Ultraluminous Supersoft X-ray sources

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ULXs and their environments – Strasbourg, France – 06/14/2016
Motivation for ULSs

- Do ULSs bear “clean” evidence for IMBHs?

Two examples

- M101 ULX-1
- M81 ULS-1

summary
Two breeds of black holes

Stellar black holes \( \sim 10 M_\odot \)
From collapse of massive stars
\( \sim 10^7 \) in the Milky Way
\(~ 20 \) detected and confirmed

Super-massive black holes
Of millions of solar masses
in the center of every large galaxy

How to form?

\( \rightarrow \) Stellar BHs merge into intermediate mass black holes (IMBHs)
\( \rightarrow \) IMBHs sink to the center of proto-galaxy and merge into an even larger BH
\( \rightarrow \) This BH accretes gas and grow up, along with the galaxy, into the super-massive BH we see today

Missing link: where are the IMBHs of thousands of solar masses?

Intermediate mass black holes (IMBHs) are expected to exist
- in the center of globular clusters? …No!

Where are IMBHs then?
Ultraluminous X-ray Sources

**UltraLuminous X-ray sources**

$10^{39} - 10^{42}$ erg/s

Large surveys show (Liu+2005, 2011)
- average rate: $0.52 \pm 0.04$ ULX per survey galaxy
- late-type galaxy: $0.70 \pm 0.06$
- early-type galaxy: $0.23 \pm 0.05$

Ground optical

Hubble optical

Chandra X-ray image

14ULXs in the Antennae galaxy pair
Accretion onto black holes

- Galactic black holes are bounded by Eddington limit: \( L_x \) usually less than \( 10^{39} \) erg/s

- The inferred accretion disk temperature of the innermost portion \( (T_{in}) \) is \( kT_{in} \propto M^{-\frac{1}{2}} \)

- Stellar mass black holes usually have \( T_{in} \sim 1 \) keV

- IMBHs should have \( L_x \) above \( 10^{39} \) erg/s, and have disk temperature \( \sim 0.1 \) keV
X-ray spectral signatures for IMBHs

Early efforts decompose ULX spectra into a hard power-law plus a low-T disk component (~0.1 keV): evidence for IMBH?

- However, the dominant power-law component (>70%) implies corona that may reprocess the disk emission, and the low fitted Tin may not be directly related to BH mass

- Are there any ULXs that do not have any hard components? But only soft components as clean evidence for IMBHs?

- Yes! Ultraluminous Supersoft X-ray sources (Kong+2003; Liu+2007,…)

- Independent evidence? two examples
  - M101 ULX-1
  - M81 ULS-1

Miller et al. (2003)
M101 ULX-1: an IMBH?

- Once the brightest source in M101
- Alternates between low-hard states ($2 \times 10^{37}$ erg/s) and high-soft states ($3 \times 10^{39}$ erg/s)
- Super-soft in the high state: 80-150 eV,
  - No hard photons above 1.5 keV, thus no need for the hard power-law component
- Its low temperature corresponds to an IMBH of a few thousand solar masses
M01 ULX-1 is identified with a blue object of $V=23.5\,\text{mag}$

- It was first misclassified as a B supergiant star or a F-star whose light was drowned in the optical light from the disk.
- Kuntz+ (2005) took a Gemini spectrum showing He II 4686Å emission line, but he explained that as emission from the X-ray irradiated wind and the B supergiant.

Liu (2009) analyzed 26 HST and 33 X-ray observations over 16 years, and found that its optical SED is consistent with a Wolf-Rayet star with strong broad helium emission lines, and Kuntz’s Gemini spectrum is consistent with this interpretation.

We carried out a Gemini/GMOS campaign to monitor M101 ULX-1
New Gemini/GMOS spectrum

Strong broad helium lines without similar hydrogen lines

Confirms that the secondary is indeed a Wolf-Rayet star (WN8)
Motion of the secondary

- Ten spectra taken over three months during the expected X-ray low state (to avoid light contamination from X-ray heated disk)

Radial motion from He II 4686A line

Reveals an orbital period of 8.2 days

Leading to a mass function

\[ f(M_s,M_\ast,i) = \frac{PK^3}{2\pi G} = 0.18M_\odot \pm 0.03M_\odot \]
Black hole mass

- But we know the secondary mass from
  - Fitting spectrum to WR model
  - Empirical luminosity-mass relation
  - Secondary is a WN8 star (19M$_\odot$, 11R$_\odot$)

- This means a black hole mass of 5M$_\odot$ even if the binary is edge-on, and a larger mass for smaller inclination
  - $i=19^\circ \leftrightarrow 20M_\odot$
  - $i=5^\circ \leftrightarrow 300M_\odot$
  - $i=3^\circ \leftrightarrow 1000M_\odot$

- It is unlikely to be an IMBH: the probability to detect a binary pole-on ($i<3^\circ$) is only 0.1%.

