Abstract. I give a brief review of how X-rays from nearby galaxies are used as direct tracers of recent star formation. This leads to the conclusion that it is the most luminous point-like sources that are associated with star formation and that the majority of these are high-mass X-ray binaries. I then discuss a recent study that shows that ULXs are preferentially found in regions as young as or younger than typical H II regions in their host galaxies. Finally, I describe a new study that attempts to determine the maximum luminosity of ULXs in the local universe by searching for them in interacting galaxies where the star formation rate is high.

1 X-ray Sources as Tracers of Recent Star Formation

David, Jones, & Forman (1992) performed the first large survey of galaxies that showed a correlation between the total X-ray luminosity and galaxy-wide star-formation rate as measured by FIR (IRAS) luminosities. Although the X-ray data were not of a quality sufficient to distinguish among different types of X-ray sources, they argued on energetic grounds that most of the X-ray light came from high-mass X-ray binaries, with typical X-ray luminosities on the order of $10^{38}$ ergs s$^{-1}$ and lifetimes of $10^5$ to $10^6$ yr rather than OB-star winds and SNe (both of which are much fainter though late O stars live longer than XRBs; see also Helfand & Moran (2001); Dalton & Sarazin (1995)).

The next major step forward awaited Chandra’s superb angular resolution and broadband (CCD) spectral sensitivity to isolate individual X-ray sources in nearby galaxies. The definitive work is Grimm et al. (2003). They showed that the point-source X-ray luminosity functions (XLFs) of individual normal and starburst galaxies all had roughly the same power law index over a wide range of source luminosities from $<10^{36}$ ergs s$^{-1}$ up to about the highest luminosities observed of $>10^{40}$ ergs s$^{-1}$ (Figure 1, left panel). Furthermore, they showed that the overall normalization of these XLFs scaled with the total star-formation rates (SFRs) of the individual host galaxies. Thus, by rescaling observed XLFs to their universal XLF (Figure 1, right panel) one could deduce the star formation rate of the observed galaxy. Since the total X-ray luminosity is just the integral of the XLF, it follows (rather circularly back to the work of David, Jones, & Forman (1992)) that the SFR can also be deduced from a measure of the total X-ray luminosity even when individual sources cannot be resolved such as at high redshifts.

Another key result of the Grimm et al. (2003) study was that the (cumulative) XLF slope was rather flat, $N(> L) \propto L^{-0.61}$, where $N(> L)$ is the number of sources with luminosity greater than $L$. This means that the most lumi-
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nous sources dominate the total X-ray luminosity and hence the most luminous sources trace recent star-formation activity.

![Figure 1](image-url)

**Figure 1.** *Left:* Cumulative XLFs for normal spiral and starburst galaxies. *Right:* Same XLFs but normalized to the star-formation rate of the Antennae galaxies. Note that the scaled XLFs occupy only a narrow range in $N(>L)-L$ space. From Grimm et al. (2003), by permission of Blackwell Publishing.

2 Some Properties of Ultraluminous X-ray Sources

The most X-ray luminous off-nucleus point-like objects in nearby galaxies are referred to as Ultraluminous X-ray sources or ULXs. Their high X-ray luminosities ($L \gtrsim 10^{39}$ ergs s$^{-1}$ in the few tenths to $\sim 10$ keV range) imply high accretor masses; hence their interest as a possible evolutionary link between stellar-mass black holes ($M_{BH} \sim 1-20 M_\odot$) known throughout the Local Group and supermassive black holes ($M_{BH} \sim 10^6-10^9 M_\odot$) ubiquitous in the nuclei of galaxies.

Numerous X-ray spectral and time-variability studies have shown that ULXs are, as a class, not steady thermal sources as expected from hot gas or SNRs but must be some form of X-ray binary (XRB). The association of the most luminous sources with galaxy-wide star-formation indicators, such as FIR luminosity as discussed above, favor high-mass rather than low-mass XRBs.

High-mass XRBs in our Galaxy and the Magellanic Clouds are those with short-lived, O or B type mass-donor stars. If this is the case also for ULXs, then they should be found preferentially in young star-forming regions such as H II regions. Population synthesis models have shown that the highest X-ray luminosities, corresponding to the highest mass-transfer rates, are expected for high-mass XRBs aged roughly 4 to 10 Myrs old when the mass-donor companion evolves off the main sequence. However, unambiguously identifying optical counterparts to ULXs requires monitoring campaigns at high spatial resolution using *Hubble* or ground-based 8-m class telescopes. More fruitful are studies of CMDs of objects in the neighborhood of ULXs, (e.g., Soria et al. 2005), which can narrow down the age of all likely counterparts in the region.
What is needed is a broadly-applicable method to easily quantify the star-forming properties of the local environments of ULXs without the expense of deep pointed observations of individual ULXs. We have recently completed a survey using such a method (Swartz et al. 2009), calibrated on the SDSS optical colors of known H\textsuperscript{ii} regions, to distinguish young, star-forming regions in nearby galaxies. We have used these criteria to examine the 100×100 pc\textsuperscript{2} regions around ULX candidates to determine if they are associated with the young stellar population. ULX environments in our study are designated as “star-forming” if they are as blue as, or bluer than a typical H\textsuperscript{ii} region in its host galaxy (taking also into account the reddening effects of dust and of old underlying stellar populations). A useful feature of this method is that colors are distance-independent quantities, and are measured on distance-independent regions.

