New observations of ULX supershells, and their implications

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What’s to come?

→ Brief introduction to nebulae & supershells associated with ULXs (ULXN)

→ Energetics: photon and collisional excitation

→ Analogies to nebulae associated with normal X-ray binaries and AGN

→ New results: 5 galaxies, 8 ULXs, how many nebulae?

→ Summary
What are supershells / bubbles?

Demonstration by example:

- ULX Holmberg II X-1
- He III region surrounding ULX
- Excitation from UV or X-ray source
- Consistent with Lx of ULX if isotropic
- Kaaret et al. (2004) - HST imaging

1" = 15 pc

X-ray Ionized Nebulae (XIN) have been detected before: LMC X-1 (Pakull & Angebault 1986, Cooke et al. 2008)
What are ULXN / supershells?

Demonstration by example:

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\[ 1'' = 15 \text{ pc} \]

- ULX Holmberg IX X-1
- Shell 1 order of magnitude larger (e.g. Miller 1995, Pakull & Grisé 2008)
- Kinetic energy of the shell is \(10^{52} \text{ erg/s}, \) from expansion velocity and density \(\rightarrow\) not SNR (Ramsey et al. 2006)
Quasars and Microquasars

FR II Radio Galaxy
NVSS 2146+82
at 1.4 GHz
(Palma et al. 2000)

Supermassive
black hole jets

Cen A
Multiwavelength
(Kraft et al. 2008)

Radio lobes

Stellar-mass
black hole jets

Bow shocks

Black Hole X-ray Binary
1E 1740.7-2942
(Mirabel et al. 1992)

Black Hole X-ray Binary
GRS 1758-258
(Marti et al. 2002)

Cygnus X-1: Gallo et al. 2005, Russell et al. 2007
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Radio lobes

Cygnus X-1: Gallo et al. 2005, Russell et al. 2007

GRO J1655-40  (Miller-Jones, Russell, et al. in prep.)
Quasars and Microquasars

3C 83.1 (Odea & Owen 1986)

Predicted by Heinz et al. 2008 for fast moving LMXBs

Possible first detected XB head-tail source: SAX J1712.6-3739 (Wiersema et al. 2009)

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Head-tail trails

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Bow shocks
New observations

• We imaged 5 galaxies containing ULXs using 2 telescopes:
  The Isaac Newton Telescope and Wide Field Camera (La Palma; north)
  The Danish 1.5m Telescope and EFOSC (La Silla, Chile; south)

• Many emission line filters:
  \[\text{[O II]}\] 3727 Å
  \(\text{He II}\) 4686 Å
  \(\text{H}\beta\) 4861 Å
  \[\text{[O III]}\] 5007 Å
  \(\text{H}\alpha\) 6563 Å
  \[\text{[S II]}\] 6716 + 6731 Å doublet

• Continuum subtraction using redshifted \(\text{H}\alpha\) line filter and V-band

• Gemini North + GMOS: 48 mins of integration on NGC 5204 X-1
  PI: J. Gladstone
  Slit 0.75”x330”, spectral coverage 3250–6000 Å
  orientated north–south, strong nebula lines detected
NGC 5204 X-1

ULX has $L_x = 7 \times 10^{39}$ erg/s (0.5 - 8 keV)  

- Continuum:  
  $\text{H}\alpha$ redshifted  
  600 sec  
- Optical counterpart:  
  e.g. Roberts et al. papers  
- $\text{H}\alpha$ (continuum subtracted) taken with CFHT (Pakull & Mirioni 2002)  
- Abolmasov et al. 2007: nebula lines  
- $[\text{S II}]$ (continuum subtracted)  
- $\text{He II}$ (continuum subtracted)  
- $[\text{O II}]$ (continuum subtracted)  
- $[\text{O III}]$ (continuum subtracted)

Galaxy is a warped spiral.
NGC 5204 X-1

ULX has $L_x = 7 \times 10^{39}$ erg/s (0.5 - 8 keV)

Galaxy is a warped spiral
$D = 4.8$ Mpc

Strong [S II], [O II], [O III], weak He II

SS 433 / W50 complex

Continuum

Hα

Hβ

[S II]

[O II]

He II

[O III]

• ULXN: similar morphology to W50, about 2.5 times larger

• Gemini spectra: a further 6 lines are detected
NGC 5204 X-1

ULX has $L_x = 7 \times 10^{39}$ erg/s (0.5 - 8 keV) 

Galaxy is a warped spiral
$D = 4.8$ Mpc

Gemini GMOS spectra:

