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X-ray sources in dwarf galaxies in the Virgo cluster and the nearby field

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ABSTRACT

The extent to which dwarf galaxies represent essentially scaled down versions of giant galaxies is an important question with regards the formation and evolution of the galaxy population as a whole. Here, we address the specific question of whether dwarf galaxies behave like smaller versions of giants in terms of their X-ray properties. We discuss two samples of around 100 objects each, dwarfs in the Virgo cluster and dwarfs in a large Northern hemisphere area. We find nine dwarfs in each sample with *Chandra* detections. For the Virgo sample, these are in dwarf elliptical (or dwarf lenticular) galaxies and we assume that these are (mostly) low-mass X-ray binaries (LMXB) [some may be nuclear sources]. We find a detection rate entirely consistent with scaling down from massive ellipticals, viz. about one bright (i.e. $L_X > 10^{38}$ erg s⁻¹) LMXB per $5 \times 10^9 M_\odot$ of stars. For the field sample, we find one (known) Seyfert nucleus, in a galaxy which appears to be the lowest mass dwarf with a confirmed X-ray emitting nucleus. The other detections are in star-forming dwarf irregular or blue compact dwarf galaxies and are presumably high-mass X-ray binaries (HMXB). This time, we find a very similar detection rate to that in large late-type galaxies if we scale down by star formation rate, roughly one HMXB for a rate of 0.3 M_\odot per year. Nevertheless, there does seem to be one clear difference, in that the dwarf late-type galaxies with X-ray sources appear strongly biased to very low metallicity systems.

Key words: surveys – galaxies: clusters: individual: Virgo – galaxies: dwarf – X-rays: binaries.

1 INTRODUCTION

Dwarf galaxies are numerically dominant but harder to study compared to their higher luminosity counterparts. There exist many correlations between luminosity (or mass) and other galaxy properties, and the extent to which dwarfs represent scaled down versions of high-mass giants – or whether perhaps stochastic effects dominate – has implications for many areas of the study of galaxy formation and evolution

In this paper, we consider what X-ray observations of dwarf galaxies can tell us in this regard. In galaxies in general, ignoring diffuse emission from interstellar gas (e.g. Grimes et al. 2005; Mineo, Gilfanov & Sunyaev 2012b), we can expect reasonably bright sources to be primarily due to active galactic nucleus (AGN) [i.e. supermassive black holes; SMBH], high-mass X-ray binaries (HMXBs), and low-mass X-ray binaries (LMXBs), each reflecting different aspects of the build-up of galaxies' structure and stellar content, and we assume that the same should be true in dwarfs.

It is now thought that all giant galaxies contain SMBH. The Magorrian relation between BH mass and host spheroid (elliptical

galaxy or spiral bulge) mass (Magorrian et al. 1998), and the corresponding one between BH mass and stellar velocity dispersion (e.g. Merritt & Ferrarese 2001), further indicates a close connection (often referred to as co-evolution) between the build-up of the black hole – presumably by merger between, or accretion on to, existing BHs – and of the stellar mass itself (e.g. Haehnelt 2004). In addition, semi-analytic models of galaxy formation and evolution require the presence of an AGN to provide sufficient feedback to prevent an excess of very high luminosity galaxies (e.g. Bower, Benson & Crain 2012).

On the other hand, the models usually invoke alternative mechanisms to prevent the overproduction of low-luminosity galaxies, so the linkage between BH mass and galaxy mass is not so clear for objects at this end of the mass function. Observationally, known AGN, even low-luminosity ones, are quite rare in dwarf galaxies (Greene & Ho 2007; Gallo et al. 2008), though see Reines, Greene & Geha (2013) for a recent larger sample. If we simply scale down those seen in giant early-type galaxies via a standard Magorrian-type relation, this is not perhaps surprising, as it suggests that even a reasonably bright dwarf elliptical (dE) galaxy of luminosity $\sim 5 \times 10^7$ to $5 \times 10^8 L_\odot$ (magnitude $M_r \sim -14.5$ to -17) should only have an SMBH of mass $\sim 10^5$ – $10^6 M_\odot$ (Gallo et al. 2008; Reines et al. 2013). In fact, it has been suggested (e.g. Ferrarese et al. 2006b,

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Wehner & Harris (2006) that at low masses, galaxies actually contain nuclear star clusters rather than SMBH, though Seth et al. (2008) and Graham & Spitler (2009) have noted a small population of dwarf galaxies that are observed to contain both. Conventionally, AGN searches such as this have been performed optically, via the characteristic emission lines (e.g. Decarli et al. 2007; Reines et al. 2013). Here, we follow Seth et al. (2008) and Gallo et al. (2008) and complement this with a search for nuclear X-ray emission. If we can again scale down the emission from larger galaxies, we expect X-ray luminosities $\sim 10^{38}$ erg s $^{-1}$ (Dudik et al. 2005; Panessa et al. 2006).