- An IMBH needs to capture a secondary to light up as a ULX, it is extremely unlikely for it to capture a WR star – there are only 2000 WR stars out of 200 billion stars in a galaxy.

It is a stellar black hole rather than an IMBH!
NGC 7793 P13: a $<15 \, M_\odot$ black hole

Given its high X-ray luminosity ($5 \times 10^{39} \text{erg/s}$) and its black hole mass ($<15 \, M_\odot$), P13 is a genuine super-Eddington source (by a factor of at least 2) that its extremely high luminosity does not reflect the presence of an IMBH.

The best models have a $<15 \, M_\odot$ black hole!!

Fitting $u,v$ light curves and the radial velocity curve to ELC

What causes the supersoft emission?

Its color temperature (~0.1KeV) is 10X lower than the disk temperature for a stellar black hole, suggesting an emission radius 10000X larger than its innermost stable circular orbit.

⇒ The supersoft X-ray emission comes from a hot, optically thick wind from the accretion disk (Shen+2015,2016)
M81 ULS-1: an IMBH or a massive WD?

Another Prototype: M81 ULS-1

Blackbody temperature: $\sim 70$eV
Bolometric luminosity: $2 \times 10^{39}$ erg/s
--may drop by 10X ($nH$, WD Atmospheric Model)

M81 ULS-1 could be an IMBH, or a massive WD close to Chandrasekhar mass limit, hereby a SN Ia progenitor

(Swartz+2002; Liu+2008a; Liu2008b)
Optical spectroscopic observations

- Identified with HST as V=22 mag
  - Blue component: accretion disk?
  - Red component: giant companion?
- Keck/LRIS campaign @ 2010
  - Disk signatures: continuum slope + broad Balmer emission lines
- Unidentified very broad line: 5530Å

(Liu+2008a)

(Bai & Liu 2015)
New GTC and Keck spectra

(Liu+2015)
The shifting unidentified line is the blue-shifted Hα! (Liu+2015)
New GTC and Keck spectra

The shifting unidentified line is the blue-shifted Hα!

(Liu+2015)
Relativistic baryonic jets: another SS 433

- SS 433: a jet source that has educated astronomers for three decades (e.g., Margon 1984; Blundell+2007)
  - Blue-shifted and red-shifted optical emission lines from approaching & receding baryonic jets
  - Precession period: 164 days
  - Intrinsic velocity: 0.26c

- M81 ULS-1: in comparison to SS 433
  - Blueshifted Hα and redshifted Hα+ (?)
  - Precession period: >154 days
  - Intrinsic velocity: >0.17c
Implications for M81 ULS-1

- **M81 ULS-1 cannot be a white dwarf anymore!**
  - Studies of jets across all scales suggest that jet velocities are comparable to the surface escape velocities *(Livio 2001)*
  - The surface escape velocity is less than 5,000 km/s for a typical white dwarf with a solar mass and the Earth's size
  - Low velocity bipolar outflows of a few thousand km/s have been observed for two SSSs, but no relativistic jets from SSSs previously
    - RX J0019.8+2156: ~800 km/s *(Becker+1998)*
    - RX J0513-69: ~3800 km/s *(Southwell+1996)*
  - The baryonic jets observed in M81 ULS-1 have intrinsic velocities above 0.17c, or 50,000 km/s!
  - This adds **strong evidence** to the idea that SSSs, especially the ultraluminous ones, do not necessarily contain accreting white dwarfs with quasi-steady shell burning.
    *(Di Stefano+2010)*
Relativistic jets from microquasars

20+ microquasars known so far
Measured or thought to contain BH/NS
Identified thru superluminal motion or just radio emission presumed from jets

(Mirabel & Rodriguez, 1994)

(Paredes + 2003)
M81 ULS-1: not just another microquasar

- M81 ULS-1 is only the 2nd microquasar identified thru blue-shifted Hα−, and the 1st identified outside the Local Group (and the farthest)
- But it is not just another microquasar
  - M81 ULS-1 has exhibited supersoft X-ray spectra during all 19 Chandra observations regardless high or low flux states
  - Microquasars exhibit hard X-ray spectra in distinct contrast

