DO ULTRALUMINOUS X-RAY SOURCES EXIST IN DWARF GALAXIES?

DOUGLAS A. SWARTZ, ROBERTO SORIA, AND ALLYN F. TENNANT

Received 2007 October 16; accepted 2008 February 16

ABSTRACT

A thorough search for ultraluminous X-ray source candidates within the Local Volume is made. The search spatially matches potential ULXs detected in X-ray images or cataloged in the literature with galaxies tabulated in the Catalog of Neighboring Galaxies compiled by Karachentsev et al. The specific ULX frequency (occurrence rate per unit galaxy mass) is found to be a decreasing function of host galaxy mass for host masses above \( \sim 10^{8.5} M_\odot \). There is too little mass in galaxies below this point to determine whether this trend continues to lower galaxy mass. No ULXs have yet been detected in lower mass galaxies. Systematic differences between dwarf and giant galaxies that may explain an abundance of ULXs in dwarf galaxies and what they may imply about the nature of ULXs are discussed.

Subject headings: galaxies: general — X-rays: galaxies — X-rays: general

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are defined as the most X-ray luminous, typically \( L_X \gtrsim 10^{39} \text{ergs s}^{-1} \), nonnuclear point-like objects in nearby galaxies. What environments and what types of stellar systems give rise to the ULX phenomenon is a subject of considerable topical interest.

The study of ULXs as a class has matured beyond mere number counts. The general approach is to search for statistically significant correlations between ULXs and properties of their galactic environments. In this way, one hopes to eventually understand what physical processes are responsible for their formation, what influence they have on their environment, and how they have evolved over cosmic time. Studies of ULXs as a class have reached some robust conclusions; ULXs are associated with active star formation, at least on galaxy-wide scales (Swartz et al. 2004; Gilfanov et al. 2004; Liu et al. 2006; Winter et al. 2006) being more common and more luminous in starburst and interacting/merging galaxies (e.g., Zezas & Fabbiano 2002, Gao et al. 2003) than in normal galaxies and occurring more frequently in the past (Lehmer et al. 2006) consistent with the observed rise in star formation density with redshift. ULXs are less luminous in early-type galaxies, potentially revealing a secondary population of unusually bright low-mass X-ray binaries or perhaps fortuitous beaming of a fraction of this population toward the observer (Irwin et al. 2004; Swartz et al. 2004; Liu et al. 2006; see also King 2004).

There are circumstantial reasons to suspect that there may be differences between the rate of ULXs in nearby dwarf and giant galaxies. Dwarf galaxies typically lack organized structure like bars and density waves that drive star formation yet their star formation rate (SFR) per unit area can be comparable to those of spiral galaxies (Hunter & Gallagher 1986). Dwarf galaxies have evolved more slowly, retaining a higher gas fraction than giants in the current epoch (Geha et al. 2006) and resulting in a lower metallicity (Lee et al. 2006 and references therein). Environment factors, such as ram-pressure stripping, can strongly affect star formation in dwarfs, whereas star formation in giant field galaxies is determined more by their merger history (Haines et al. 2007). If ULXs (or the luminous subset of ULXs) are preferentially associated with star formation, then there may be differences in the rates of ULXs in dwarfs compared to giants because of the different internal and environmental influences on star formation activity in galaxies of different mass.

The ULX population in the Local Volume (\( D \leq 10 \text{ Mpc} \)) is investigated in the following. Section 2 describes the sample of galaxies included in the study and defines three subsamples with differing selection criteria and hence different sample biases. The results of the search for ULXs in these subsamples are presented in § 3, where it is shown that the specific ULX frequency (number per unit galaxy mass) increases toward lower galaxy mass down to a limit of \( \sim 3 \times 10^8 M_\odot \), below which no ULXs have yet been detected. The significance of this result is discussed in § 4.