LMXBs are found in old stellar populations in galaxies and approximately trace the number of old stars, with roughly one bright LMXB (above 10^{38} erg s $^{-1}$) per $5 \times 10^9 M_{\odot}$ of stellar mass in giant galaxies (e.g. Boroson, Kim & Fabbiano 2011). Globular clusters show much higher rates of LMXBs (by factors of 100 or more, e.g. Sarazin et al. 2001) – probably because of their high star densities (e.g. Jordan et al. 2007) – with of the order of 10 per cent of large globulars, mass $\sim 10^6 M_{\odot}$, containing detectable LMXB at the same flux levels (Kim et al. 2006; Humphrey & Buote 2008). Little is known about the LMXB content of dwarf galaxies, though in a previous paper (Phillipps et al. 2013) we found that they are much rarer in ultracompact dwarfs (UCDs) than in globular clusters of almost comparable masses. If LMXBs are equally prevalent (per unit stellar mass) in dwarf as in giant ellipticals (perhaps because of similar stellar initial mass functions and/or star formation processes), then at least some dEs in the same range as above $M_r \sim -14.5$ to -17 (significantly brighter than UCDs) should be expected to contain them. This provides the second part of our search.

HMXBs, on the other hand, come from short-lived stars and hence reflect recent star formation (Grimm, Gilfanov & Sunyaev 2003). From Mineo, Gilfanov & Sunyaev (2012a), the conversion between the number of HMXBs and the star formation rate (SFR) implies that on average there are 3.2 bright ($> 10^{38}$ erg s $^{-1}$) HMXBs for an SFR of $1 M_{\odot}$ yr $^{-1}$. We can therefore check that the same applies in dwarf galaxies, in order to investigate whether the results of the star formation processes are consistent with those in higher mass objects.

The rest of the paper is divided up as follows. Section 2 describes the dwarf galaxy samples which we use, one in the Virgo cluster and one in a large surrounding field area, but which still samples primarily galaxies in a similar distance range. We present the X-ray data used and the sources detected which are coincident with our dwarf sample in Section 3. Section 4 summarizes the results.

2 DWARF GALAXY SAMPLES

2.1 Virgo dwarfs

For our starting sample of Virgo Cluster dwarfs, we have taken the 1055 galaxies in the Virgo Cluster Catalog (VCC) of Binggeli, Sandage & Tammann (1985) which the original authors classified as dE, dE,N (nucleated dwarf elliptical), dwarf spiral, dS0 (dwarf lenticular), Im (Magellanic irregular) or BCD (blue compact dwarf), and flagged as definite cluster members. As the VCC coordinates are not always particularly accurate, we checked Sloan Digital Sky Survey (SDSS) imaging at the reported positions and corrected these to the centres of the corresponding SDSS galaxies from DR8¹ (Aihara et al. 2011); clearly we need accurate centre positions if

we are to confirm nuclear emission, in particular. In a few cases, the VCC positions appeared to be significantly in error so we took the position to be that of the nearest dwarf-looking object visible on the SDSS image. We also checked all our positions visually on the ALADIN Sky Atlas² to ensure that the nearest SDSS match was consistent with the appearance of VCC cluster dwarfs (not a much smaller, probably background, object). If there were two plausible matches, we selected the one whose diameter better matched that in the VCC. A handful of VCC objects were rejected from our sample as we could not be certain of the matching SDSS galaxy (if any). In cases where an SDSS spectrum existed, we also checked that the redshift was consistent with Virgo cluster membership. This led to the rejection of some further galaxies. Finally, we searched for archival *Hubble Space Telescope* (HST) data to provide high-resolution images.

