Ultra- Luminous X-ray Sources in Nearby Galaxies

Numerous (in ~1/4 of all galaxies) population of possible intermediate mass (20-5,000M_☉) black holes.

Unique properties not shared by AGN or galactic black holes

True nature not well understood - several types of objects?

ULX’s definition:
- bolometric luminosity > Eddington limit for a 20 M_☉ black hole (2.8x10^{39} ergs/sec) - M_{BH} < 20M_☉ from “normal” stellar evolution (even from very massive stars)
- not at galaxy nucleus
- Unresolved (< 0.6” with Chandra)

there can be a large correction from x-ray luminosity in a given band to bolometric luminosity

Chandra image of the rapidly star forming galaxy NGC4038-the “Antenna”
Collaborators

- NGC4559 MNRAS 2004
  M. Cropper PI R. Soria, C. Markwardt (timing), M. Pakull, K. Wu
  T. Strohmayer (NASA)
  M81 X-9 in prep
- Radio counterparts- submitted
  S. Neff (NASA), N. Miller (NASA)
- Giant elliptical galaxies
  L. Angelini, M. Loewenstein (NASA)
- NGC2276 ApJ 2004 Dave Davis (NASA)
- L. Winter U of Md graduate student
  - survey of ULX in nearby galaxies AAS

Thanks to J. Miller (presentation at Kyoto meeting and Con-X workshop)
IXOs – Model Classes

- Supernovae in dense environments **Exist** $L_x \sim 10^{38}-10^{41}$ ergs/sec (e.g. SN 1995N)
  - Blast-driven SNR
  - Pulsar wind nebula
  - Anomalous luminous old SNR (ngc4449)

**The other possibilities are “theoretical” objects**

- **Non-isotropic** emission from X-ray binaries
  - "Normal" high-mass x-ray binaries (HMXB)
  - Micro-blazars (beamed emission, relativistic jets)

- Accretion onto massive objects $M<10^6$
  - Intermediate-mass Black Holes (IMBH)
  - “Lost” LLAGN (Low-luminosity AGN-low mass objects exist)
Ultra- Luminous X-ray Sources in Nearby Galaxies

What data do we have?

- census from archival Rosat (Colbert and Ptak 2002), Chandra and XMM data

- Counterparts in other wavelength bands (optical, radio)

- X-ray spectra from ASCA, Chandra and XMM

- X-ray time variability on long (years) to short (seconds) time scales

- Environment of ULX

- Luminosity functions

- Correlations with galaxy properties

This talk

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Ultra- Luminous X-ray Sources in Nearby Galaxies

What are the arguments against M>20M objects?

Primarily astronomical (see King 2003)

- Difficulties in forming and feeding them
  - if M>20M\(\odot\) cannot form from stellar evolution of single “normal” massive stars
  - binary stellar evolutionary scenarios - the companion (which provides the “fuel”) should be massive and short lifetime
  - To “acquire” a stellar companion maybe difficult
  - High accretion rate (>10\(^{-7}\) M\(\odot\) /yr; \(L_{\text{bol}}\sim10^{39}\), 10% \(\varepsilon\)) - short lifetimes of stellar companion
  - Possible ablation of companion

Statistical properties

- tend to be associated with recent star formation
- small number have possible optical associations with bright stars
- some show transitions similar to that seen in galactic black holes
- the overall luminosity function of galaxies does not have a “feature” associated with the ULXs

“low” masses and high luminosities requires beaming
Ultra- Luminous X-ray Sources in Nearby Galaxies

What are the arguments against ULX being “normal” M<20M objects?

DATA

• X-ray spectra are often not like AGN or normal galactic black holes
• State transitions are often in the opposite sense from galactic objects
• Luminosities can reach 1000 $L_{\text{edd}}$ for $M_\odot$
• Evidence against beaming (QPOs, broad Fe Lines, eclipses)
• At least one object has a break in the PDS at the frequency predicted for $M\sim1000M_\odot$
• Associated extended radio sources
• General lack of optical IDs (massive stars would be seen)
• They lie near, but not in star forming regions

Theory

• There are a few ULXs with highly luminous photo-ionized nebulae around them - require high luminosity to photoionize them
• Quite a few have “soft” components well fit by low kT black body - consistent with high mass (Miller et al).

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Origin ??

If they are 20-1000 M BHs where do they come from?

- The early universe? - detailed calculations of the first stars to form (e.g. Abel et al)
  - M~200-1000M objects should be created.
  - numerous and lie in regions that will later become galaxies

- Created in dense stellar regions (e.g. globular clusters Miller et al 2002, dense star clusters Portegies Zwart, et al 2002)

Only 1 luminous source in N2276
What are they related to??

