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On the association of ULXs with young superclusters: M82 X-1 and a new candidate in NGC 7479

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ABSTRACT
We investigate the spatial coincidence of ultra-luminous X-ray sources (ULXs) with young massive stellar clusters. In particular we perform astrometry on Chandra and HST data of two ULXs that are possibly associated with such clusters.

To date M82 X-1 is the only ULX claimed to be coincident with a young massive stellar cluster. We remeasure the position of this source with a high accuracy and find that the position of the X-ray source is 0.65 arcsec away from the stellar cluster, corresponding to an offset significance of 3 sigma.

We also report the discovery of a new candidate, based on observations of NGC 7479. One of the ULXs observed in three X-ray observations is found to be spatially coincident (within 1 sigma of the position error) with a young super-cluster observed in the HST images. In the brightest state, the absorbed luminosity of the ULX is a few times $10^{39}$ erg s$^{-1}$, and in the faintest state below the detection limit of $\sim$ 4 times $10^{39}$ erg s$^{-1}$. The luminosity in the brightest state requires an accreting black hole mass of at least $10^5$ M$_\odot$ assuming isotropic emission. However it is possible that the source is contaminated by X-ray emission from the nearby supernova SN2009jf. In this case the luminosity of the ULX is in a range where it is strongly debated whether it is a super-Eddington stellar mass black hole or an intermediate mass black hole.

The colours of the host cluster indicate a young stellar population, with an age between 10 and 100 Myr. The total stellar mass of the cluster is $\sim 5 \cdot 10^5$ M$_\odot$.

1 INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are defined as bright ($> 10^{39}$ erg s$^{-1}$) X-ray sources located off-centre in their host galaxies. Their luminosities are above the Eddington limit for a $\sim 10^5$ M$_\odot$ black hole (BH) assuming spherical accretion of hydrogen, approximately the highest mass expected from normal stellar evolution in a solar metallicity environment (e.g. Heger et al. 2003). It is possible that such luminosities are caused by beaming (King et al. 2001), or that systems achieve super-Eddington accretion (Begelman 2002, King & Pounds 2003). Alternatively, it means that the accreting objects are intermediate mass black holes (IMBHs) or super-massive black holes (SMBHs) formed through other processes than stellar evolution. The formation of such massive black holes is expected to take place in massive stellar clusters, where dynamical effects cause stars to sink to the centre (Ebisuzaki et al. 2001, Portegies Zwart & McMillan 2002). Alternatively, they can be formed in the central parts of the galaxy and be ejected by BH-BH interactions (recolliding SMBHS) (Bonning, Shields & Salviander 2007). In recent years a sample of extremely bright hyper-luminous X-ray sources (HLXs) have been observed with X-ray luminosities in excess of $10^{41}$ erg s$^{-1}$, the brightest of which is $> 10^{42}$ erg s$^{-1}$ (Farrell et al. 2009), strengthening the IMBH/SMBH interpretation, as such high apparent luminosities are very difficult to achieve through anisotropic radiation.

The birth environment of ULXs can provide important clues to their nature. Stellar mass black holes will be formed in any region with star formation, although their formation could be diminished in dense clusters due to the merger of their progenitors. On the other hand, intermediate mass black holes are believed to be formed from mergers of massive stars. They can therefore only be formed in the dense environment of young massive star clusters. It is therefore important to investigate the coincidence of ULXs with stellar superclusters. These clusters are the most massive young stellar clusters, with masses in excess of a few times $10^5$ M$_\odot$, and a very high specific stellar density. They are relatively rare and confined to galaxies with high star-formation rates (the Milky Way does not host any superclusters). Optical observations of a large number of ULXs have yielded only three possible associations. M82 X-1 is a ULX in M82 that has been associated with a cluster of mass of a few times $10^5$ M$_\odot$, and age of $\sim$ 10 Myr (Portegies Zwart et al. 2004). However, the astrometric accuracy of this study was low, and below we re-analyze the association and show that there is a significant offset between the X-ray source and the proposed host cluster. The other two ULXs are located in the Antennae galaxies (Zezas et al. 2006), but both were recently found to be located at distances of $\sim$ 0.6 arc-
sec from the stellar clusters \cite{Clark2011}, corresponding to an offset significance of 2-3 sigma. This does not mean that the three ULXs are not related to the stellar clusters, but rather that they were most likely ejected from these relatively recently.