2.2 Field dwarfs

As an additional sample, and in order to obtain a different mix of dwarf types (dEs being predominant in clusters), we also searched the entire Northern hemisphere portion of the SDSS spectroscopic sample (excluding Virgo) for emission line dwarfs. In this case, we chose all SDSS DR7 galaxies with calculated absolute magnitudes (from the SDSS ‘modelmag’) fainter than $M_r = -16$ (we assume $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$) and with a significant measurement of at least one emission line (from [O III]5007, N II6585, H α , and H β). This gave a sample of 2869 ‘field’ dwarfs and will include star-forming dwarfs and any which possess AGN. In fact, some are non-central or ‘broken off’ parts of larger galaxies and we examined these manually. We then checked the remainder for their classification and kept all late-type spirals (Sd onwards) and irregulars (including BCD), which left 2421. Because of the relatively bright limiting magnitude for the SDSS spectroscopic surveys, these dwarf galaxies are all at low redshifts, and in fact tend to be at rather similar distances to the Virgo galaxies.

3 X-RAY OBSERVATIONS

3.1 Data

For the X-ray data we use that provided by the *Chandra* Data Archive.³ We initially downloaded all the available archival observations in an 8 $^{\circ}$ radius circle centred on M87. Not all the cluster area has been observed by *Chandra*, so the first step was to check, for each VCC dwarf that survived the cuts described above, whether there existed observations in which our target galaxy position (obtained as above) was in the detector footprint. Since the source detection sensitivity decreases with off-axis angle, we only consider galaxies within 7 arcmin of the aim point. We have also ignored observations shorter than 2 ks. For galaxies with multiple *Chandra* observations, the observations were analysed individually so that the `srcflux` tool could be used to measure fluxes and upper limits. These were then co-added to ensure that no sources had been missed. Data analysis was performed using standard CIAO tools (Fruscione et al. 2006). This provided data covering the positions of 119 Virgo dwarf galaxies.

We searched around our target positions over a region covering the optical extent of each of the dwarf galaxies, as we were not

¹ www.sdss3.org/dr8

² aladin.u-strbsb.fr/java/nph-aladin.pl

³ <http://cda.harvard.edu/chaser/>

looking only for sources at the centres of galaxies. As well as running `wavdetect` on our fields, all of the *Chandra* fields were examined by eye for potential counterparts to the galaxies of interest. We then used essentially the same method as described in Phillipps et al. (2013), with X-ray counts determined in apertures of radius appropriate to the point spread function at the position of the X-ray source, using the CIAO routine `srcflux` (see the CIAO imaging analysis threads on the *Chandra* website⁴).

The significance of any possible detection was determined using `wavdetect` with a requirement that the significance be larger than 4σ . Upper and lower limits to source fluxes, or upper limits on non-detections, were determined using `srcflux`. The errors reported for the detected galaxies are 90 per cent confidence limits (roughly 1.7σ errors).

Though exposure times and hence detection limits vary, we find limits of $7 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ or better for virtually all (98 per cent) of our target positions. Approximately 70 per cent have detection limits $\leq 3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$.

The corresponding X-ray luminosities were calculated with an assumed distance to Virgo of 16.5 Mpc. The limit of $3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ then corresponds to our standard ‘bright’ source of $10^{38} \text{ erg s}^{-1}$. In addition to the statistical errors listed, different assumed spectral slopes or absorbing columns will cause further uncertainties in the X-ray luminosities at the 10–20 per cent level. (In our modelling, we take $\Gamma = 1.8$ and use a total column density, primarily from the foreground Galaxy, of $2.5 \times 10^{20} \text{ cm}^{-2}$, which is typical of the region).

Positions for the X-ray sources are as given by `wavdetect`. The astrometric uncertainties include contributions both from the photon statistics, $\simeq 0.2 \text{ arcsec}$ at our 4σ detection levels (see Gallo et al. 2008) and from systematic ‘bore sight’ corrections for each *Chandra* observation, $\simeq 0.4 \text{ arcsec}$ (Zhao et al. 2005). SDSS astrometric uncertainties are $\simeq 0.1 \text{ arcsec}$, implying an overall uncertainty in position cross-matching of $\simeq 0.5 \text{ arcsec}$. In the one case where we have a known AGN, the difference between the X-ray and optical derived centres is 0.4 arcsec , consistent with this expectation.

