Implications of the Observed Ultraluminous X-ray Source Luminosity Function

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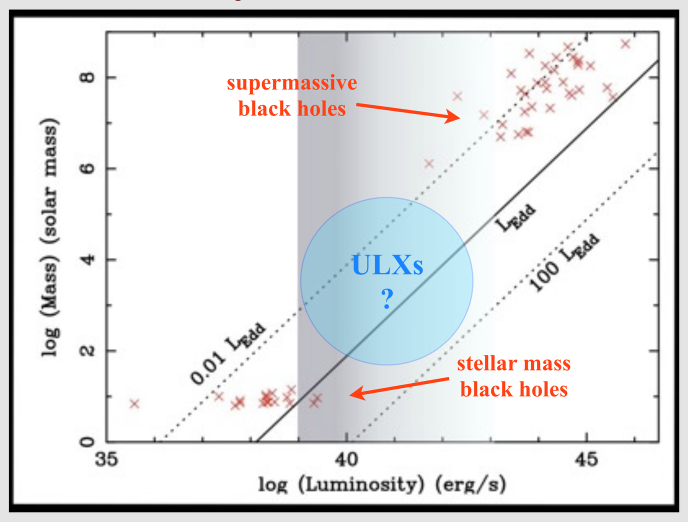
We present the X-ray luminosity function (XLF) of ultraluminous X-ray (ULX) sources with 0.3-10.0 keV luminosities in excess of 10^{39} erg/s in a complete sample of nearby galaxies. The XLF shows a break or cut-off at high luminosities that deviates from its pure power law distribution at lower luminosities. The cut-off is at roughly the Eddington luminosity for a 90-140 $M_\odot$ accretor. We examine the effects on the observed XLF of sample biases, of small-number statistics (at the high luminosity end) and of measurement uncertainties. We consider the physical implications of the shape and normalization of the XLF. The XLF is also compared and contrasted to results of other recent surveys.

What are ULXs and Why Study Them?

Ultra-luminous X-ray sources are defined as the most X-ray luminous off-nucleus (non-AGN) point-like objects in nearby galaxies. Their extreme X-ray luminosities are higher than that of stellar-mass black holes, typically $>10^{39}$ erg/s. Thus, ULXs are potentially beacons of intermediate-mass black holes lying somewhere between stellar-mass black holes and supermassive galactic nuclei. Alternatively, ULXs may be mildly super-Eddington sources powered by more modest mass accretors but with high mass accretion rates, mass outflows, and thick accretion disks (see Feng & Soria 2011 for a recent review). Regardless, ULXs remain among the most extreme and enigmatic objects known.



How was the Sample Chosen?

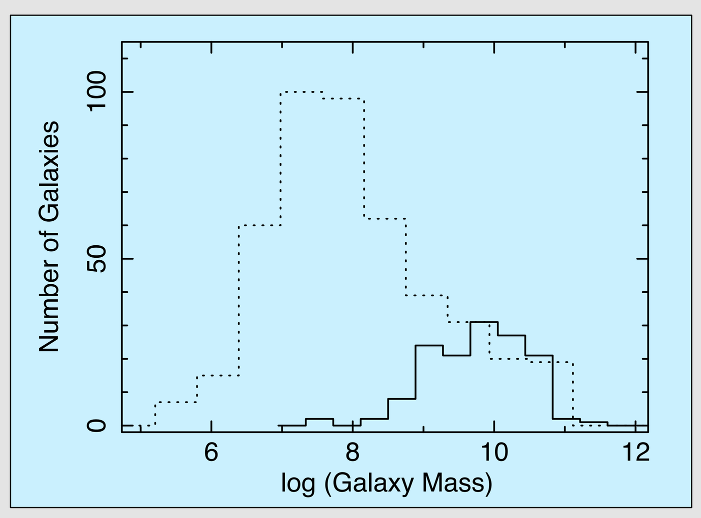
Our aim was to produce a statistically rigorous sample of ULXs by using a well-defined sample of nearby galaxies. We began with all galaxies within 14.5 Mpc in the Uppsala Galaxy Catalog (UGC) that meet its completeness limit $m_p < 14.5$ mag. The UGC (Nilson 1973) contains all galaxies north of B1950 $\delta = -2°30'$ in both of two complete samples: galaxies with angular diameters $>1'$ on the first POSS blue prints and galaxies brighter than photographic magnitude $m_p = 14.5$ mag in the Zwicky Catalog of Galaxies and Clusters of Galaxies. This resulted in a sample of 266 galaxies. We then eliminated those galaxies below the completeness limit of the Infrared Astronomical Satellite (IRAS) survey, ~1.5 Jy at 60 µm (Beichman+1988). The final sample consists of 127 galaxies and covers 6100 Mpc^3.