Other luminous sources have been claimed to be compatible with the position of a young cluster, but none have a color consistent with stellar ages below 10^8 years \cite[e.g.][]{Ptak2006}. In general ULXs are predominantly found in regions with high star-formation rates \cite[IFS1](Irwin, Bregman & Athey 2004) and low metallicities \cite[Pakull & Mirioni 2003; Zampieri & Roberts 2009; Mapelli et al. 2010]. Observations of individual ULXs have found associations also with relatively poor stellar clusters \cite{Gris2008}, and in some cases with large super-bubbles in the ISM \cite{Pakull2003}. This clearly shows that ULXs are related to young stars, with ages of tens to a few hundred Myr. However, a number of ULXs have been found to reside in globular clusters \cite[Maccarone et al. 2007, 2011]. These are likely BHs created during the early evolution of the globular clusters.

\section{REVISITING M82 X-1}

The only other ULX that has been found to be spatially coincident with a massive young cluster is M82 X-1, which is claimed to be associated with the stellar cluster MGG-11 \cite{Clark2011}. This was based on an analysis with an astrometric accuracy of \sim 1 arcsec \cite{PortegiesZwart2004}. Motivated by the results presented above, we revisit the astrometry of this source. The region is covered well both by \textit{Chandra} and \textit{HST}. We select the two deepest archival \textit{Chandra ACIS} observations of M82 X-1 \cite[10542 and OBSID 10543]. With \sim 120 ks of exposure in each, they are deep enough to obtain a precise astrometric solution. We have compared them to the existing \textit{HST} images in the vicinity of M82 X-1, and we find no secure matches that can be used for a direct registration of the images. Instead we register the X-ray images to \textit{Sloan Digital Sky Survey data release 4} \cite[SDSS], with 6 (5) matching sources in OBSID 10542 (10543). The results from the two observations agree within 0.05 arcsec, and we use the position from OBSID 10542 in the following. We choose two \textit{HST} observation sets that both have clear SDSS matches and where MGG-11 is clearly observed. Archival NICMOS F160W images obtained in April 1998 were used for the original matching \cite{Mccrady2003, PortegiesZwart2004}, and three matches are found in SDSS. As an alternative we used archival WFC3 F110W images obtained November 2009. For these we find four SDSS matches (of which only two are the same as in the NICMOS images). Again the positions agree within 0.05 arcsec. Based on these, we translate the position of M82 X-1 into the \textit{HST} images with a precision \sim 0.2 arcsec. The results are shown in figure \ref{fig1}. We find that MGG-11 is located \sim 0.65 arcsec south of M82 X-1 and that the positions are inconsistent at the 3 sigma level.

\section{A NEW CANDIDATE IN NGC 7479.}

NGC 7479 is located at a distance of 33 Mpc \cite[We adopt a distance modulus of 32.65, assuming a radial velocity corrected for infall onto Virgo of 2443 km s^{-1} and a Hubble constant of 72 km s^{-1} Mpc^{-1}]{McCrady2003}. It is a barred spiral galaxy \cite{Sandage1987} and contains a number of superclusters \cite[e.g.][]{Zurita2001} seen in \textit{HST} images. NGC 7479 has been observed two times with \textit{Chandra} and two times with \textit{XMM-Newton}. It hosts several ULXs and we find that one of them is spatially coincident with a supercluster. The source is currently not found in the \textit{Chandra Source Catalog}, and we label it CXOU J230453.0+121959 according to the \textit{Chandra naming convention} \cite based on the position of the source.

\subsection{The position of the source.}

The absolute astrometry of both the \textit{Chandra} and the \textit{HST} images are uncertain at the \sim 1 arcsec level. We have therefore searched for sources that are both observed in X-rays and in the optical, and have a reliable position in both. One such source exists, a bright foreground star. While this is clearly not an ideal case, the distance of the reference source to ULX CXOU J230453.0+121959 is relatively small (\sim 23 arcsec), and it is therefore possible to use it to precisely match the X-ray images to the \textit{HST} images. We use the \textit{HST ACS WFC F814W} image j135+53020 for the matching. As both the \textit{HST} and the \textit{Chandra} images are well-calibrated, we assume that there is no distortions between the two images, and the rotation of the \textit{HST} image was corrected using \textit{2MASS} counterparts. The positions of the \textit{Chandra} images were then shifted to match the reference source in the \textit{HST} image. In figure \ref{fig1} we show the position of the X-ray source on the \textit{HST} image. The thick black circle indicate the position found from \textit{Chandra OBSID 11230} (having the best statistics), and an the thin red circle indicates the position found from \textit{Chandra OBSID 10120}. The size of the circles indicate the statistical error on the position of the X-ray source and the boresight correction (\sim 0.3 arcsec). The positions of the stellar cluster and the ULX are consistent within the 1 sigma confidence limits. The ULX is therefore most likely related to the cluster, even if it could likely be located outside of it (similar to the other three ULXs discussed above). An older set of \textit{HST WFPC2} observations cover the same region. Comparison with these shows that the foreground reference star has a small proper motion \sim 0.01 arcsec per year. The \textit{HST ACS} images used for the matching are taken \sim 1 year ago.

