometimes as hot ($\sim$1 keV) as in Galactic black hole X-ray binaries (e.g., Foschini et al. 2002). **(2)** Due to the low fluxes of ULXs, QPOs in ULXs are usually detected as tentative breaks or broad bumps in the low quality power density spectra, unlike QPOs in Galactic X-ray binaries where narrow QPO peaks and well defined breaks are present simultaneously. It is thus unclear to which break frequency in the scaling relation we should (or whether we should at all) link the detected QPO to estimate the black hole mass. **(3)** Swartz et al. (2004) studied the luminosity function of ULXs with a Chandra survey, and found that ULXs are a smooth extension of the lower luminosity X-ray binaries, suggesting ULXs are stellar mass black holes with special emission mechanisms. We (Liu2005c) find similar conclusions from a ROSAT HRI survey, except that the extreme ULXs above 10^{40} erg/sec may be a different class from the ULX between 10^{39} and 10^{40} erg/sec, which make up the majority of the ULX sample in Swartz et al. (2004).

At current stage, the understanding of ULXs will be greatly furthered with the available instruments if we combine the capacities of the Chandra and XMM-Newton X-ray observatories, the Hubble Space Telescope, and the ground based telescopes. Here I propose a series of projects utilizing both archival and new observations to promote the understanding of ULXs.

(1) The luminosity function of ULXs is informative on the underlying distributions of black hole masses, binary properties and accretion rates, although the quantities may be entangled and we must practice caution in interpreting the luminosity function features. Not without problems, luminosity functions from early Chandra surveys (Swartz et al. 2004) and our ROSAT HRI survey (Liu2005b,Liu2005c) have led to preliminary results on ULXs in comparison to low luminosity X-ray binaries. Here I propose to construct improved luminosity functions using the growing wealth of Chandra and XMM archival data, with particular attention to the contamination from background/foreground objects as I did in the HRI survey (Liu2005c). I have already processed the Chandra archival data with my analysis pipeline, which led to 359 ULX candidates within the D25 isophotes of 147 nearby galaxies, including 28 extreme ULXs above 10^{40} erg/s (cf. Chapter 4 of my dissertation). The number of ULXs is more than 3 times that in the HRI survey, which will enable the construction and comparison of luminosity functions of ULXs in different types of galaxies, with much better statistics expected.

(2) The ensemble X-ray timing and spectral properties of ULXs as a class derived from a large uniform sample of ULXs will shed light on the nature of ULXs when compared to well studied Galactic X-ray binaries. This sample will be constructed from the archival Chandra and XMM data. Knowledge from individual ULXs will be checked among all ULXs to answer (1) *what fraction of ULXs show cool accretion disk components?* and (2) *are they correlated with the luminosities?* Since many galaxies have been observed in multiple (monitoring) observations, this project will study the long term variability of flux, spectral and timing properties for ULXs to answer (3) *how do the spectral states change with time/flux?* (4)

how does the disk temperature change with time/flux? and (5) *how do the timing features (such as QPOs) change with spectral states?*

(3) Follow-up long XMM and Chandra observations for ULXs with QPOs will improve the power density spectrum, in the hope of detecting clear breaks and QPO peaks simultaneously in order to remove the above mentioned ambiguity in applying the $M_\bullet - f_b$ scaling relation to estimate the black hole mass. We have proposed a long look (130 ksec) at the ULX with QPOs in M74 (Liu2005a) in the coming XMM cycle for this purpose; we will propose more follow-up observations when further ULXs with tentative QPOs are detected. Such a long observation will have the sensitivity to bring up the Fe K_α emission line as evidence for a standard accretion disk and against relativistic beaming as in M82-ULX (Strohmayer & Mushotzky 2003), and detect soft X-ray emission lines as indicators of the diffuse optically thin plasma around the accretion disk.

(4) Optical studies of a large sample of nearby ULXs may provide information on the intermediate vicinity of ULXs and lead to identifications of the ULX secondaries. There have been optical studies with HST and ground-based telescopes, such as the optical study of 16 nearby ULXs by Pakull & Mirioni (2002), which revealed some ULXs surrounded by XINs, and an extremely bright He II λ4868 emission line as evidence for isotropic super-Eddington luminosity in the Holmberg II ULX. Here I propose to study a much larger sample of 81 ULXs within 10 Mpc from my Chandra survey (Chapter 4 of my dissertation), using our privileged access to the Magellan 6.5m telescopes and the MDM 2.4m telescope, complemented by HST archival data. Surrounding XINs and optical counterpart candidates are expected for some of the ULXs, which we will follow up with optical spectroscopy to search for He emission lines, and with HST narrow/broad-band imaging to study the high resolution ULX environments.