What are the Main Results?

One hundred seven ULXs were identified in the sample galaxies (see Swartz+2011 for complete details). The luminosity distribution is shown in the right-hand column. ULXs are detected in this sample at rates of one per 3.2×10^{10} $M_\odot$, one per 0.5 $M_\odot$ yr^{-1} star formation rate and one per 57 Mpc^3; corresponding to a luminosity density of 2×10^{37} erg s^{-1} Mpc^{-3} or about 10% of the AGN X-ray luminosity density in the current epoch. At these rates we estimate as many as 19 additional ULXs remain undetected in fainter dwarf galaxies within our survey volume. An estimated 14 objects, or 13%, of the 107 ULX candidates are expected to be background sources.

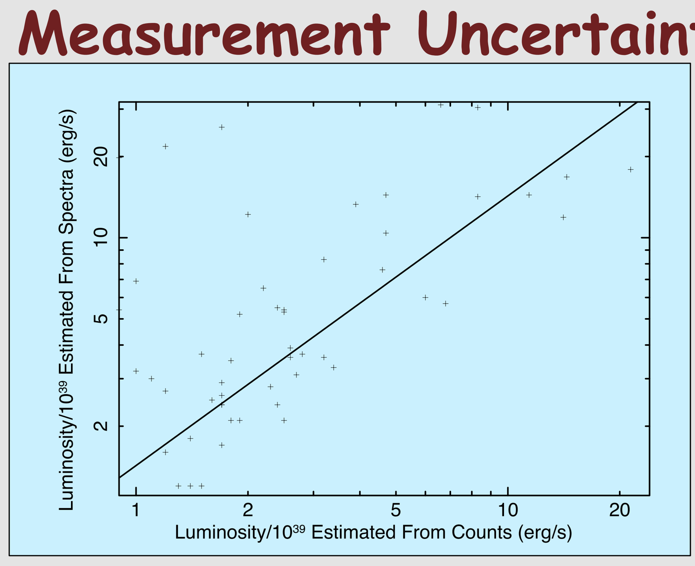
Sample Biases

Dwarf Galaxies: Our selection criteria omits most dwarf galaxies as shown by the mass distribution of our sample galaxies (solid histogram) compared to the Local Volume. But the numbers of ULXs are known to correlate with galaxy-wide star formation rate in spirals (indicating a HMXB contribution) and with galaxy mass in ellipticals (from the LMXB population). Dwarf galaxies account for 85% of local galaxies by number but only 4% by mass and contribute <15% of the SFR. From the SFR in dwarf galaxies, we estimate up to 19 additional ULXs exist in dwarf galaxies but are missed in our sample. The effect of this bias is to decrease the normalization of the XLF.



Field vs Cluster Galaxies: Our sample volume does not include galaxy clusters. Thus we have a larger fraction of spirals than would a sample including the many elliptical galaxies typical of dense clusters. However, ULXs in ellipticals rarely exceed 3×10^{39} erg s^{-1}. The possible effect of this bias is then to flatten the slope of the XLF at low luminosities and to decrease the number of ULXs per unit volume and per unit SFR. However, there is no effect on the XLF luminosity cutoff because the brightest ULXs are always in spiral galaxies.