(Liu 2008b; Liu+2015)
It goes beyond the jet paradigm

- Jet paradigm for black hole binaries (e.g., Fender+2004)
  - steady jets during low-hard states
  - Ballistic jets in very high state or during the transitions between hard and soft states

- Disk-jet coupling in neutron star binaries (e.g., Migliari & Fender 2006)

Abundant hard photons above 1keV are expected from microquasars!
It challenges the standard accretion scenarios

- Standard accretion scenarios
  - Quiescent state
  - Low-hard state
  - High-soft state
  - Steep power-law state

- Persistently supersoft spectra from M81 ULS-1 are not expected from any of these spectral states

- The standard accretion scenarios implicitly refer to accretion below the critical (i.e., Eddington) rates...

(Esin+1997; Remillard+2006)
Supercritical Accretion onto a black hole

Standard disks

Thick disks

Very High State

High State

Intermediate State

Low State

Beam

UV

Radiation supported thick disc

Possible corona

X-rays

Black hole

Cusp

(e.g., Paczynski & Wiita 1980; Abramowicz et al. 1988)
Numerical simulations

Global structure of accretion flows and outflows around black holes from 2D radiation MHD simulations

Radiatively inefficient due to photon trapping
But mild beaming may drive up to \(22L_{\text{Edd}}\)

Radiative efficiency \(\sim 4.5\%\), comparable to thin disk!

High luminosities

Figure 3. Snapshot of disk structures for density (left) and radiation energy density (right) at time \(1.13 \times 10^4 t_*\). Units for \(\rho\) and \(E_r\) are \(\rho_0\) and \(a_r T^4_0\) respectively.
Relativistic baryonic jets expected!

Powerful radiative jets in supercritical accretion discs around non-spinning black holes

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ABSTRACT

We describe a set of simulations of supercritical accretion on to a non-rotating supermassive black hole (BH). The accretion flow takes the form of a geometrically thick disc with twin low-density funnels around the rotation axis. For accretion rates $\gtrsim 10\dot{M}_{\text{Edd}}$, there is sufficient gas in the funnel to make this region optically thick. Radiation from the disc first flows into the funnel, after which it accelerates the optically thick funnel gas along the axis. The resulting jet is baryon loaded and has a terminal density-weighted velocity $\approx 0.3c$. Much of the radiative luminosity is converted into kinetic energy by the time the escaping gas becomes optically thin. These jets are not powered by BH rotation or magnetic driving, but purely by radiation. Their characteristic beaming angle is $\approx 0.2$ rad. For an observer viewing down the axis, the isotropic equivalent luminosity of total energy is as much as $10^{48}$ erg s$^{-1}$ for a $10^{7} M_\odot$ BH accreting at $10^3$ Eddington. Therefore, energetically, the simulated jets are consistent with observations of the most powerful tidal disruption events, e.g. Swift J1644. The jet velocity, however, too low to match the Lorentz factor $\gamma > 2$ inferred in J1644. There is no such conflict

(Sadowski & Narayan 2015)
Supersoft emission from optically thick outflows

Supercritical accretion necessarily generate disk winds (e.g., King & Pounds 2003; Gu 2015)

Blackbody emission from these hot, optically thick winds may generate supersoft X-ray radiation...

Numerical simulations always confirm outflows (e.g., Ohsuga+2005, 2011)
Or even clumpy winds (Takeuchi+2013)
Vivid manifestation of supercritical accretion

M81 ULS-1: High luminosities + supersoft X-ray emission + relativistic baryonic jets

(Liu et al. 2015, Nature, 528, 508)  (Pinto et al. 2016, Nature, 533, 64)
Super-Eddington Accretors: ULXs and ULSs

Unified scenarios based on accretion rates and inclination angles

(Gu et al. 2016)
ULSs as a subclass of ULXs were originally expected to be IMBHs with supersoft emission from their large accretion disks.

Intensive studies carried out for two ULSs

- M101 ULX-1 turns out to be a stellar black hole, with supersoft emission from hot, optically thick disk wind
- M81 ULS-1 exhibits relativistic baryonic jets, manifesting supercritical accretion onto a black hole that generate baryonic jets and optically thick disk wind responsible for supersoft emission

ULSs are also stellar black holes under supercritical accretion viewed at not small viewing angles.