Outline

- Old(ish) and new examples of ionized ULX bubbles
  NGC 7793 S26: a triple system (X-ray core + lobes)

- Interpretation: SNRs or jet/wind - inflated bubbles?
  More likely inflated by BH outflows

- General problem of radiative vs mechanical power
  ULX accretion states different from Galactic BHs?
Holmberg IX X1

Pakull & Mirioni 2002
Grise’ et al 2008

IC342 X1 ("foot nebula")

Pakull & Mirioni 2002
Feng & Kaaret 2008
NGC1313 X2
Grise’ et al 2008
Grise’ et al 2010 in prep

Hα VLT

VLT, FORS
Holmberg II X1
Miller, Mushotzky & Neff 2005

NGC5408 X1
Kaaret et al 2003
Soria et al 2006
Lang et al 2007
ULX

MF16 in NGC 6946
Radio source steep synchrotron $L_R \sim 4 \times \text{Cas A}$
(Van Dyk et al 1994)

Chandra X-ray spectrum
(Roberts & Colbert 2003)

(Swartz et al, in prep.)
New discovery: ULX & bubble in NGC 5585 (d ~ 7 Mpc)

SDSS image
Check with Matonick & Fesen’s Ha survey

Chandra image

ULX with Lx = 5 E 39 erg/s
Another new entry:
**NGC 7793 S26**
(d ~ 3.9 Mpc)

S26 nebula discovered by Blair & Long 1997
S26 in NGC 7793

Ha contours (CTIO, SINGS) over *Chandra* image

10 arcsec ~ 190 pc
S26 in NGC 7793

\[ L_x \sim 5 \times 10^{36} \text{ erg/s} \]
\[ kT \sim 0.25-1.0 \text{ keV} \]

\[ L_x \sim 7 \times 10^{36} \text{ erg/s} \]
\[ G \sim 1.7 \]

\[ L_x \sim 1.1 \times 10^{37} \text{ erg/s} \]
\[ kT \sim 0.25-1.0 \text{ keV} \]

10 arcsec \( \sim \) 190 pc
ATCA maps at 5.5 GHz (left) and 9 GHz (right)
(Soria et al 2009, arXiv:0912.2732)
Inner jet has a flat spectrum (recent ejections?)

Lobes have a steep spectrum

Spectral index map, from our 2009 ATCA data
(Soria et al 2009, arXiv:0912.2732)
ATCA contours (5.5 & 9 GHz) superposed over *Chandra* image

(Soria et al 2009, arXiv:0912.2732)
Energetics of ULX bubbles

Size $2R \sim 250 \times 150$ pc

$v_s \sim 300$-400 km/s?

(typical sizes $\sim 50$ – $300$ pc)
(from $T \sim 0.5$ keV at shock front and Ha line width).

$v \sim 80$-100 km/s in other sources

$n \sim 0.6 I_{\alpha, -6} v_{100}^{-2.4} \, \text{cm}^{-3}$

Ha intensity for fully radiative shock (Dopita & Sutherland 1996)

$n \sim 0.1 - 1$ cm$^{-3}$

Two alternatives: SNR or jet-inflated (Pakull et al 2006)

$E_{SNR} \sim 1.9 \times 10^{52} R_{100}^3 v_{100}^2 n \, \text{erg}$

$P_J \sim 3.8 \times 10^{39} R_{100}^2 v_{100}^3 n \, \text{erg/s}$
Energetics of ULX bubbles

\[ E_{SNR} \sim \text{few } 10^{52} \text{ erg} \]
\[ P_J \sim 5 \times 10^{39} \text{ erg/s} \quad \text{over an age} \]
\[ \tau \approx (3/5)(R/v) \sim 2 \times 10^5 - 1 \times 10^6 \text{ yrs} \]

Arguments AGAINST SNR scenario

Too energetic
SNR don't survive that long
No O stars available to explode 1 Myr ago
(ULXs surrounded by B stars with ages \sim 10-20 Myr)
Energetics of ULX bubbles

ULX bubbles inflated by jets and winds

\[ P_J \sim 5 \times 10^{39} \text{ erg/s} \] over an age
\[ \tau \approx \frac{3}{5} \left( \frac{R}{v} \right) \sim 2 \times 10^5 - 1 \times 10^6 \text{ yrs} \]

Age of the active phase of mass transfer

Energy consistent with \( E \) inferred from resolved radio-synchrotron ULX nebulae (flux + slope)

Age consistent with nuclear timescale of B donor evolving off the main sequence (filling the RL)
(stellar evolution models by Rappaport, Podsiadlowski et al)
Adapted from Lozinskaya & Moiseev 2007
Fundamental problem: radiative versus mechanical power in accreting BHs
Power

Low/hard state
Steady jet
(radio loud)

High/soft state
Thermal disk
(radio quiet)

$P \sim 0.1 \dot{m}$

$P \sim 10 \dot{m}^2$

Thin accretion flow

$P \sim \ln \dot{m}$

Very high state
Slim disk state?
ULX state?

Wind-dominated
Jets?
(radio flaring?)

mdot

0.001  0.01  0.1  1
In Galactic BHs:
steady jet power $\sim 1/100$ Eddington power
$P_{\text{jet}} \sim \text{few E37 erg/s for 10-M}_{\odot} \text{BHs}$

At least some ULX bubbles inflated by jets

Long-term-avg jet power required $>\sim \text{few E39 erg/s}$

Does this imply BH masses $\sim 1000 \text{M}_{\odot}$ in ULXs?

Personal opinion: No, not enough evidence of IMBH
(recall Tim Roberts’ arguments against IMBHs)
Two poorly understood properties of ULXs

Average jet power may be $\gtrsim$ few $10^39$ erg/s

X-ray spectrum often dominated by hard power-law even at $L_x \sim 10^{40}$ erg/s

(To be discussed at Ferrara workshop)

Speculation:

Many ULXs never switch to thermal-dominant state
Never collapse the flow to a thin standard disk
Never suppress the jet, even at $\dot{m} \to 1$
(low/hard $\leftrightarrow$ high/hard states)
Things we know

ULXs blow bubbles
with total energy $\sim 1E52$ erg
and characteristic age $\sim 0.2 - 1$ MYr

Large "SNR" are more likely ULX bubbles

Recently discovered bubbles:
NGC 5585 X1: contains active ULX
NGC 7793 S26: contains X-ray triple:
two (jet) hot spots and
a central BH in low/hard state
Things we don’t know

Relativistic jets or massive winds in ULXs?
Do jet and winds coexist when \( \text{mdot} \geq 1 \) ?
Ratio of radiative/mechanical power at \( \text{mdot} \geq 1 \) ?

“Canonical” ULX accretion states?
(most luminous ULXs have hard power-law spectrum)

Are ULXs a good analogy for quasars?
Fast-growing in the early universe with \( \text{mdot} > 1 \)
But no (or different) feedback in ULXs:
ULX bubbles do not shut off BH accretion from star