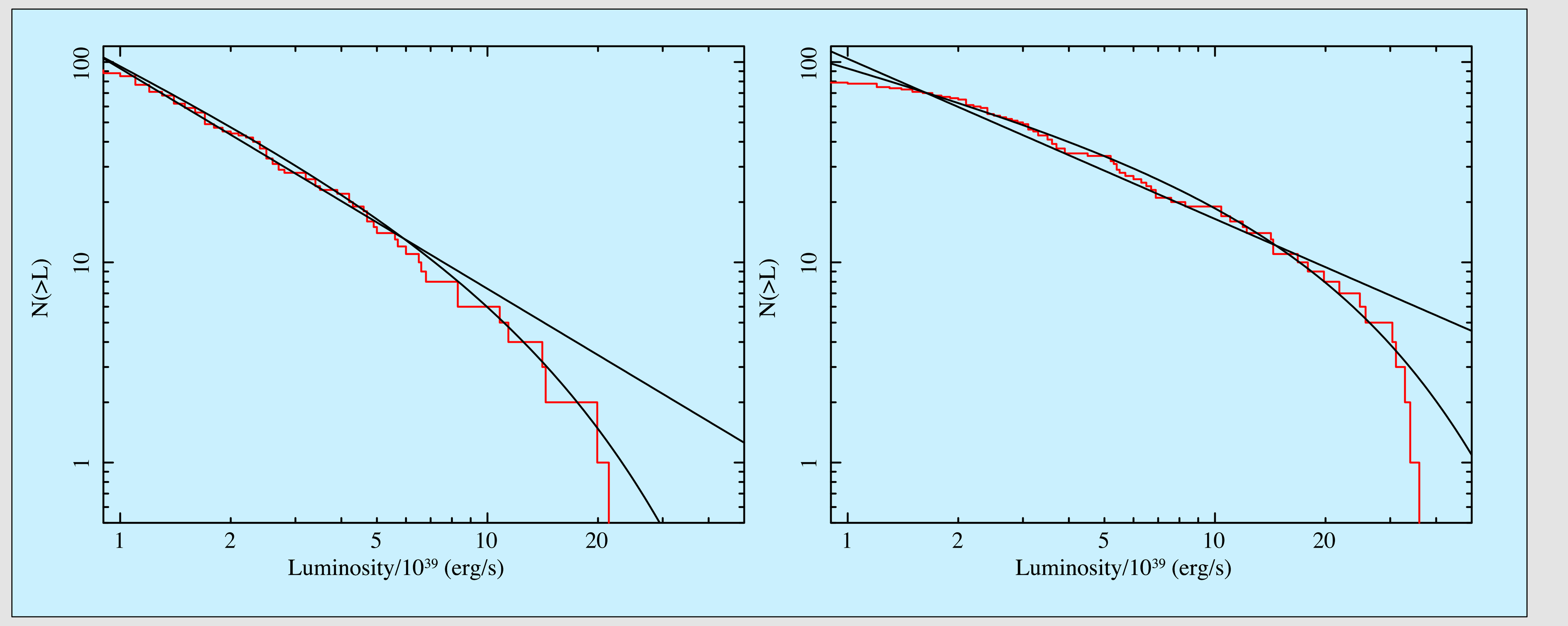
Measurement Uncertainties



Luminosities: Absorption-corrected luminosities were estimated in two ways. For all ULX candidates, a conversion from aperture- and background-corrected source counts was made using the PIMMS (Mukai 1993) simulator assuming an absorbed power law with column density equal to the line-of-sight Galactic column and a power law index of 1.8. For sources with >130 counts, spectral fits were made using XSPEC (Arnaud 1996) applying absorbed power law, blackbody accretion disk, and optically-thin diffuse gas models until an acceptable fit was obtained. The later method gives ~5-10% luminosity uncertainties while the former gives larger uncertainties because of the neglect of intrinsic absorption.

Distances: Luminosities depend on the square of the distance. We used critically-assessed redshift-independent values in order of preference: Cepheid distances from the Hubble Key Project, other Cepheid-based distances, SBFs, TRGB, globular cluster luminosity functions, brightest stars, and Tully-Fisher relation. Otherwise, we used flow-corrected redshifts corrected for Local Group motions. Distance uncertainties are thus only 5-10% for most galaxies which is comparable to our spectroscopically-derived luminosity estimate uncertainties.