2. THE SAMPLES

By definition, ULXs are the most luminous nonnuclear sources in galaxies. Nevertheless, their 0.5–8.0 keV flux, \( f_X > 8.3 \times 10^{-12}/D^2 \text{ergs cm}^{-2} \text{s}^{-1} \) (for a \( L_X = 10^{39} \text{ergs s}^{-1} \) source; the traditional definition of a ULX), quickly falls below detection sensitivities of most X-ray observatories for sources beyond \( D \sim 20–30 \text{ Mpc} \) when observed for typical exposure times. Similarly, properties of dwarf galaxies are best known for nearby objects. In this case, the galaxies of interest are the least intrinsically luminous and have the smallest physical size. For these reasons, a study of ULXs in dwarf galaxies is currently restricted to nearby objects within roughly the Local Volume. The recent compilation of galaxy properties by Karachentsev et al. (2004, hereafter K04) is purported to be about 70%–80% complete out to a distance \( D = 8 \text{ Mpc} \). The catalog includes galaxies brighter than \( B_i \sim 17.5 \text{mag and angular sizes larger than } D_25 \sim 0.4 ' \). This Catalog of Neighboring Galaxies will be referred to as the CNG in this paper and various samples of galaxies and their properties will be taken from the values reported in K04.

In all samples, only galaxies in the CNG with tabulated masses are considered. This is a subset of 313 of the 451 galaxies in the CNG. For this subset, log(\( M/M_\odot \)) = −0.39 M_B + 2.65. K04 define dwarf galaxies as those with \( M_B > -17.0 \text{ mag which corresponds to a mass } M < 10^{9.3} M_\odot \). Galaxy mass is computed by K04 from H\alpha rotational velocity measurements (inclination-corrected H\alpha line widths). Consequently, 93 of the 138 galaxies omitted in the subset are gas-poor early-type galaxies with revised Hubble type \( T \leq 0 \). This leaves five giant and 10 dwarf early-type galaxies in the subset of 313 galaxies. The CNG sample of galaxies is

1 Universities Space Research Association, NASA Marshall Space Flight Center, VP62, Huntsville, AL.
2 Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey RH5 6NT, UK.
3 Space Science Department, NASA Marshall Space Flight Center, VP62, Huntsville, AL.
shown as the uppermost histogram of Figure 2. The histogram for the subset of galaxies with tabulated masses is similar. As pointed out by K04, about 85% of galaxies in the local volume are dwarf galaxies although these galaxies contribute only 4% of the luminosity density. From the CNG subset, three subsamples are considered with different selection criteria and hence different potential biases:

2.1. The Optical and FIR Flux-limited Subsample

This subsample contains all galaxies within the Uppsala Galaxy Catalog of (northern hemisphere) galaxies above the completeness limit of the UGC, $m_{ph} < 14.5$ mag (Nilson 1973), with far-infrared (FIR) flux above the completeness limit of the Infrared Astronomy Satellite (IRAS) Point Source and Faint Source catalogs, $f_{\text{FIR}} \sim 1.5$ Jy (Beichman et al. 1988), and within 15 Mpc of the Milky Way. There are 49 galaxies that meet these criteria among the 313 CNG subset. This subsample is biased toward the intrinsically optically luminous galaxies with high gas (dust) content and hence relatively high current star formation rates. Figure 1 shows that the subsample is, indeed, comprised of relatively luminous and hence massive galaxies but that there are a few nearby low-luminosity (low-mass) objects included as well.

2.2. The Nearby RASS Subsample

This subsample contains all galaxies within 4.0 Mpc (a value based on expected count rates for ULXs, typical exposure times, and distances as tabulated by K04) located within 3$^\circ$ of the centers of ROSAT All Sky Survey (RASS) fields. These fields are 6.4$^\circ \times 6.4^\circ$ regions observed in scanning mode by the ROSAT PSPC with typical exposures of $400 \text{s}$ in typical galaxy-sized regions of the sky. The RASS covers nearly the entire sky but the search algorithm used to query the data archive uses circular search regions resulting in sampling only 70% of the field’s total area (using a 3$^\circ$ search radius). There are 107 galaxies in the CNG subset within 4.0 Mpc and 72, or 67%, in the subsample. This subsample contains the least bias of any of the subsamples. As shown in Figure 1, the distribution of blue luminosities for galaxies in this subsample most closely matches the CNG distribution.