10 nebula emission lines are detected

Balmer decrement constrained: $E(B-V) = 0.44 \pm 0.04$

Preliminary results:

- We compare the de-reddened line ratios to models of radiative shock waves (MAPPINGS; Allen et al. 2008)

- We infer a probable shock velocity of ~200 km/s

- May be powered by the jets of the ULX? Further investigation required.
NGC 4395 X-1

ULX has $L_x = 2 \times 10^{39}$ erg/s (0.1 - 2.4 keV) \hspace{1cm} D = 3.6 Mpc

No nebula reported so far, But galaxy is close

$H\alpha$ 1200 sec
NGC 4395 X-1

ULX has $L_x = 2 \times 10^{39}$ erg/s (0.1 - 2.4 keV)  

$D = 3.6$ Mpc

No nebula reported so far,  
But galaxy is close

$H\alpha$ 1200 sec  
Continuum subtracted using H-alpha redshifted  
1200 sec
ULX has $L_x = 2 \times 10^{39}$ erg/s (0.1 - 2.4 keV) 

D = 3.6 Mpc

No nebula reported so far, 
But galaxy is close

$H_\alpha$ 1200 sec 
Continuum subtracted 
using H-alpha redshifted 
1200 sec

$[S \ II] \ 1200$ sec 
Continuum subtracted
NGC 4395 X-1

ULX has $L_x = 2 \times 10^{39} \text{ erg/s (0.1 - 2.4 keV)}$

$D = 3.6 \text{ Mpc}$
NGC 7793

Central X-ray source has $L_x = 6 \times 10^{36} \text{ erg/s} (0.3 - 8 \text{ keV})$

$D = 3.9 \text{ Mpc}$

Pakull & Grisé (2008); Soria et al. (2009): three X-ray sources coincident with radio and $H\alpha$ nebula

Our data
NGC 4861: 2 ULXs

Lx = $6 \times 10^{39}$ and $2 \times 10^{40}$ erg/s (2 - 10 keV)  

D = 17.8 Mpc

[S II] - continuum  

H$\alpha$ - continuum

H$\alpha$ nebulae close to both ULXs (mentioned also in Pakull & Mirioni 2002)
NGC 4559: 3 ULXs

$L_x = 2 \times 10^{40}, 1 \times 10^{40} \text{ and } 3 \times 10^{39} \text{ erg/s (0.3 - 10 keV)} \quad D = 9.7 \text{ Mpc}$

Continuum:
$H\alpha$ redshifted 1200 sec
$H\alpha$ 1200 s (-continuum)
$[S \, II]$ 1200 s (-continuum)
$\text{He II}$ 1200 s (-continuum)
$[O \, II]$ 1200 s (-continuum)
$[O \, III]$ 1200 s (-continuum)
NGC 4559: 3 ULXs

$L_x = 2 \times 10^{40}, 1 \times 10^{40}$ and $3 \times 10^{39}$ erg/s (0.3 - 10 keV) \hspace{1cm} D = 9.7 \text{ Mpc}

$H\alpha$ $[S\ II]$ $[O\ II]$ $[O\ III]$
NGC 4559: 3 ULXs

$L_x = 2 \times 10^{40}, 1 \times 10^{40} \text{ and } 3 \times 10^{39} \text{ erg/s (0.3 - 10 keV)} \quad D = 9.7 \text{ Mpc}

$H\alpha$

[S II]

$He \ II$

[O II]

[O III]

$H\alpha\text{ nebula also mentioned in Pakull & Mirioni (2002)}$
X-ray Binary Jets

Radio emission: → is synchrotron in nature
→ originates in collimated outflows (2 types of jet)

The spectrum of a steady jet:
Optically thick

\[ F_v \propto \nu^{-0.6} \]

The power carried in the jets is uncertain and highly dependent on the position of the turnover

Black hole XB: GRO J1655-40

Neutron star XB: Sco X-1

Radio X-ray?

Tingay et al. 1995

Fomalont et al. 2001
Summary

• Many ULXs are associated with hundred-pc scale superbubbles - we may have discovered some examples (results are preliminary)

• These emission line nebulae seem to be visible with moderate size telescopes, but their Galactic analogues are fainter

• Photoionized nebulae may be the easiest way to infer UV spectra of ULXs and constrain beaming of X-rays

• Many ULXs are likely to be microquasars; some show bipolar nebulae

• It may be possible to constrain the jet/wind power in ULXs - this is very difficult in most microquasars! (at least using jet–ISM interactions)