• Are ULXs intermediate mass black holes?
  – properties should scale from AGN at high mass and galactic black holes at low mass
  • Time variability
  • Broad band spectra
  • Detailed spectra in x-ray/radio/optical

• Are they something else?
  • Beamed lower mass objects
  • Black hole accreting/radiating in a “new” mode?

Properties that scale with mass
• x-ray spectral form- kT of BB component
• Characteristic x-ray time scale

These scalings have been observed for some of the objects but not most
Not All Bright Sources in/near galaxies are ULXs

- Sometimes the bright objects can be associated with either background AGN or foreground stars.
- Usually these are ‘easy’ to figure out because of the $L_{\text{opt}}/L_x$ ratios.
- Most extreme case is a QSO, 8” from NGC 7319 nucleus (Galianni et al 2004)
What can we learn from optical associations

• If unique “identification” of optical counterpart estimate mass of ULX, estimate its evolutionary history and discriminate between models.

• If nebulae associated with ULX use as calorimeters to derive true isotropic luminosity of object

IC342 - Association of ULX with an unusual supernova remnant (Roberts et al. 2003) Hα+ [NII] image

At least 2 ‘SNR’ in nearby galaxies are really ULX nebulae
**Optical nebulae**

- ULX nebulae are very big ~200-600pc, very energetic, kinetic energies ~$10^{52}-10^{53}$ ergs/sec much more than SNR
- Detailed optical spectra of these nebulae can
  - distinguish shock vs. photoionization and whether excited by central x-ray source,
- Nebulae are unusual - OIII, Ne III and He II along with OI and SII

Some associations of ULX with highly ionized nebula (Pakull and Mirioni 2003)
IXO’s – Counterparts

- 1 inside X-ray ionized nebula
  - strong HeII 4686 and [OI] 6300
  - requires 3-13x10^{39} ergs/sec to produce observed optical emission lines
- 4+ in bubble-like nebulae, 200-400 pc
  - 2+ with probable O-star counterpart
- 4+ in other nebulae
  - diffuse H alpha centered on X-ray source,
  - 1 with possible stellar counterpart
- 11 within/near larger HII regions
  - 3 with possible OB stellar counterpart
- 3+ in massive young star cluster (SSC)
- Several associated with globular clusters
  - mostly elliptical galaxies
- >>12 with radio counterparts

Combination of “old” (glob cluster) and “young” (star forming regions) locations and low mass (dwarfs) and high mass (elliptical galaxy) locations

Field is changing very fast!
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Nature of Holmberg II Nebulae

- Kaaret et al 2004 have shown that the HeII emission line nebulae is centered around the ULX in Holmberg II
- The He II luminosity requires the number of ionizing photons inferred from the x-ray spectrum without beaming.
- Direct evidence for intrinsically high luminosity in a ULX
- Dynamics of nebulae changes near the ULX (Lehman et al 2004)
Optical stellar counterparts of ULXs

- X-ray optical ratios are much larger than AGN—very little optical flux from a disk.
- HST sensitivity cannot see extension of simple x-ray models to optical band.
- The x-ray sources are often near, but not in HII regions (star forming regions).

**Disk black body fit to X-11**

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M81 x-11 (Liu and Bregman 2003)—the x-ray luminosity dominates the bolometric luminosity.

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How Much energy do we expect in other wavebands?

ULX  \( f(x)/f(\text{opt}) \sim 150-2500 \)

“typical’ active galaxy (quasar)  \( f(x)/f(\text{opt}) \sim 1 \)

x-ray binaries  optical light
•  companion star (high mass x-ray binaries)
•  accretion disk (low mass)

If light dominated by the disk \( f(x)/f(\text{opt}) \sim 100-10^4 \); optical data consistent with light from an accretion disk scaling from x-ray binaries in Milkyway - no constraint on mass of BH

not yet ruled out that much of the optical light comes from a massive companions

The x-ray flux \( f(x) \) of a \( L(x) = 10^{40} \text{ ergs/cm}^2 \)
ULX \( 3.5 \times 10^{-12} (D/5 \text{ mpc})^2 \)

22-25th mag optical counterpart has \( f(\text{opt}) \)
= \( 0.1 - 1.3 \times 10^{-15} \text{ erg/cm}^2/\text{sec} \)

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Optical counterparts of ULXs