2.3. The X-Ray Source Catalog Subsample

This subsample contains all galaxies in the CNG subset that have been imaged in the field of view (FOV) of either ROSAT (PSPC or HRI), Chandra, or XMM-Newton pointed observations of sufficient exposure to detect ULXs and that have had their ULX populations identified through the literature. This includes many CNG subset galaxies that were targets of pointed observations and, in the case of ROSAT/PSPC with its 1$^\circ$ radius FOV, several dwarf galaxies that were observed serendipitously. There are 155 galaxies in this subsample including 69 serendipitously observed galaxies (those with large offsets from the observation’s targeted aim point). This subsample should be considered an X-ray-selected subsample since the majority of the galaxies were targets of pointed X-ray observations. It, like the optical/FIR subsample (see Fig. 1), is biased toward the larger galaxies which are the preferential targets of X-ray astronomy in general but it does contain a substantial number of dwarf galaxies.

2.4. Sample X-Ray Analysis

Both the literature and available X-ray imaging data (limited to ROSAT, Chandra, and XMM-Newton) were searched for candidate ULXs in this study. In most cases, whenever a thorough analysis of existing data was previously reported through the refereed literature, we did not perform an independent study. In all cases, however, we did confirm that ULX candidates were within the angular area of the purported host galaxy and not coincident with its nucleus. For this, an initial search was made for candidate ULXs within a circle of radius $r = D_{25}$, i.e., extending to twice the optical semimajor axis of the galaxy. This allows for potential astrometric misalignments between reported X-ray source positions and galaxy locations as tabulated in the CNG and also for the large positional uncertainties that can occur in ROSAT and XMM-Newton data for weak sources because of their large point spread functions (PSFs). If candidate ULXs were identified, then the spatial coincidence was reconfirmed using an elliptical approximation of the $D_{25}$ isophote (with parameters taken from the Third Reference Catalog of Bright Galaxies; de Vaucouleurs et al. 1991), a check of the host galaxy position against the NASA/IPAC Extragalactic Database (NED) position (and references therein) and an evaluation of the X-ray source positional uncertainty. Sources coincident with host galaxy nuclei were rejected. This resulted in the exclusion of 10 nuclear sources; all are the well-known active galactic nuclei of massive galaxies. Optical data (SDSS, DSS) were then visually inspected for potential foreground stars and background active galaxy counterparts which typically appear as bright and extended optical emitters, respectively. No such interlopers were identified using this test. A check was also made to ensure the entire $D_{25}$ isophote was imaged in the X-ray observation. The several large galaxies not fully covered by Chandra’s FOV have been fully sampled by either ROSAT or XMM-Newton observations; thus no ULX candidates were overlooked.

The source-detection algorithm developed by Tennant (2006) was applied to X-ray images whenever an analysis of the X-ray point source population for a galaxy was not published or was of limited utility. All the checks for spatial coincidence with a host galaxy as outlined above were performed. X-ray fluxes were estimated from observed count rates within a 3$\sigma$ source radius (see Tennant 2006) using the Portable Interactive Multi-Mission Simulator (PIMMS; Mukai 1993) and assuming an absorbed power law source spectrum. The absorption was taken as the Galactic hydrogen column density along the line of sight to the host galaxy as tabulated from the H i map of Dickey & Lockman (1990). The power-law index was assumed to be the average, $\Gamma = 1.8$,
obtained previously from single-component spectral model fits to a large number of ULX candidates by Swartz et al. (2004). X-ray luminosities were then estimated from the PIMMS fluxes and the distances tabulated by K04. The choice of a single, fixed shape, model spectrum is appropriate in the context of this study because only a small number of source photons (≤100) were typically detected from candidate ULXs in those cases where thorough analysis was not previously reported.