For the Northern hemisphere field sample, we checked for any *Chandra* observations covering the centre of each galaxy, which reduced the potential sample to 779. Requiring the target galaxy to be less than 7 arcmin off-axis in the *Chandra* observation further reduced this to our final list of 98 galaxies. X-ray sources were again searched for over the optical extent of each galaxy. We then carried out exactly the same procedure for these field areas as we did for the Virgo sample, except that luminosities for these objects were calculated from their individual (flow corrected) SDSS redshifts, and the total absorbing columns are lower, $\sim 1\text{--}1.5 \times 10^{20} \text{ cm}^{-2}$. (The intrinsic absorbing columns in the target galaxies are likely to be low, but uncertain.)

3.2 X-ray Detections: Virgo

Within the 119 Virgo galaxies covered by *Chandra* observations, we find nine significant (4σ) X-ray detections. These are listed in Table 1. Their X-ray luminosities (for energies 0.5–7 keV) range from $\sim 5 \times 10^{37}$ to $2 \times 10^{39} \text{ erg s}^{-1}$. Five have previous identifications in the Chandra Source Catalog (CSC;⁵ Evans et al. 2010).

The significant X-ray detections are all dE and dS0 galaxies (the dominant population, both in Virgo as a whole and in our observed

Table 1. X-ray detections in Virgo. Galaxy classification is from Binggeli et al. (1985). a_{iso} is the r -band isophotal (major axis) radius from SDSS in arcsec. *VCC 795 is covered by ObsIDs 8055, 13295, 15783, 16476, 16477, 17558, and 17559. S is the offset of the X-ray source from the nominal galaxy centre in arcsec (see text for further discussion).

VCC	Other name	Type	SDSS			Chandra			Flux (cgs)	L_X (cgs)	S (arcsec)	
			RA	Dec.	M_r	ObsID	RA	Dec.				
751	IC3292	dS0	12:24:48.36	18:11:42.43	-16.9	31.2	8103	12:24:48.44	18:11:41.12	$3.4^{+4.0}_{-2.3} \times 10^{-15}$	$1.1^{+1.3}_{-0.7} \times 10^{38}$	1.7
795		dE ₁ N	12:25:23.16	14:48:12.50	-14.3	16.8	*	12:25:23.16	14:48:12.39	$5.0^{+5.3}_{-2.3} \times 10^{-15}$	$1.6^{+1.1}_{-0.7} \times 10^{38}$	0.1
833		dE ₁ N	12:25:44.64	13:01:19.57	-14.9	13.0	15149	12:25:44.66	13:01:19.94	$1.7^{+0.8}_{-0.6} \times 10^{-15}$	$5.6^{+2.6}_{-2.0} \times 10^{37}$	0.5
914		dE ₁ N	12:26:34.31	08:59:35.16	-12.8	8.1	2982	12:26:34.32	08:59:35.57	$3.3^{+1.5}_{-1.2} \times 10^{-15}$	$1.1^{+0.5}_{-0.4} \times 10^{38}$	0.4
1087	IC3381	dE ₁ N	12:28:14.88	11:47:23.39	-17.6	46.2	8078	12:28:14.63	11:47:18.01	$2.6^{+1.0}_{-0.8} \times 10^{-14}$	$8.4^{+3.3}_{-2.6} \times 10^{38}$	6.5
1348	IC3443	dE ₁ N	12:31:15.73	12:19:54.37	-16.6	21.4	11783	12:31:15.75	12:19:53.78	$1.5^{+1.1}_{-1.0} \times 10^{-15}$	$5.0^{+3.7}_{-3.3} \times 10^{37}$	0.6
1355	IC3442	dE ₁ N	12:31:20.19	14:06:54.72	-16.7	35.4	8077	12:31:20.19	14:06:54.95	$6.7^{+5.2}_{-3.4} \times 10^{-15}$	$2.2^{+1.7}_{-1.1} \times 10^{38}$	0.2
1431	IC3470	dE ₁ N	12:32:23.39	11:15:46.69	-17.5	29.1	8081	12:32:23.34	11:15:46.63	$1.4^{+1.3}_{-0.8} \times 10^{-14}$	$4.6^{+4.4}_{-2.7} \times 10^{38}$	0.8
1779	IC3612	dS0	12:39:04.70	14:43:52.07	-16.5	35.4	8091	12:39:04.78	14:44:00.40	$5.2^{+1.8}_{-1.5} \times 10^{-14}$	$1.7^{+0.6}_{-0.5} \times 10^{39}$	8.4