- only a few optical counterparts
- At sensitivity of HST - only most luminous stars can be recognized at D<15 Mpc.
- Even with Chandra error circles often no unique counterpart.
- No statistical work yet on likelihood counterparts are real
- Counterparts do not show “unusual” colors

Liu and Bregman 2003

NGC 5204- Chandra and HST images- source breaks up into 3 objects- brightest source could be a F supergiant $M_v = -8.1$ (the brightest normal stars ever get) Roberts et al 2002

ULX x-11 in M81 - possible optical counterpart a O8V star
First certain Identification of a ULX in M101

- Detection of He II and He I emission lines in stellar counterpart - no Hβ.
- He II lines are ~1200 km/sec wide

He II lines are a ‘unique’ signature of x-ray binaries in the MW.
Optical spectrum obtained when x-ray source ~1/100 of peak luminosity - low S/N x-ray spectrum makes He II photon counting argument weak

HST 6x6” FOV, Chandra 0.3” error circle
OIII lines are from unrelated diffuse gas
- Source shows very unusual x-ray spectra (Mukai et al 2002, 2004) when x-ray bright it had \( L_{\text{bol}} \sim 5 \times 10^{39} \) ergs/sec (if \( L < L_{\text{Edd}} \), \( M > 36 \, M_\odot \))
- but goes into quiescence at 100x dimmer
- No evidence for optical variability with HST data—arguing that the bulk of the light is from the companion star and not the accretion disk (!)

Star has colors and magnitude \( M_v = -5.5 \) of a B0 star in M101 -
NGC4559 Optical Analysis - R. Soria

- **Chandra error circles and HST images** -
  - X-10 no optical counterpart <25th mag,
  - X-7 5 optical objects 23-24.5 mag (M> -6)

- X-7 is near (5”= 230 pc), but not in diffuse emission nebulae.

- X-10 is not near any region of star formation

- Long term x-ray variability a factor of ~2, sources are not transients.

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NGC4559 Optical Analysis of X-7 - R. Soria et al in press

- X-7 near (5" = 230 pc), but not in diffuse emission nebulae.
- possible counterparts
  - 2 B stars $M < 9 \, M_{\text{sun}}$
  - 3 $M \sim 10$-$15 \, M_{\text{sun}}$
  - one O $M \sim 15$-$25 \, M_{\text{sun}}$

HST Image and Hα contours

CMD tracks for masses of 9, 12, 15, 20 and 25 $M_{\text{sun}}$ crosses are data for stars inside Chandra error circle

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Radio Observations of ULXs- S. Neff, N. Miller

- We (S. Neff, N. Miller, RM) cross correlated FIRST/NVSS radio catalogs with Chandra/XMM for nearby galaxies
- >12 “hits” (dθ<1.5”) between FIRST radio sources and non-nuclear x-ray sources (also NVSS and XMM with larger dθ)
- several have “good” VLA data- all sources 3-20 mJy
- radio/x-ray ratio less than for Bl Lacs
- radio/optical ratio is large (in progress)
- radio data are crucial for
  - Better angular resolution and accuracy (help in finding an optical counterpart)
  - Diagnostics for nature of the source (AGN, SNR, beaming, HII region etc)

NGC5775 Radio contour, X-ray color

D=100 Mpc 1”=500pc

Log L(x)=3.3x10^{40}

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Radio Observations of ULXs

- **major surprise** significant fraction of sources are resolved by VLA - not like galactic black holes (Fender talk today)
  - original discovery by Kaaret et al (NGC5408) indicated radio source is compact - due to insufficient angular resolution of ATCA??

- sensitivity of FIRST limits all the radio counterparts >3 Cas-A at D> 3 Mpc

- Objects are very luminous for SNR or HII regions

- Morphologies vary

- Maximal cooling times (if emission is thermal like in HII regions) is <3x10^8 yrs if no continuous energy injection

So far only one source has clear nature NGC4449 (D=3 Mpc) L(radio)~10xCas-A, L(x)>10^3 Cas-A - young SN can be this luminous in both radio and x-ray

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Radio Observations of ULXs-Holmberg II (Miller et al ApJ submitted)

- Holmberg II (UGC4305)- dwarf galaxy
  - VLA coincident with Chandra source (0.7") and overlaps He II nebula
    - source is resolved 3.7x2.7" at 1.4 Ghz (40x60pc)
    - flat spectral index 0.44+/-0.31
    - NVSS flux of 15mJy = 12xCas-A
  - VLA resolved flux ~Cas-A