1 http://www.sdss3.org/ 2 http://cxc.harvard.edu/cdo/scipubs.html#NAME
after the X-ray observations, and the error due to this is therefore negligible.

We have verified the position using other optical intermediate images/catalogues, covering larger areas. These have therefore more matching sources, but are less precise. The maximum number of matching sources found was 4 comparing the 11230 X-ray source list with 2MASS. This yields a position 0.2 arcsec directly north of the position found from the direct HST matching using OBSID 10120 (red circle in figure 2), with an error of ~ 0.5 arcsec.

3.2 The properties of the supercluster

Below we summarize the important parameters of the cluster. The metallicity of the surrounding region is found to be between solar and LMC (Valenti et al. 2011), and for estimating the physical parameters we assume a metallicity of Z = 0.012. The super-cluster is observed in two archival HST WFPC2 images taken with the F569W and the F814W filters (similar to the V and I band filters, respectively). The analysis of Valenti et al. (2011) gives VEGA magnitudes, corrected for Galactic extinction, of $M_{F569} = 19.84$ and $M_{F814} = 19.46$ (absolute magnitudes $M_{F569} = -12.81$ and $M_{F814} = -13.19$). Unfortunately the two bands are not very useful for inferring the age of the stellar association. A comparison of the colours with simple stellar population models (Girardi et al. 2000, Marigo et al. 2008) gives an age between 10 and 100 Myr. The total mass of the stellar population depends on the age and is between $7 \times 10^7 M_\odot$ and $1.8 \times 10^8 M_\odot$. From the HST ACS WFC F814 image jbu4u53020, we find that half of the mass is contained in a single unresolved central cluster. The rest of the mass belongs to a collection of smaller clusters scattered along the SW-NE axis. We note that while the surrounding conglomerate of clusters is also young, but not necessarily co-eval with the super-cluster. One pixel corresponds to 8 pc and the PSF FWHM is ~ 20 pc at the distance of NGC 7479. This is smaller than the typical distance between individual clusters in OB associations (e.g. Reipurth 2008a,b), and the central cluster is therefore unlikely to be a conglomerate of smaller clusters. However, with the current spatial resolution, it is not possible to say whether the central cluster is compact enough to be expected to form an IMBH (Portegies Zwart et al. 2004).

3.3 The X-ray properties of the source

In the two Chandra observations, the source is bright enough to extract the spectra, but the number of counts in the best observation is only ~ 120. We therefore use the Cash-statistics for spectral fitting with minimum 5 counts in each bin (needed for the Cash statistics to provide a reliable goodness-of-fit estimate). For both observations a simple absorbed power-law provides a good fit to the spectra, but both the slope and the absorbing column is poorly constrained. We therefore fix the absorption to the Galactic foreground value of 5.1 × 10^20 cm$^{-2}$ (Dickey & Lockman 1990). There is evidence for a varying spectrum, with a best-fit power-law slope of 1.73 ± 0.19 in OBSID 11230 and 1.13 ± 0.19 in OBSID 10120. However, the significance of this is marginal ≥ 2σ. As the spectral models are poorly constrained, it is not possible to infer the unabsorbed luminosities, and we instead characterize the sources by their absorbed luminosities, and we instead characterize the sources by their absorbed luminosities, noting that absorption is often important in ULXs, so the unabsorbed luminosities might be several times higher. The luminosity of the source is clearly different in the two observations, being $1.4 \pm 0.29 \times 10^{39}$ in the later observation and $5.0 \pm 1.0 \times 10^{39}$ erg s$^{-1}$ in the earlier, but well above the Eddington limit of a typical stellar mass black hole in both observations.