⁴ <http://cxc.harvard.edu/ciao/>

⁵ <http://cda.cfa.harvard.edu/cscview/cscview>

sample). All the dEs are nucleated. This is not surprising as the detections are nearly all among the optically brighter dEs, which almost always possess nuclei (e.g. Grant, Kuipers & Phillipps 2005). In the following, we briefly discuss each of the nine firm detections individually. Other details are given in Table 1. Note that all the X-ray sources lie within 9 arcsec, or ~ 700 pc, of the galaxy centres.⁶

VCC 751

The CSC contains a source within VCC 751, with the reported flux somewhat lower, but still consistent with our value. It is also a source in the Second XMM-Newton Serendipitous Source Catalog (2XMM). The SDSS spectrum at the centre of VCC 751 shows no measurable emission lines (though the fibre would just miss the position of the X-ray source, 1.7 arcsec from the galaxy centre) and is consistent with that of a standard old stellar population. This is one of the dwarf galaxies in which Seth et al. (2008) found both a nuclear star cluster (see also Coté et al. 2006) and an X-ray source close to the centre but, like us, they found the X-ray source to be slightly offset from the galaxy centre and saw no optical emission lines, so were unable to classify it as an AGN. Their X-ray luminosity of 1.6×10^{38} erg s⁻¹ is in good agreement with ours. Gallo et al. (2008, 2010), on the other hand, do not detect an X-ray source, perhaps because they were searching only for emission coincident with the nucleus or because its flux was just below their detection threshold ($\simeq 2 \times 10^{38}$ erg s⁻¹).

VCC 795

This is an otherwise unremarkable faint dE,N galaxy included in the Impey, Bothun & Malin (1988) list of low surface brightness Virgo galaxies. It is only 3.6 arcmin ($\simeq 18$ kpc in projection) away from NGC 4377, which has a number of other close companions. VCC 795 has been included in several separate *Chandra* observations, which we have co-added. The X-ray source, which appears not to have been reported previously (some of the observations are only recently released), is very close to the centre (nucleus) of the galaxy. (The individual observations all give positions within 0.5 arcsec of the centre, consistent with astrometric matching limits estimated above.) However, the SDSS spectrum (which in this case will cover the X-ray source position), while noisy, again shows no sign of emission lines. The source is therefore unlikely to be an AGN and may be more likely associated with the central nuclear star cluster.

VCC 833

This is an apparently standard dE,N galaxy 8 arcmin ($\simeq 40$ kpc) from M86. There is a particularly deep *Chandra* observation allowing us to detect one of the two faintest X-ray sources in our sample. The X-ray source position is again close to the galaxy nucleus, but the SDSS spectrum shows no signs of any emission lines so it is

⁶ For completeness, we can note that during our searches we also found sources close to, but outside, two other VCC galaxies. One is 11 arcsec from the particularly compact faint ($M_r \simeq -14.4$, half-light radius 2 arcsec) BCD VCC 1313 (e.g. Drinkwater & Hardy 1991). The other is 9.2 arcsec from the very faint ($M_r \sim -13.5$) dE VCC 2002 (isophotal radius $\simeq 6$ arcsec from VCC), which is at a projected distance of only 5 kpc from the larger galaxy NGC 4660 which has a significant population of globular clusters (Chies-Santos et al. 2011).

almost certainly not an AGN. (Indeed the best-fitting SDSS spectral template is an F9 star).

VCC 914

This is significantly fainter, and of lower surface brightness, than any of our other dwarfs with X-ray detections. Despite the presence of a nucleus, the ‘fibre’ magnitude (effectively measuring the central surface brightness) is around 3 mag fainter than our other dwarfs. There is therefore no SDSS spectrum. There is no available high-resolution imaging, to check the precise centre of the galaxy, but the SDSS centre and the position of the X-ray source agree to better than half an arcsecond. The source also appears in the CSC with flux in agreement with our value, but does not appear to have been followed up in any study of nuclei, perhaps because the original VCC position differs significantly from that measured via SDSS. (A source close to our position and another relatively nearby X-ray source were assumed by Smith et al. (2003) to be objects in the background NGC 4410 group.)