- XMM data show a strong soft component (cf Miyaji et al)- unlike galactic BH radio sources (Fender this morning)
- Optical spectra (Lehmann et al 2004)show that the radio emission is not a SNR
- Ratio of Hβ to radio flux indicates that it is not a HII region
- Coincidence of radio and x-ray to ~25pc

Chandra VLA XMM UV and

D=3.1 Mpc
2"=30pc

Ratio of radio to x-ray \sim 5\times10^{-6}

luminous ULX, with BB component inside a bright extended radio source- no beaming in our line of sight! - HST He II image

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# Radio Properties of ULX Counterparts—partial list

<table>
<thead>
<tr>
<th>NAME</th>
<th>Distance (Mpc)</th>
<th>Size (pc)</th>
<th># Cas-A’s</th>
<th>Radio Power</th>
<th>Spectral index</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>NGC2782</td>
<td>34</td>
<td>80</td>
<td>2800</td>
<td>1.5E21</td>
<td>~-0.3</td>
<td>3 peaks Resolved arc of emission</td>
</tr>
<tr>
<td>Starburst galaxy</td>
<td></td>
<td></td>
<td></td>
<td>1100</td>
<td>6E20</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td>3E20</td>
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</tr>
<tr>
<td>NGC3877</td>
<td>12</td>
<td>260x170</td>
<td>85</td>
<td>4e19</td>
<td>-0.1</td>
<td>~7” from nucleus-jet?</td>
</tr>
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<tr>
<td>NGC4314</td>
<td>13</td>
<td>&lt;125</td>
<td>20 (each)</td>
<td>1E19 (2)</td>
<td>-0.4</td>
<td>2 parts</td>
</tr>
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<tr>
<td>NGC4449</td>
<td>2.8</td>
<td>8x4</td>
<td>~10</td>
<td>5e18</td>
<td>Steep ,1.7</td>
<td>SNR</td>
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<tr>
<td>NGC4490</td>
<td>6.6</td>
<td>13 (core)</td>
<td>~6</td>
<td>3E18</td>
<td>-0.5</td>
<td>Core halo/double</td>
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<td></td>
<td></td>
<td>~65</td>
<td></td>
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<td></td>
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<tr>
<td>HoII</td>
<td>2</td>
<td>40x30</td>
<td>~1</td>
<td>5e17</td>
<td>-0.3</td>
<td></td>
</tr>
<tr>
<td>NGC3256</td>
<td>90x270</td>
<td>1000</td>
<td>1000</td>
<td>-0.8 (ULX)</td>
<td>Twin AGN + ULX</td>
<td></td>
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<tr>
<td>NGC5408</td>
<td>4.8</td>
<td>1.5</td>
<td>Texas meeting</td>
<td></td>
<td>&gt;-1</td>
<td>Kaaret et al</td>
</tr>
</tbody>
</table>
Radio X-ray Connection- example NGC4631

- Association of radio and ULXs-
  \[ \log L(x) \sim 39.7 (0.3-10 \text{ keV}) \text{ fit model } kT_{\text{diskbb}} = 1.2 \text{ keV}, N(H) = 2.6 \times 10^{22} \]
- same place as CO wind: Rand (1999) argue that it implies \(10^{54}\) ergs of KE
- brightest source (to the west- not in the image above)
  \[ F(x) = 2.6 \times 10^{-12} (0.02-200 \text{ keV}) L_{\text{bol}} \sim 3.8 \times 10^{40} \text{ well fit by simple power law + } N(H) = 3.4 \times 10^{21}. \]

NGC4631 Radio Image and Chandra Hard sources
Radio Observations of ULXs-NGC4314

- NGC4314- ring like radio structure surrounding nucleus, associated with HST ring of star formation - radio luminosity too large in “knots” to be due to simple sum of “reasonable” number of SN
- Source X1  \(L(x) \sim 3 \times 10^{39} \text{ ergs/sec}\)
- X3  \(L(x) \sim 7 \times 10^{38} \text{ ergs/sec}\)

Chandra Image radio contour

D=18 Mpc 5"=440pc

Chandra green, HST blue, VLA red
Radio Observations of ULXs-NGC3877

- NGC3877 (D=17 Mpc 1"=83 pc)

VLA source exactly coincident with Chandra source (+/-0.5")
  - Source resolved 2x.4" at 4.86 Ghz and smaller at 1.4Ghz -150x300pc (!)
  - Spectral index is flat -0.13+/-0.35
  - Flux is ~3mJy or 80x Cas-A

~7" away from optical nucleus -5 Chandra observations - nothing obvious in HST images