The 58 galaxies included in this study are a subset of a complete sample of 140 galaxies selected for X-ray analysis of their ULX populations. The X-ray sample galaxies are those in both the set of all galaxies within 15 Mpc contained in the UGC with photographic magnitude \(m_p < 14.5\) mag and the set of all galaxies listed in the IRAS catalogs with a flux \(f_{\text{FIR}} \geq 10^{-13.3}\) ergs cm\textsuperscript{-2} s\textsuperscript{-1}. The 58 galaxies included in our study were those within the SDSS DR6 footprint with inclination \(i < 65^\circ\).

We found that fully 60\% of those ULX regions with sufficient signal (21/35) are in star-forming regions. By definition, these regions are as blue or bluer than typical H\textsuperscript{ii} regions of their host galaxies and therefore are likely of an age also typical of H\textsuperscript{ii} regions which is \(\lesssim 10\) Myr; the characteristic lifetime of the least-massive LyC-producing stars, i.e., late O to early B stars of about 15 to 20 M\(_\odot\).

At the same time, we found that many of the most luminous ULXs in our sample are located in faint or non-starforming regions. Some of these may be heavily reddened by dust. However, we speculate that the most luminous ULXs (or equivalently, the most common phases of very high mass transfer) are biased towards early B-type donors with an initial mass of \(\sim 10–15\) M\(_\odot\) and an age \(\sim 10–20\) Myr (perhaps at the stage where the B star expands to become a blue supergiant). In that case, we expect very little residual H\(\alpha\) emission from their surroundings, the O stars having already evolved and died. Thus, we are beginning to constrain the age of the donor stars in ULX binary systems. We hope to soon constrain the age and mass of the accretor.

3 A Search for the Most Luminous ULXs

It was shown in §1 that the X-ray luminosity function (XLF) of sources in the Milky Way and nearby normal spiral and starburst galaxies is a smooth power-law distribution from \(\lesssim 10^{39}\) up to \(\sim 10^{40}\) ergs s\textsuperscript{-1} (Grimm et al. 2003; Swartz et al. 2004; Liu et al. 2006). There are too few ULX candidates above \(\sim 2 \times 10^{40}\) ergs s\textsuperscript{-1} to state definitively whether or not the smooth distribution continues to higher luminosities. There are hints that a break or cutoff occurs at this point which, if real, imposes fundamental constraints on the physical properties of ULXs.

The most important of these constraints is the mass of the accretor. We know empirically, from studies of Galactic sources, that the most reliable indirect mass indicator is the Eddington limit. If there is a cutoff in the luminosity
distribution at $\sim 2 \times 10^{40}$ ergs s$^{-1}$, then this suggests a maximum black hole mass of $\sim 100$ M$_{\odot}$. The precise mass limit would depend on the degree of anisotropy in the emission pattern (e.g., King 2008) and on the degree of super-Eddington luminosity; perhaps allowing for a factor of 1 to 2 lower limiting mass. On the other hand, if ULX luminosities extend beyond $\sim 5 \times 10^{40}$ ergs s$^{-1}$ (or if the luminosity function flattens), then masses $> 100$ M$_{\odot}$ are indicated, at least for the brightest sources.

This is a critical dividing line. Theoretically, stellar cores up to $\sim 70$ M$_{\odot}$ can form equal mass black holes by direct collapse (Yungelson et al. 2008; Heger et al. 2003). The final black hole mass may be even slightly larger if there is residual fall-back of any remaining stellar envelope. Above this core mass, stars disrupt via pair instability supernovae, leaving no remnant. Thus, something beyond normal single-star evolution will be required if ULXs are found to have luminosities much higher than a few $10^{40}$ ergs s$^{-1}$.

Figure 2 shows the differential XLF for spiral galaxies taken from our original survey (Swartz et al. 2004). There are 57 spiral galaxies in this sample and 97 ULX candidates but only a dozen above $10^{40}$ ergs s$^{-1}$. The fitted curves indicate a potential cutoff in the XLF at $2.07 \times 10^{40}$ ergs s$^{-1}$ but the change in the fit statistic corresponds to an improvement over a single power law model at only 85% confidence.

We can estimate the number of ULXs needed to distinguish with high confidence between the power law and exponentially cutoff power law from the trends in the existing data. Assuming that the exponential cutoff power law is the true
functional form, we made a Monte Carlo simulation that computed the expected number of sources in each luminosity bin then generated a random variable with mean equal to the expected number and with a Poisson distribution. We then fit the simulated XLF with both models and compared the difference in the (maximum-likelihood) fit statistic. We conclude from this that about twice the current number of ULXs are needed to distinguish between these models at a >95% confidence level. This corresponds to ~30 additional ULXs above a luminosity $5 \times 10^{39} \text{ergs s}^{-1}$.

Since both the number and peak luminosity of ULXs strongly correlates with galaxy-wide SFR and anti-correlates with nearest-neighbor distance, a logical choice of targets for our search are the high SFR interacting galaxies. Happily, Smith et al. (2007) have performed an in-depth study of the properties of a sample of pre-merger interacting galaxy pairs based on Spitzer luminosities and colors. They selected isolated, tidally disturbed, binary systems from the Atlas of Peculiar Galaxies (Arp 1966) that are within ~150 Mpc and that have large angular size to allow for good spatial resolution with Spitzer. Of the 35 Arp pairs that met their criteria, we selected 7 galaxy pairs for a snapshot X-ray survey with Chandra which we believe will provide us with about 30 ULXs more luminous than $5 \times 10^{39} \text{ergs s}^{-1}$. These are being observed during the current Chandra observing round and the results will be combined with archival data from several other galaxy pairs in the Smith et al. (2007). So far, four Arp galaxy pairs have been observed and 13 ULX candidates have been detected above $5 \times 10^{39} \text{ergs s}^{-1}$.

Acknowledgments. This research is supported in part by Chandra Award GO6-7081A issued by the Chandra X-ray Observatory Center which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060.

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