Special mention must be made of the selection criterion of the RASS subsample (§ 2.2) and the subsequent analysis results. As mentioned above, the distance limit criterion was chosen based on the expected count rate for ULXs (using PIMMS) and exposure times typical of the RASS and ~10 counts needed for detection (for each galaxy in this subsample, the actual exposure time at the location of the galaxy was determined from the exposure maps accompanying the RASS X-ray event lists). Our source-finding analysis of the RASS data did not detect 10 of 18 ULX candidates previously described in the literature (from pointed observations) and expected to be visible in the RASS according to this simple prescription. All nondetections are members of giant galaxies: Six are buried within the strong diffuse emission of the galactic bulge, one is a heavily absorbed source in Circinus, and one is a weak source in NGC 7793 that must have faded compared to pointed observations reported in Read & Pietsch (1999). Thus, we attribute the nondetections to a combination of source confusion (aggravated by a rapidly increasing off-axis PSF width; see Hasinger et al. 1994), high source column density (that decreases the detectable signal), and intrinsic source variability. For these sources, we included the flux values obtained from the literature.

3. THE RESULTS

A total of five dwarf galaxies ($M < 10^{9.3} M_\odot$, corresponding to $M_B > -17$ mag) were found to host a ULX in the present study. For comparison, there are a total of 35, 19, and 57 ULX candidates in the three (overlapping) subsamples described, respectively, in §§ 2.1–2.3. Within these subsamples there are 10, 58, and 91 dwarf galaxies, respectively. One new ULX candidate was discovered in a dwarf galaxy. This object was detected in the RASS image of E059–01 (PGC 21199), an IB(s)m dwarf of mass $1.7 \times 10^9 M_\odot$.

3.1. The Specific ULX Frequency

Histograms displaying the number of ULX candidates per unit mass, which we will refer to as the specific ULX frequency, against host galaxy mass were constructed for each subsample. The specific ULX frequency for the $i$th mass bin, $S_{i\nu}$, is defined as $N_i/M_{10}$, where $N_i$ is the number of ULX candidates detected in the $i$th galaxy, $M_{10}$ is that galaxy’s mass in units of $10^{10} M_\odot$, and the sum extends over all galaxies. Labels in the upper panels denote the number of ULX candidates predicted, $N(P)$, from extrapolation of the linear function to the next lower mass bin and scaling by the relative mass in that bin, $M_{10}$ (see text).

For comparison, there are a total of 35, 19, and 57 ULX candidates in the three (overlapping) subsamples described, respectively, in § 2.1–2.3. Within these subsamples there are 10, 58, and 91 dwarf galaxies, respectively. One new ULX candidate was discovered in a dwarf galaxy. This object was detected in the RASS image of E059–01 (PGC 21199), an IB(s)m dwarf of mass $1.7 \times 10^9 M_\odot$.

3.1. The Specific ULX Frequency

Histograms displaying the number of ULX candidates per unit mass, which we will refer to as the specific ULX frequency, against host galaxy mass were constructed for each subsample. The specific ULX frequency for the $i$th mass bin, $S_{i\nu}$, is defined as $N_i/M_{10}$, where $N_i$ is the number of ULX candidates detected in the $i$th galaxy, $M_{10}$ is that galaxy’s mass in units of $10^{10} M_\odot$, and the sum extends over all galaxies. Labels in the upper panels denote the number of ULX candidates predicted, $N(P)$, from extrapolation of the linear function to the next lower mass bin and scaling by the relative mass in that bin, $M_{10}$ (see text).

For comparison, there are a total of 35, 19, and 57 ULX candidates in the three (overlapping) subsamples described, respectively, in § 2.1–2.3. Within these subsamples there are 10, 58, and 91 dwarf galaxies, respectively. One new ULX candidate was discovered in a dwarf galaxy. This object was detected in the RASS image of E059–01 (PGC 21199), an IB(s)m dwarf of mass $1.7 \times 10^9 M_\odot$.
1.1 ULXs per unit SFR.

... the number of galaxies per bin are the same as in the bottom two leftmost panels of... IRAS... the specific ULX frequency deduced above...