Chandra L(x) ~6x10^{38}

Sub-luminous ULX inside an extended radio source

Neff, Miller are now analyzing the set of radio data obtaining images, spectra; as Chandra and XMM data go public sample will increase. Archival VLA data of very variable quality- new observations are needed. Some are bright enough for VLBI

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Radio Observations of ULXs-NGC4490

- NGC4490 (D=8 Mpc 1"=39 pc) radio image with the VLA is coincident with the Chandra source (+/-0.5"")
  - Source resolved 2x.4" at 4.86 Ghz about 75x150pc
  - Spectral index is flat - 0.13 +/- 0.35
  - Flux is ~3mJy or 15x Cas-A

X-ray flux varies between Chandra and XMM epochs;
Chandra L(x) ~8x10^{38}

~ULX inside an extended radio source.
The page contains a discussion on the flux variations of IXOs (intermediate-mass x-ray sources). The key points are:

- Variability is frequently observed, usually between observations (months-years).
- Sometimes intra-observation (hours).
- Some IXOs may be periodic. For example:
  - IC 342; 31 or 41 hrs (HMXB).
  - Cir X-1; 7.5 hrs (>50 M\(_{\odot}\) BH).
  - M51 X-1; 2.1 hr? (LMXB?).

In addition, there are references to specific cases:

- M51 X-1: P ~ 2.1 hr
  - Liu et al. 2002

- IXOs in NGC 4485/4490: All less than factor of 3 variability
  - Roberts et al. 2002

- Cir X-2; P = 7.5 hrs
  - Consistent with >50 M\(_{\odot}\) BH in eclipsing binary
  - Bauer et al. 2001

An image of a light curve for NGC 5194 X-7 is also included, showing the variability over time.
X-ray Time Variability

- Most ULXs vary—many show low amplitude variability on long time scales—very different than Galactic Black holes or Seyfert galaxies (except LMC X-1 !)

Holmberg II long term light curve

25 years of data for M81 X-9

11 years of data for NGC2276

NGC4559-3 yrs

1000 d
X-ray Time variability

Detection of periodicities can help determine the mass of the objects. For a mass ratio of \( q = \frac{M_1}{M_2} < 0.8 \), the Roche Lobe radius is

\[
R_{cr} = 0.46 \alpha \left( \frac{M_1}{M_1 + M_2} \right)^{1/3}
\]

in which \( \alpha \) is the separation between the donor and the accretor, and \( M_2 \) is the mass of the accretor. Combined with Kepler's 3rd law, \( P_{orb} = 8.9(R)^{3/2}(M)^{1/2} \) hours.

For a late-type low mass star, the mass-radius relation is \( R = M \) (solar units) and periods of 2-8 hours translate to mass of the donor of 0.2-0.4M.

The mass of the compact object (the accretor) cannot be determined from the period alone- if eclipses are detected then other constraints are possible.

The fraction of the period spent in eclipse is related to the size of the Roche lobe of the binary companion and hence to the companion to compact object mass ratio.

Periodic “Dips” - Material in the accretion stream?
X-ray Time Variability \textbf{M82 QPO}

- Many galactic black holes exhibit “quasi-periodic oscillations” (QPOs)
- Clearly associated with the accretion disk and represent characteristic length scales close to the black hole
- If QPO frequency associated with Kepler frequency at innermost circular orbit for Schwarzschild black hole,

\[
\nu_{\text{QPO}} \leq \frac{1}{2\pi} \left( \frac{GM}{R_{\text{in}}^3} \right)^{1/2}
\]

\[
\left( \frac{R_{\text{in}}}{R_g} \right) \leq 220 \nu_{\text{QPO}}^{-2/3} \left( \frac{M}{10 M_\odot} \right)^{-2/3},
\]

- M82 QPO frequency of 0.06 Hz translates to an upper limit on the mass of $1.9 \times 10^4 M_\odot$, consistent with observed luminosity and efficiency of ~0.1
- Only QPO so far (2-3 other data sets sensitive enough)

Detection of 0.06Hz QPOs in the x-ray flux from the ULX in M82-the x-ray brightest ULX (Strohmeyer and Mushotzky 2003)
Power Density Spectra

- Power density spectra, for many galactic black holes and AGB are flat at low frequencies steep at high frequencies
- This form seems to be ‘ubiquitous in black holes
- The break frequency scaling as mass of object
- Only XMM has signal to noise for accurate PDS
  - ~5-10 ULXs (>0.5 cts/sec for 30ks exposure) if PDS scales from Cyg X-1 or Seyfert galaxies

NGC3516 Nandra and Edelson

NGC4559 x 7

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Power Density Spectra (T. Strohmayer and C. Markwardt)