Two XMM-Newton observations from 2001 (OBSID 0025541001) and 2005 (OBSID 0301651201) cover the same region. The source is not detected through the standard data processing (PPS source lists), but a low-significance source is apparent in the 2001 observation. No source is visible by eye in the 2005 observation. There is a nearby brighter source, and contamination is therefore a serious issue. We therefore perform photometry using an encircled energy fraction of 50 per cent. The source is detected with a (corrected) EPIC PN (medium filter) count rate of 0.010 cts s$^{-1}$ in observation 0025541001, corresponding to an absorbed luminosity of ~ 3.6 ± 0.9 × 10^{39} erg s$^{-1}$, assuming the spectral shape found in Chandra OBSID 11230. There is no source in observation 0301651201. There we determine the 3σ upper limit on the EPIC PN (thin filter) count rate to be 0.012 cts s$^{-1}$, corresponding to an absorbed luminosity of 4.2 ± 10^{39} erg s$^{-1}$.

ROSAT covered the region in the all-sky survey, but not with any pointed observations. CXOU J230453.0+121959 was not detected in the survey, but neither were nearby brighter ULXs.
4 DISCUSSION

Out of the several hundred currently known ULXs (Liu & Mirabel 2005; Walton et al. 2011), only four (including CXOU J230453.0+121959) have been associated with young massive stellar clusters. The two Antennae ULXs have been shown to be displaced from the stellar clusters (Clark et al. 2011), and above we have shown that this is also the case for M82 X-1. We have found a new ULX, CXOU J230453.0+121959, that is associated with a supercluster. However, the displacement found for the other three ULXs is also possible for this new ULX. Below we first discuss the possible relation between CXOU J230453.0+121959 and SN2009jf, and then we discuss the implications of the low number of ULXs found in clusters and their displacement.

4.1 Is the ULX related to supernova SN2009jf?

The latest X-ray observation, Chandra OBSID 10120 is taken shortly after the explosion of the type Ib supernova SN2009jf at a distance of ~0.3 arcsec from the position found from Chandra OBSID 11230. The luminosity of the ULX is much higher in this observation, compared to the three other X-ray observations. In some cases type Ib/c supernovae have been shown to be very bright in X-rays (up to ~10^{40} erg s^{-1} Sutaria et al. 2003; Chevalier & Fransson 2006; Immler et al. 2008) within the first months after the supernova explosion, comparable to (but never as bright as) the observed luminosity of ULX CXOU J230453.0+121959 in Chandra OBSID 10120. This could indicate that the brightness is actually caused by the supernova explosion. This is also consistent with the hardening of the spectrum, which is opposite to the behaviou seen in most ULXs (although some ULXs do show such transitions Fabbiano et al. 2003). However, the luminosity changes seen in ULX CXOU J230453.0+121959 are common in other ULXs (Fabbiano et al. 2003), and the spectrum is still softer than what is typically seen shortly after the supernova explosion (Chevalier & Fransson 2006).

A chance superposition is not unlikely, given that the large area covered by the error region of an X-ray source at this distance, and the fact that CXOU J230453.0+121959 and SN2009jf might have been born in the same cluster (or at least in the same association of clusters). It is even possible that CXOU J230453.0+121959 could be related to SN2009jf. Indeed it is believed that some type Ib supernovae come from binaries (Podsiadlowski, Joss & Hsu 1992), where a massive progenitor star transfers mass to a neutron star or a black hole, causing the emission of X-rays. Indeed such a candidate progenitor was proposed for the type Ib supernova SN2010O (Nelemans et al. 2010). The connection between ULXs and star-forming regions (Irwin, Bregman & Athey 2004) indicates that the donor stars in ULXs are high-mass stars transferring mass to a BH, similar to the class of supernova type Ib with HMXB progenitors.

We note that both if CXOU J230453.0+121959 is related to SN2009jf and if not, the short distance to the supercluster is interesting. The discussion below is valid in both cases.

4.2 Single star remnant

If the ULX is the remnant of a single star, the radiation would either have to be beamed, or the BH mass would have to be very high. At low metallicities (\(\lesssim 0.4Z_\odot\)) mass loss from the massive star progenitors of black holes is expected to be inefficient Maeder 1992, Heger et al. 2003, Vink & de Koter 2005. This can lead to very high core masses at the end of their life, and they can therefore form black holes with masses up to \(\sim 100M_\odot\). It is therefore possible to form ULXs through normal binary evolution, without invoking beamed radiation. However, the environment of CXOU J230453 is found to have a metallicity only slightly below solar, and if the current understanding of stellar evolution is correct, it is not possible to form black holes more massive that \(\sim 15M_\odot\) in this environment Heger et al. 2003.