... dwarf and giant galaxies in this subsample. However, the SFR per... to a linear function is not a significant improvement according to... (e.g., Kennicutt 1998). Here, L_FIR is the FIR luminosity estimated from the IRAS 60 and 100 μm flux densities, L_FIR/4πD^2 = 1.26 × 10^{-11} (2.58S_{60} + S_{100}) ergs s^{-1}. We have computed the star formation rate for the galaxies in the optical and FIR flux-limited subsample... mass bin increases toward higher mass bins so, again, the potential contamination is higher for the higher mass bins. Thus, any bias introduced by background sources applies in the opposite sense to the trend determined here, namely, that the specific frequency of ULXs increases with decreasing galaxy mass.

The probability of detecting transient sources increases with the rate of observations sampling a particular target galaxy. The present study does not differentiate between transient and non-transient ULX candidates but it can be surmised that the giant galaxies in the Local Volume are more apt to have been observed multiple times over the course of the decades spanned by the ROSAT, Chandra, and XMM-Newton missions than are the dwarf galaxies. Thus, any bias introduced by ULX transience would favor an increase in the number of ULX candidates discovered in giant over dwarf galaxies.

The nucleus regions of sample galaxies were not a priori excluded from our search for ULX candidates. However, X-ray-luminous active galactic nuclei may hide nearby ULXs in their bright glow, effectively imposing an exclusion region in the area of highest galactic surface mass density. As the brightest AGNs are associated with the most massive galaxies, ULXs hidden by AGN brilliance could lead to an underestimate of the ULX population in the higher mass bins. This is further exacerbated by the fact that the radial distribution of ULXs in general peaks toward the centers of galaxies (Swartz et al. 2004; Liu et al. 2006). A total of 18 galaxies in the present study are listed as quasars or AGN in the catalog of Véron-Cetty & Véron (2006). Of these, 11 host X-ray-bright nuclear sources (all are giant galaxies). Fortunately, all have been observed with Chandra so that a careful evaluation of the nuclear regions of these galaxies at high angular resolution could be made. No evidence was found for hidden ULXs; thus, no bias is apparent in the present results due to nuclear sources.

4. DISCUSSION

Ultraluminous X-ray sources occur in dwarf galaxies in the Local Volume; at least down to galaxy masses of ~3 × 10^8 M_☉. In fact, for the galaxies studied here, the specific frequency of ULXs in low-mass galaxies is higher than in massive giants. This trend in the population of ULXs is unanticipated.

Still, ULXs in dwarf galaxies are rare, of order one ULX per 10^{10} M_☉ in the galaxies studied here, which means one in only 100 10^6 M_☉ dwarf galaxy is expected to host a ULX. Five ULX candidates were identified in 118 dwarf galaxies (M < 10^{9.3} M_☉, corresponding to M_B > −17 mag) in the present study. Assuming the sample of galaxies was randomly selected, the Gehrels...
It is worthwhile to consider what physical differences exist between dwarf and giant galaxies that could give rise to the observed trend. Past studies have concluded that a strong correlation exists between star formation rate (SFR) and the number and luminosity density of ULXs (Swartz et al. 2004; Liu et al. 2006; although see Ptak & Colbert 2004). For the one subsample purposefully chosen here to include FIR-luminous galaxies, the specific current SFR in dwarfs is larger by a factor of 3 than in giants. Thus, an increase in the specific ULX frequency in dwarf galaxies relative to giants would be expected at least for this subsample.

There are also, potentially, differences in the stellar evolution and star formation processes in nearby dwarf galaxies compared to the giants that may favor the formation of ULXs. Dwarf galaxies tend to evolve more slowly than giants; hence their metallicity at the current epoch is systematically lower than that of giants (Lee et al. 2006). Massive stars of low metallicity lose less mass through winds than do high-Z stars and leave higher mass compact objects following core collapse (Heger et al. 2003). Higher mass black hole remnants, in turn, can radiate at higher luminosities without violating the Eddington limit. Low-Z donor stars may transfer more mass in Roche lobe overflow, and/or over a longer period of time, than do high-Z donors with high wind mass loss rates. This would allow higher luminosity and longer-lived ULXs to arise in low-Z systems.