- PDS for several XMM sources are well sampled, good signal to noise

- Preliminary analysis for several ULXs - many with low overall power - no more QPOs (yet)

- ULX, in general, do not have the “characteristic BH” power spectra - with the exception of X-7 in NGC4559

Circinus galaxy ULX PDS - pure power law - no evidence for a break at low frequency
Power Spectrum of NGC4559 Sources Cropper et al MN 2004

- **X-7** has “classical” Cyg X-1 power spectrum, flat at low frequencies and steep at high.
  - RMS variability of 37% very similar to Cyg X-1.
- **break frequency is 28mHz**.
  - scaling break frequency to mass (as for AGN and Cyg X-1) \(M \sim 10^3M\).

- **X-10** steep power law PDS
  - little power, no characteristic frequency
- **XMM data** now know how bright/how long we need to look to get the PDS well determined
Nature of the X-ray Spectrum

spectra of Milkyway black holes fall into 2 broad classes
- Powerlaw spectra (low state)
- Disk Black body +power law (high state)

• The x-ray spectra of the ULXs can be different
  • ~1/4 of bright objects are better fit by a very hot disk black body model or comptonized spectrum than a power law,
  • A significant fraction ~1/3 of ULX require a soft black body (kT<0.5 keV) component (Winter et al 2005, Miller et al 2004)
- Spectral fits are not unique—high S/N XMM data confirm some sources have curving spectra.
- **M81 X-9 (~180Kcts)** power law + bb, comptonization model + BB and diskbb + power law fits all acceptable—best fit is Comptonization + BB (δχ²=60/100 against power law or diskbb)
  \[ L_{0.01-100\text{ keV}} = 2.5 \times 10^{40} \text{ ergs/sec} - 1.3 \times 10^{40} \text{ ergs/sec} \]
- Holmberg II -200Kcts
  Pow + bb, BMC and Comp + BB equally good, diskbb + bb is a poorer fit
  \[ kT_{BB} \approx 0.15 \text{ keV} \]
**FACTORS of 2-3 uncertainty in bolometric correction** (\( L_{0.01-100} \approx 1.3-4 \times 10^{40} \))

Both Holmberg II and Holmberg IX very little variability between 2 observations ~5-10 days apart spectra are virtually identical!

hot ‘DISKBB’ spectra can be interpreted as Comptonized similar to VHS BHC spectra—alleviate problems with high kT disk black body models.
Possible Spectral Signature of IMBH

- The Effective temperature of the accretion disk scales as

\[ T_{\text{col}}^{(\text{max})} \approx 1.3 \text{keV} \left( \frac{T_{\text{col}}}{1.7} \right)^{1/4} \left( \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{1/4} \left( \frac{M}{7M_\odot} \right)^{-1/4} \]

- \( kT_{\text{col}} < 0.4 \) keV
- \( M > 700 \) M for \( L = L_{\text{Edd}} \)
- Only if \( L \ll L_{\text{Edd}} \) can the temperature be low for a lower mass object

J. Miller et al
Two sources in NGC 1313

Fig. 2. — The unfolded MOS-1 and MOS-2 spectra of NGC 1313 X-1. The total spectrum, cool \((kT \approx 150 \text{ eV})\) disk component, and power-law components are shown in black, blue, and red, respectively.

Fig. 3. — The unfolded MOS-1 and MOS-2 spectra of NGC 1313 X-2. The total spectrum, cool \((kT \approx 160 \text{ eV})\) disk component, and power-law components are shown in black, blue, and red, respectively.

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X-ray Spectra- Soft Components

- With XMM quite a few sources require soft components
- Can be fit by black body with $0.1<kT<0.3$ keV
  exact value of $kT$ depends on model used for hard component
- Most luminous sources require soft component

The low temperature of the soft components is hard to detect with ASCA and Chandra ACIS
NGC4559 Spectral Analysis for X-7, X-10

- **X-7** spectrum (~20,000 counts) power law ($\Gamma = 2.23$) and “black body” like component of
  - luminosity in BB component and
temperature give $R \sim 3 \times 10^9$ cm
  - King and Pounds wind model mass
    $M \sim 2 \times 10^3 M$
  - $R_{diskbb} = 1.2 \times 10^9$ cm - *if* this corresponds to $6R_\odot$
than $M \sim 1.6 \times 10^3 M$

The BMC model (Titarchuk and Shrader 1999) similar mass.