VCC 1087

The X-ray emission comes from a point $\simeq 500$ pc from the centre of this quite large galaxy (the SDSS *r*-band isophotal radius corresponds to $\simeq 3.5$ kpc). There are just sufficient counts to attempt to determine a Hardness Ratio (in the sense $H - S/H + S$) between the 0.5 to 2 keV (soft) and 2 to 7 keV (hard) bands. We obtain a value $HR \simeq -0.6$, implying a relatively soft spectrum with photon index $\Gamma \simeq 1.8$.⁷ The CSC contains a matching object with flux limits entirely consistent with ours. One of our brightest sources, it has been included in the Plotkin et al. (2014) list of potential ultraluminous X-ray (ULX) sources in elliptical galaxies. VCC 1087 has quite a large globular cluster population, but our X-ray position is not coincident with any of the globulars visible in *HST* imaging and spectroscopically confirmed by Beasley et al. (2006). The SDSS spectrum shows the expected absorption lines from an old stellar population. According to Jergen, Binggeli & Barazza (2004), from a surface brightness fluctuation study, its stellar population has typical dE metallicity, $[Fe/H] = -0.9$, and age 8–12 Gyr.

VCC 1348

Despite a rather noisy background in the *Chandra* data, we obtain a significant detection for an X-ray source close to the centre of VCC 1348, a galaxy only 35 kpc in projection from M87. The source has an estimated $HR \simeq -0.4$ (implying $\Gamma \simeq 1.4$). Paudel, Lisker & Kuntschner (2011) find the nucleus of VCC 1348 to be one of the oldest in their Virgo sample, at around 11 Gyr. There is a source suggested to correspond to VCC 1348 in the 2XMM catalogue but this appears to be offset 12 arcsec from the galaxy centre and is reported to have a much higher flux than our object. On closer inspection, the *XMM* detection appears to be at the edge of an instrumental artefact and we see no corresponding source in the *Chandra* data.

⁷ To make this transformation, we use ISIS (Houck & Denicola 2000) to simulate counts for spectra that follow a range of absorbed power-law distributions, with the same instrumental set-up as our data, and calculate the corresponding HR. We reverse this to obtain Γ from a measured HR. Realistic variations in the absorbing column change Γ by less than $\simeq 0.1$, much less than the error due to the low photon statistics.

VCC 1355

We find a source essentially coincident with the nucleus, with flux lower than, but just consistent with, values quoted by both Seth et al. (2008, 4.4×10^{38} erg s⁻¹ from 2XMM) and Gallo et al. (2010) (3.8×10^{38} erg s⁻¹). Although VCC 1355 does not have an SDSS spectrum, Paudel et al. (2011) do not see any emission lines.⁸ They do find a very young age for the nucleus, however, around 1.6 Gyr. Coté et al. (2006) find the nucleus to be just resolved, with a size ~ 3 pc, slightly smaller than the typical nuclear star clusters in their sample galaxies (4.2 pc).

VCC 1431

VCC 1431 is towards the bright end of dwarf luminosities. The X-ray source position, though close to the nucleus, seems to be genuinely offset from the optical centre, 0.8 arcsec being beyond the expected combined astrometric and centring errors of the optical and X-ray data [see above and Gallo et al. (2008) for a discussion]. Even if a nuclear origin were possible, the X-ray source is well within the SDSS fibre and there is no hint of AGN-like emission lines in the SDSS spectrum. Interestingly, VCC 1431 has one of the largest nuclear star clusters in the Coté et al. (2006) sample, with radius 0.25 arcsec or about 20 pc. The source does not appear to have been detected previously. Gallo et al. (2010) quote an upper limit at 4×10^{38} erg s⁻¹ consistent with our detection if it is at the lower end of our error range. (Changing the model spectrum used could also change our derived flux downwards.)

VCC 1779

VCC 1779 was classed as a dwarf S0 by Binggeli et al. (1985), but later authors suggest that it may be a transition dIrr/dE object (Ferrarese et al. 2006a) with signs of spiral structure and dust (Peng et al. 2006). The X-ray source we detect is $\simeq 700$ pc from the centre, compared to the SDSS isophotal radius 3 kpc, and matches a CSC object. Peng et al. (2006) note several likely globular clusters around VCC 1779, but none spatially match the X-ray source. The brightest of our detections (see also Plotkin et al. 2014), the source has enough photons to estimate a hardness ratio $HR \simeq 0.0$, implying $\Gamma \simeq 0.65$. The galaxy spectrum shows no emission lines but does appear to have strong Balmer absorption, perhaps indicative of recently ended star formation, consistent with a transitional status.