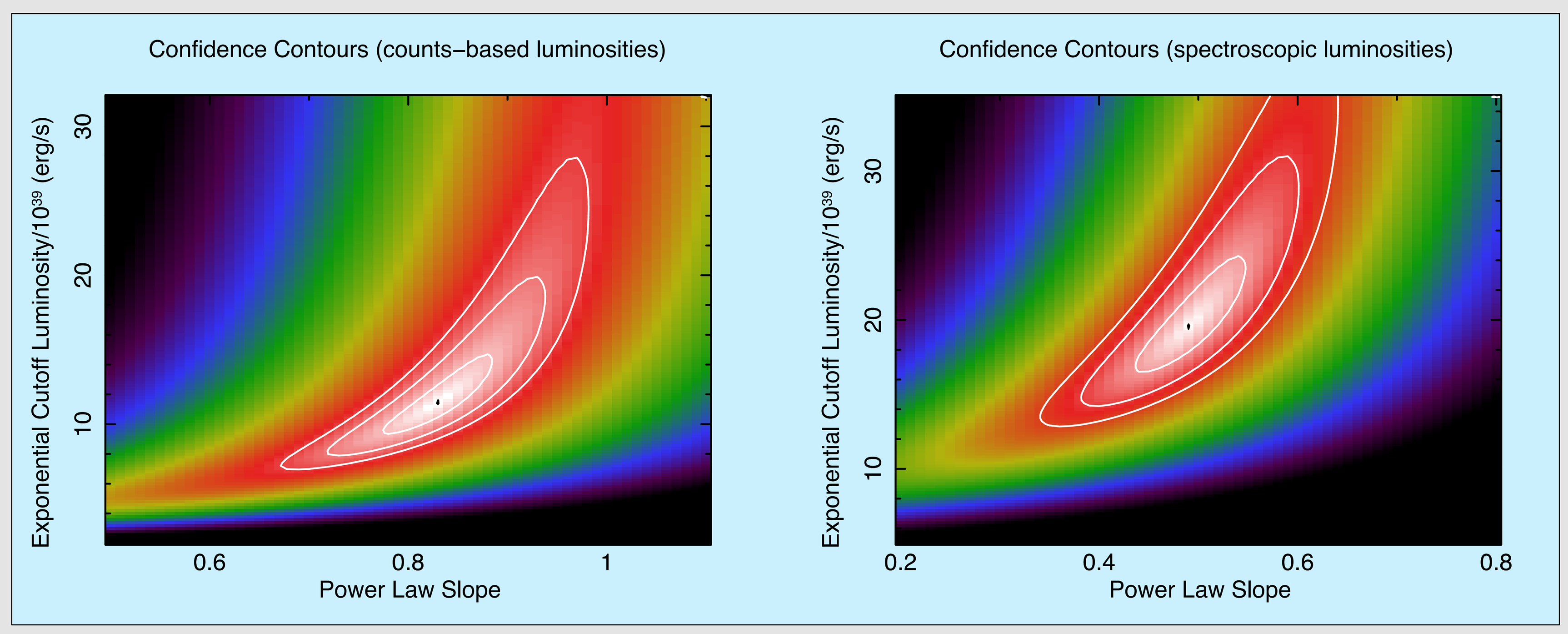
The ULX Luminosity Function



We fitted exponentially cutoff power law and pure power law models to the cumulative XLFs (above) computing luminosities (left) scaled from the observed numbers of counts and (right) estimated from fits to their X-ray spectral energy distributions.

Is there an upper limit to L_X?

A cutoff is clearly indicated but the best-fit value is difficult to determine precisely as shown in the figure below. The contour lines are drawn at 1, 2, and 3-σ confidence and the cutoff luminosity is therefore most likely between about 5 and 40×10^{39} erg s^{-1}. At the Eddington luminosity, this implies ***ULXs with accretor masses above about 35 $M_\odot$ (but perhaps as high as ~300 $M_\odot$) are extremely rare in the local Universe.***



Implications of the Observed XLF

- The observed **cutoff luminosity** or break in the XLF implies an upper limit to the mass of the ULX accretor which is similar to the theoretical upper limit that can be obtained for black holes from single star evolution in the current epoch. This suggests that the vast majority of ULXs represent the extreme end of the normal X-ray binary population
- The rather flat **slope** of the observed XLF means that the X-ray luminosity of a normal (non-AGN) galaxy is dominated by the most luminous X-ray point sources.
- The overall **normalization** of the observed XLF and the luminosity density of ULXs implies that ULXs account for roughly 5% of the cosmic X-ray background. With 80-90% resolved into AGN and QSOs, this leaves as little as 5% of the X-ray background unaccounted for.
- The rare ULX with luminosity far above the cutoff luminosity (e.g. Farrell+2009) cannot be accounted for suggesting a new class of object, perhaps the elusive intermediate mass black hole

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