- bolometric correction $L_{bol} \sim 6 \times 10^{40}$ ergs/sec $\sim 0.1 L_{Edd}$ for $M \sim 10^3 M$
- **X-10** power law in XMM and Chandra
  $\Gamma = 1.82$ no variation in slope or $N(H)$ ;
  $L_{bol} \sim 3 \times 10^{40}$ ergs/sec
- No Fe K line with EW < 100 eV for a narrow line
  and 200 eV for a broad line
The Temperature Luminosity Relation

- Miller et al 2004 show
  - galactic black hole candidates have BB component temperatures appropriate for their dynamical masses and observed luminosities
  - If the BB components in ULXs are not indicative of their mass then additional (unknown) physics is required to account for the BB component

\[
\frac{L}{L_{\text{Edd}}} \sim 0.3, M=1600M_{\odot}
\]

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Soft Black Body

- One is then left with a conundrum
- If we want objects with $L(x) \sim 10^{40}$ erg/s and $kT_{\text{col}} \sim 0.4$ keV to be less than $80M_\odot$ then
  - the object radiate at less than the Eddington limit by a large factor—e.g. to have $kT=0.4$ keV and $M \sim 80M_\odot$ then $L/L_{\text{Edd}} \sim 0.1$
  And the luminosity would be too low by a factor of $\sim 10$!

As shown by Miller et al the GBHCs ‘behave’ in this fashion while the ULXs do not

$kT$ vs $L_{\text{bol}}$
X-ray Spectral Features

- In many AGN and galactic black holes broad Fe K line
- This line is broadened by dynamics in the disk
  - disk “directly sees” radiation from central source
- “Beamed” AGN (e.g. Bl Lac objects) do not show this feature
- The ULXs in M82 and Circinus show a broad Fe K line-few other ULX do
  Existence of broad Fe K line shows that continuum is not beamed

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- XMM data for bright sources with good S/N typically do not show Fe Lines with exception of M82 and the Circinus dipper.
- For the best spectra the upper limits are ~50 eV; for several <100eV.
- So far no data on time variability of lines
- Can ‘make’ broad line in M81 X-9 with powerlaw continuum- ‘disappears’ if use comptonization spectrum
X-ray Spectra- Fe K lines

- For M82 and Circinus dipper the Fe K line is complex and broad
- The EW is >100 eV; (in Circinus 2 lines of ~180 and 320 eV EW, In M82 ~ 70 (narrow)>130 eV EW (broad gaussian)- 250 eV (diskline)
- Existence of broad Fe K line shows that continuum is not beamed
XMM Survey of Nearby ULXs

- L. Winter and RM have conducted a survey of 31 galaxies closer than 7 Mpc with XMM.
- Our selection criteria corresponds to a luminosity $>2 \times 10^{38}$ ergs/sec so that we can find low state ULXs as well as high state objects.
- We have found $\sim 45$ objects meeting this criteria.
- $\sim 1/2$ have ‘high state’ spectra - e.g. well fit by a sum of a power law and a black body.
- $\sim 1/2$ have simple power law spectra - low state.
- 10% have spectra that are curving downwards - well fit by a comptonized spectrum.

Distribution of $kT$ for BB+ Power Law fits

![Distribution of kT for BB+ Power Law fits](image_url)
XMM Survey of Nearby ULXs

- The median index and distribution of power law indices for the low state spectra is very similar to that of AGN $<\Gamma>=1.9$
- The high state power law indices distribution is broader and centered near 2.3, similar to that of high state galactic black holes and narrow line Seyferts
XMM Survey of Nearby ULXs

- As expected from galactic analogs
  - the pure power law spectra objects tend to have lower luminosities -
  - all the objects above $10^{40}\text{ergs/sec}$ have PL+BB spectra (high state)

- High state spectra
- Low state spectra

If the low state spectra are direct analogs of galactic black holes it occurs at $<0.05 \, L_{\text{Edd}}$; thus indirect evidence for $M \sim 40\text{--}500M_{\odot}$ objects

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Temperature of Black Body vs Luminosity

- There is tendency for the ‘cooler’ objects to have high $L(x)$ - consistent with idea of small range in Eddington ratio for high state objects and $kT$ depends on mass.

- Most of the ‘hot’ BB+Pl fit objects can also be well fit by the comptonization model (3 exceptions NGC5204 XMM-1, NGC253 and M81)
ULX Environment

- While, statistically, ULX are more common in rapidly star forming galaxies, what is their local environment?
- Utilizing the XMM OM, we have obtained UV images of the ULX locations- look for star formation

NGC2403 ULX-2 \( L(x) = 5 \times 10^{38} \)  
Power law spectrum

M81 ULX-1 \( L(x) = 8 \times 10^{39} \)  
Pl+BB spectrum

SN 1993J \( L(x) = 22 \times 10^{39} \)

NGC5204
ULX-1
\( L(x) = 15 \times 10^{39} \)
\( kT = 1.5 \text{ kev} \)
Is location related to state??