Stacked Virgo Spectra

In order to explore the typical shape of the spectra of our detected sources, we also stacked the counts from them. This should be a reasonable approach as all the sources are in similar galaxies, in a similar environment, and at the same distance. This provides an effective total exposure time of ~ 100 ks and we can obtain a summed spectrum which we can fit directly with a $\Gamma = 1.16 \pm 0.34$ spectrum, corresponding to $HR \simeq -0.3$ (assuming a typical foreground Galactic absorption column). As would be expected, this mean slope

⁸ A spectrum supposedly of VCC 1355 (IC3442) in the Updated Zwicky Catalog (Falco et al. 1999), available via NASA/IPAC Extragalactic Database (NED), shows strong emission lines but is clearly of a different object as the redshift of the lines does not match that of VCC 1355, which is a definite cluster member based on redshift-independent indicators.

is between the values obtained for the three individual objects for which the HR could be estimated.

3.3 X-ray Detections: Field

As noted above, 98 dwarf field galaxies with M_r (nominally) fainter than -16 were found to be covered by *Chandra* observations. We should note that SDSS magnitudes are not always very accurate for low surface brightness dwarfs and that for the global search we simply took the observed redshift and a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We correct these distances and magnitudes for the galaxies of interest via the flow models available in NED. Running our CIAO script for this sample, we find 10 secure X-ray detections associated with nine separate galaxies (Table 2). Luminosities are similar to those in the Virgo dwarfs, $\sim 2 \times 10^{37}$ to 2×10^{39} erg s⁻¹. Eight have previous CSC detections.

Galaxy 236; SDSSJ150822.69+014754.9

Based on its SDSS spectrum, this galaxy has a Seyfert 2 AGN (Hao et al. 2005), but the galaxy does not seem to have been detected previously in X-rays. Note that the nominal positional mismatch between the SDSS centre and the X-ray source – which we can be confident coincides with the AGN in this case – is 0.4 arcsec. Mahdavi, Trentham & Tully (2005) suggest that this galaxy is in the NGC 5846 group and classify it as a dE,N. This would make it one of the rare class of objects containing both, a nuclear star cluster and a black hole (Graham & Spitler 2009)

Galaxy 330; SDSSJ093401.92+551427.9

This is the well-known extremely metal-poor object IZw18, a BCD/H II galaxy containing numerous star-forming regions. IZw18 is detected at all wavelengths from the X-ray and UV to far infrared and radio. We measure a flux which matches that of the previously catalogued *Chandra* and *XMM* source (see, e.g. Humphrey et al. 2003; Kaaret, Schmidt & Gorski 2011). Its position is very close to the centre of the SDSS galaxy, where there is a bright star-forming region.

Galaxy 678; SDSSJ111934.36+513012.1

This is also known as ‘Arp’s Galaxy’ (Arp 1965) and has extremely blue colours, $g - r \simeq 0$, as befitting its BCD classification (Thuan & Martin 1981; Corbin et al. 2006). Like IZw18, above, it is a very metal-poor system (e.g. Moiseev, Pustilnik & Kniazev 2010). We observe a powerful X-ray source with $L_X > 10^{39}$ erg s⁻¹, but it does not appear to have been noted as a *Chandra* source prior to the work of Prestwich et al. (2013) who specifically searched in low-metallicity systems. The computed hardness ratio is $HR \simeq -0.8$, implying $\Gamma \simeq 2.6$. In this case, there are enough photons to attempt a direct fit of the spectrum and this results in a photon index $\Gamma \simeq 2.1$, giving reasonable agreement between our two values. The galaxy is very irregular, so the centre is not well defined, but the source appears to be just outside the main bright star-forming region.

Galaxy 1200; SDSSJ113202.62+572236.6

Galaxy 1200 (PGC035568) has very blue $g - r \simeq 0$ and is in catalogues of both emission line galaxies/UV excess galaxies (Markarian & Stepanian 1983) and BCDs (Thuan et al. 1999), and is

Table 2. X-ray detections in Field. Galaxy classifications are as noted in the text. D is the distance to the galaxy in Mpc. a_{iso} is the r -band isophotal (major axis) radius from SDSS in arcsec, where available: the value marked ^d is from the RC3 (de Vaucouleurs et al. 1991). S is the offset of the X-ray source from the nominal galaxy centre in arcsec (see text for further discussion).