The continued detection of the source at luminosities above few times \(10^{39} \text{erg s}^{-1}\) over several years shows that it is not a short super-Eddington outburst. The highest reliable (ignoring the possibly contaminated observation) observed absorbed X-ray luminosity is \(5 \cdot 10^{39} \text{erg s}^{-1}\). It is difficult to extrapolate this, in particular since there are no real constraints on the absorbing column, but the bolometric luminosity is likely \(\gtrsim 2\) times the X-ray luminosity in the Chandra energy band. Sources emitting at super-Eddington luminosities are known in the Milky Way. GRS1915+105 has been found to occasionally reach a luminosity in excess of \(7 \times 10^{39} \text{erg s}^{-1}\) Greiner, Morgan & Remillard 1998, similar to CXOU J230453.0+121959, and the black hole accretor is 14M_\odot Greiner, Cuby & McCaughrean 2001. However, the duration of this very bright state is only \(\sim 10\) s, and the average luminosity over a few hours around this state is a factor of \(\sim 3\) lower. From the RXTE ASM lightcurve we find that GRS1915+105 spends less than 1 per cent of the time at luminosities above \(10^{39}\) erg s^{-1}, and is therefore not a good comparison for CXOU J230453.0+121959 and similar ULXs.

As discussed above the association of ULXs with massive clusters is rare. Also HMXBs with sub-Eddington luminosities are rarely found in clusters (e.g. Kaaret et al. 2004). There are two reasons for this. Less dense clusters can dissolve before the formation of HMXBs, and most HMXBs are ejected from their host clusters, either due to the high velocities imparted by the supernova explosion, or due to dynamical interactions in the cluster.

4.3 IMBH

In this scenario stellar interactions in a dense cluster causes the massive stars to fall to the center on a timescale that is shorter than their evolutionary timescale. Once accumulated there, they collide and form a massive “runaway star”, which most likely collapses directly into a black hole without significant mass loss Ebisuzaki et al. 2001, Portegies Zwart & McMillan 2002. It should be noted that the evolution of such massive stellar objects is highly uncertain, and it is therefore not clear that an IMBH is actually formed in this way. To become a ULX the black hole must capture a companion star, which is natural in the dense environment in the centre of the cluster. In this scenario it is therefore natural to find a ULX associated with a massive cluster. However, several hundred ULXs are known (e.g. Liu & Mirabel 2005) only four are possibly related to massive young clusters, and of these CXOU J230453.0+121959 is the only one that could still be inside the cluster. In the IMBH scenario, it is hard to explain why so few ULXs are associated with clusters, as they are dense enough to remain bound (and evolve into globular clusters). It is possible that most of the IMBHs are ejected from the clusters. The short distances (<few tens of pc) to the clusters makes this a likely explanation for M82 X-1, and the two Antennae ULXs, and also CXOU J230453.0+121959 if it is found to be outside the cluster. Such distances can be reached within a Myr, even with moderate velocities of tens of km s^{-1}. Once ejected the IMBHs are unlikely to capture companion stars, and they must therefore accrete from companion-
ions that were ejected together with the IMBHs from the clusters. On the other hand, the observations of ULXs in globular clusters (Maccarone et al. 2007, 2011) indicates that some IMBHs might be retained in these clusters. If these indeed are IMBHs, it is puzzling why they are not seen in the early phases of the clusters.

5 CONCLUSIONS

We have re-analyzed the position of M82 X-1 and found that the X-ray source is offset from the cluster with a confidence of 3 sigma. We have also identified a new ULX, CXOU J230453.0+121959, that is associated with a young massive supercluster of a mass \( \sim 10^9 \, M_\odot \). The X-ray source is observed three times over 9 years with Chandra and XMM-Newton, but is probably contaminated by SN2009jf in the last observation. CXOU J230453.0+121959 is therefore the currently best candidate for a ULX inside a massive young cluster. The rarity of observing ULXs inside massive clusters makes it unlikely that most ULXs are formed inside clusters, unless they are kicked out of the clusters at birth.

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