Dwarf galaxies form massive star clusters at a rate higher than expected for their size. Billet et al. (2002) explain this as due to a lack of shear in dwarf galaxies that tends to fragment large molecular clouds and prevent formation of large stellar clusters in spiral galaxies. There may be a connection between an excess of massive compact clusters and an excess of ULXs in dwarf galaxies. Both objects may be the end products of rapid collapse of molecular clouds with the ULXs formed from the most massive stars created in the collapse. Gravitational coalescence of intermediate-mass protostars to form massive stars is observed in Galactic protoclusters (Peretto et al. 2007). The cold initial conditions (low turbulent energy relative to gravitational energy) needed for protostar merger are the same conditions envisioned by Billet et al. (2002) to explain the formation of massive clusters in dwarf galaxies. These conditions may result from rapid compression by external processes caused by galactic-scale interactions (e.g., Kato et al. 2005)—processes that are more effective in dwarfs because of their smaller size. Interestingly, Billet et al. (2002) conclude that the smallest galaxies cannot sample the high end of the cloud mass spectrum and that they will fail short of producing massive compact clusters. Perhaps a similar cutoff occurs in the production of ULXs and they are lacking in very low-mass galaxies.

We have determined that ULXs occur in dwarf galaxies and that their specific frequency increases with decreasing host galaxy mass. This suggests that there may be special (although not unique) environmental conditions in dwarf galaxies that preferentially lead to the formation of ULXs. This result should be addressed by theoretical models proposed to explain the ULX phenomenon.

This work was 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.

REFERENCES

Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., & Chester, T. J. 1988, NASA RP-1190 (Washington: GPO)

Billet, O. H., Hunter, D. A., & Elmegreen, B. G. 2002, AJ, 123, 1454

Colbert, E. J. M., Heckman, T. M., Ptak, A. F., Strickland, D. K., & Weaver, K. A. 2004, ApJ, 602, 231

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr. H. G., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (NewYork: Springer)

Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215

Gao, Y., Wang, Q. D., Appleton, P. N., & Lucas, R. A. 2003, ApJ, 596, L171

Geha, M., Blanton, M. R., Maji, M., & West, A. A. 2006, ApJ, 653, 240

Gehrels, N. 1986, ApJ, 303, 336

Gilfanov, M., Grinn, H.-J., & Sunyaev, R. 2004, MNRAS, 347, L57

Grinn-H., Gilfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793

Haines, C. P., Gargiulo, A., La Barbera, F., Mercurio, A., Merluzzi, P., & Busarello, G. 2007, MNRAS, 381, 7

Hasinger, G., et al. 1994, Legacy, 4, 40 (CAL/ROS/93-015)

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288

Hunter, D. A., & Gallagher, J. S. 1986, PASP, 98, 5

Irina, J. A., Bregman, J. N., & Athey, E. A. 2004, ApJ, 601, L143

Karachentsev, I. D., Karachentseva, V. E., Huchneiter, W. K., & Makarov, D. L. 2004, AJ, 127, 2031

Kenneicutt, R. C., Jr. 1998, ARA&A, 36, 189

Keto, E., Ho, L. C., & Lo, K.-Y. 2005, ApJ, 635, 1062

King, A. R. 2004, MNRAS, 347, L18

Lee, H., et al. 2006, ApJ, 647, 970

Lehmer, B. D., et al. 2006, AJ, 131, 2394

Liu, J.-F., Bregman, J. N., & Irwin, J. 2006, ApJ, 642, 171

Mukai, K. 1993, Legacy, 3, 21

Nilson, P. 1973, Uppsala General Catalogue of Galaxies (Uppsala: Astron. Obs.)

Peretto, N., Hennebelle, P., & André, P. 2007, A&A, 464, 983

Ptak, A., & Colbert, E. 2004, ApJ, 606, 291

Read, A. M., & Pietsch, W. 1999, A&A, 341, 8

Swartz, K. A., Ghosh, K. K., Tennant, A. F., & Wu, K. 2004, ApJS, 154, 519

Tennant, A. F. 2006, AJ, 132, 1372

Véron-Cetty, M.-P., Véron, P. 2006, A&A, 451, 851

Winter, L. M., Mushotzky, R. F., & Reynolds, C. S. 2006, ApJ, 649, 730

Zezas, A., & Fabbiano, G. 2002, ApJ, 577, 726