- 39 of the XMM ULX have UV data-
- Of the High state objects
  - ~30% are in star forming regions,
  - 40% are near star forming regions,
  - 35% are not near or in
- Of the low state objects ~60% are in and 30% have no star formation and only 1/10 are near. (Only 10 ULX)

- If there is a difference it is between the fraction of high and low state objects that are near star forming regions
- **Roughly 1/3 of all the ULX are not in or near regions of UV bright star formation** - similar conclusion by Colbert et al and Swartz et al that both old and young stellar populations contribute to ULX based on statistical analysis

akedown of basic Xันon:

High state $kT: 0.77 \ \Gamma=2.89 \ L(X)=6.4 \times 10^{39}$

Low state $\Gamma=2.09 \ L(X)=6.1 \times 10^{39}$

A significant fraction of ULX are not young objects

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Conclusion

- **There is no direct evidence for beaming** - and in 5 sources direct evidence against beaming (1 QPO, one Cyg X-1 PDS, 2 eclipsing sources and broad Fe lines, 1 He II nebula)
  - in many sources indirect evidence against (soft BB like components)
- Evidence for high intrinsic luminosity in several objects (optical nebulae, BB components)
- The x-ray spectra do no resemble theoretical predictions
- Most x-ray PDS different from expectations
- There are associated luminous, large radio sources whose origin is not clear - a new “type” of object (?) associated with ULXs
- ULX ‘live’ in a wide variety of environments - not just near or in star forming regions - not clear why there is a strong statistical association with star formation
- The ULXs do not “look like” scaled up GBHCs or scaled down AGN nor like beamed versions of either one

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IXOs in NGC 3256

- *Chandra* finds 14 discrete sources,
  - All IXOs
  - 20% $L_X$ in IXOs
- IXO Locations
  - Mostly in starburst
  - Two at “nuclei”
  - Several IXO near high metallicity starburst knots (IXOs 7,10,11,13,9,6)
- X-ray Sizes $< 140$pc
  - Sizes + $L_X$’s $\rightarrow$ 10-30 "normal" HMXB
in each of 14 regions 1/2 size of 30 Dor.
NGC 3256 – IXO Radio Counterparts

- 3 IXO’s have radio counterparts
  - 2 compact, one resolved
  - Other IXO’s near but not coincident with radio emission

- Both radio “nuclei” are IXO’s
  - Sizes < 50pc
  - Points embedded in diffuse emission
  - Steep radio spectra

- Radio + X-ray \(\rightarrow\) two LLAGN
  - Radio too bright for XRB’s
    - Requires 600-1000 HMXB’s
  - Radio and X-ray too bright for SNR
    - Requires \(\sim\)1000 CasA’s
    - No GRB observed in N3256
  - Properties consistent with LLAGN
    - \(L_{\text{rad}}/L_{\text{x}}\) consistent with LLAGN
    - SED is right shape
ULX in M82: XMM/EPIC Observations

- From May, 2001, 30 ks
- Now public
- Compact source dominates > 2 keV.
- We use > 2 keV photons for timing analysis.

ULX in M82: 2 - 10 keV lightcurve

ULX in M82: 54 mHz QPO
ULX in M82: 54 mHz QPO properties

- 54.3 ± 0.9 mHz
- $Q = \frac{f_0}{\Delta f} = 5$
- 2 - 10 keV amplitude of 8.5 % (rms).
- No strong energy or time dependence of QPO frequency and amplitude.
- $\Delta \chi^2 \sim 70$ without QPO component.
- F-test => $1 \times 10^{-14}$
- BB noise, powerlaw slope ~1 and amplitude of 13.5 %
Spectroscopy of M82 Source: EPIC PN

Total spectrum of M82 inside 18'' extraction radius
Line is best fit to the Luminous Source
Column density fixed to 5e21 atms/cm²

normalized counts/sec/keV

Energy (keV)

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X-ray Spectroscopy of M82 ULX

- Curving continuum; diskbb or compst (> 3 keV).
- Broad Fe line required in all fits. Details sensitive to continuum model, \( n_H \).
- No evidence for power law component.
- No reflection.
- \( L_{bol} \sim 4 - 5 \times 10^{40} \text{ ergs s}^{-1} \)