(5) A series of optical spectroscopic observations for bright ULX secondaries will give the radial velocity curves and lead to the ultimate determination of the mass (function) of ULXs. Optical studies have so far led to six ULXs with bright secondaries, i.e., NGC5204-ULX (B=21.9; Liu2004), Holmberg II-ULX (V=22; Kaaret et al. 2004), NGC3031-ULX (B=23.5; Liu2002a), NGC4559-ULX (B=22.8; Liu2005d, Cropper et al. 2004), NGC1313-ULX (R=22; Liu2005d, Zampieri et al. 2004), and M101-ULX (B=23.5; Kuntz et al. 2005). The spectroscopic observations for these secondaries are feasible with HST or ground-based telescopes such as Magellan, Gemini, and Keck. Kuntz et al. (2005) have observed M101-ULX with Gemini/GMOS and detected clear He emission lines. I and my collaborators have observed NGC1313-ULX with HST ACS/prism and are currently analyzing the data; we are also observing NGC1313-ULX with the Magellan 6.5m telescopes. We will propose to observe all these secondaries and monitor those under favorable viewing geometry in hope to obtain the radial velocity curves.

The above projects are extensions of my current efforts to understand the nature of ULXs, which, given funding for my research, are expected to complete in the coming two or three years with my expertises developed in the past few years.

REFERENCES

Bauer, F.E., Brandt, W.N., Sambruna, R.M., et al. 2001, AJ, 122, 182

Belloni, T., and Hasinger, G, 1990, A&A, 227, L33

Colbert, E. and Mushotzky, R. 1999, ApJ, 519, 89 (CM1999)

Cropper, M., Soria, R., Mushotzky, R., et al. 2004, MNRAS, 349, 39

Foschini, L., Di Cocco, G., Ho, L. C., et al. 2002, A&A, 392, 817

Kaaret, P., Ward, M., and Zezas, A., MNRAS, 2004, 351, 83

Kaaret, P., Corbel, S., Prestwich, A., and Zezas, A., 2003, Science, 299, 365

King, A.R., Davies, M.B., Ward, M.J., et al. 2001, ApJ, 552, L109

Kong, A.K.H., Di Stefano, R., and Yuan, F, 2004, ApJL, 617, L49

Koerding, E., Falcke, H., Markoff, S., 2002, A&A, 382, L13

Kuntz, K. et al. 2005, ApJ, 620, L31

Liu, J., dissertation, August 2005, http://www.cfa.harvard.edu/∼jfliu/dissertation.ps

Liu, J., Bregman, J., Seitzer, P., and Irwin, J., 2005, astro-ph/0501310 (Liu2005d)

Liu, J., Bregman, J., and Irwin, J., astro-ph/0501312, ApJ accepted (Liu2005c)

Liu, J., and Bregman, J., 2005, ApJS, 157, 59 (Liu2005b)

Liu, J., Bregman, J., Lloyd-Davies, E., et al. 2005, ApJL, 621, 17 (Liu2005a)

Liu, J., Bregman, J., and Seitzer, P., 2004, ApJ, 602, 249 (Liu2004)

Liu, J., Bregman, J., Irwin, J., and Seitzer, P., 2002, ApJL, 581, 93 (Liu2002b)

Liu, J., Bregman, J., and Seitzer, P., 2002, ApJL, 580, 31 (Liu2002a)

Miller, C. & Hamilton, D. 2002, MNRAS, 330, 232

Miller, C. and Colbert, E. 2004, Int.J.Mod.Phys. 1-64 (MC2004)

Miller, J., Fabbiano, G., Miller, C., and Fabian, A., 2003, ApJL, 585, 37

Miller, J., Fabian, A., and Miller, M., 2004, ApJ, 607, 931

Mushotzky, R., 2004, astro-ph/0411040

Pakull, M, and Mirioni, L., 2002, astro-ph/0202488 (PM2002)

Portegies Zwart, S. & McMillan, S., 2002, ApJ, 576, 899

Strohmayer, T, and Mushotzky, R., 2003, ApJ, 586, 61

Soria, R, and Motch, C., A&A, 2004, 422, 915

Stobbart, A.-M.; Roberts, T. P.; Warwick, R. S., 2004, MNRAS, 351, 1063

Sugiho, M., Kotoku, J., Makishima, K., et al. 2001, ApJ, 561, L73

Swartz, D., Ghosh, K., Tennant, A., and Wu, K., 2004, ApJS, 154, 519

Zampieri, L., Mucciarelli, P., Falomo, R., et al. 2004, ApJ, 603, 523

This preprint was prepared with the AAS LaTeX macros v5.2.