Galaxy	Type	D (Mpc)	SDSS			a_{iso}	Chandra			S (arcsec)	
			RA	Dec.	M_r		RA	Dec.	Flux (cgs)		L_x (cgs)
236	dE _s N	29	15:08:22.69	01:47:55.00	-15.3	15.1	15:08:22.71	01:47:54.94	$1.1^{+1.0}_{-0.6} \times 10^{-14}$	$1.1^{+1.0}_{-0.6} \times 10^{39}$	0.4
330	BCD	15	09:34:1.92	55:14:27.90	-14.4	9.1	09:34:01.97	55:14:28.25	$6.3^{+0.5}_{-0.5} \times 10^{-14}$	$1.7^{+0.1}_{-0.1} \times 10^{39}$	0.6
678	BCD	25	11:19:34.36	51:30:12.10	-15.1	7.3	11:19:34.13	51:30:12.44	$3.7^{+0.7}_{-0.7} \times 10^{-14}$	$2.7^{+0.5}_{-0.5} \times 10^{39}$	2.1
1200	BCD	28	11:32:02.54	57:22:45.70	-16.1	26.0	11:32:02.57	57:22:36.90	$1.4^{+0.6}_{-1.2} \times 10^{-14}$	$1.3^{+0.5}_{-1.1} \times 10^{39}$	8.8
1631	dI?	16	14:31:55.74	36:18:20.81	-15.0	31.6	14:31:56.34	36:18:16.21	$4.1^{+1.8}_{-1.4} \times 10^{-14}$	$1.3^{+0.6}_{-0.4} \times 10^{39}$	8.6
2079a	Im/BCD	6	9:56:45.70	28:49:35.00	-14.0	81 ^d	09:56:45.99	28:49:29.64	$4.5^{+3.1}_{-2.2} \times 10^{-15}$	$1.9^{+1.4}_{-0.9} \times 10^{37}$	6.6
2079b							09:56:45.75	28:49:20.26	$1.3^{+0.6}_{-0.5} \times 10^{-14}$	$5.5^{+2.8}_{-2.1} \times 10^{37}$	14.8
2386	Sdm	8	12:22:19.47	30:03:41.51	-14.9	48.2	12:22:19.40	30:03:40.80	$2.0^{+1.1}_{-0.8} \times 10^{-14}$	$1.6^{+0.8}_{-0.6} \times 10^{37}$	1.1
2508	LSBG	19	10:19:00.93	21:16:56.28	-15.5	16.2	10:19:01.02	21:16:54.54	$2.3^{+1.7}_{-1.1} \times 10^{-14}$	$9.8^{+7.2}_{-4.8} \times 10^{38}$	2.1
2593	dI?	28	11:17:46.30	17:44:24.68	-15.6	15.0	11:17:46.29	17:44:24.22	$7.6^{+4.0}_{-3.0} \times 10^{-15}$	$7.2^{+3.8}_{-2.8} \times 10^{38}$	0.5
									$1.1^{+0.8}_{-0.6} \times 10^{-15}$	$1.1^{+0.7}_{-0.5} \times 10^{38}$	-

classified as part of an interacting pair by Huchtmeier et al. (2008). It is another extremely metal-poor galaxy (Morales-Luis et al. 2011). The X-ray source appears coincident with one of the major bright knots within, but well off-centre of, the image (≈ 1.2 kpc south of the nominal SDSS coordinates). There appears to have been no previous X-ray detection of this source prior to the specific search by Prestwich et al. (2013). It has $\text{HR} \approx -0.1$, or $\Gamma \approx 0.7$.

Galaxy 1631; SDSSJ143155.74+361820.8

This irregular looking galaxy appears as part of the interacting system VV262 (Vorontsov-Velyaminov 1959) but the object VV262b is actually much less distant than its apparent companions, as judged by its SDSS redshift (762 km s^{-1} compared to around 3800 km s^{-1}). We find a source about 700 pc south-east of the quoted galaxy centre which agrees with a CSC detection. There is another nearby CSC source, which lies within another member of the system; we see this too, but strictly this latter galaxy is not in our sample as it lacks an SDSS redshift. Note that given its sky position, there is a significant flow correction to the distance of VV262b.

Galaxy 2079; SDSSJ095646.04+284943.7

The nearest object in our sample, identified with UGC5340 and DDO68, is a highly irregular system included in the Vorontsov-Velyaminov catalogue as VV542. (The closest SDSS source, SDSSJ095646.04+284943.7, is only part of this larger galaxy). It has been classified as a very metal-deficient Im/BCD by Pustilnik, Kniazev & Pramskij (2005) and included in the Pustilnik et al. (2011) list of extremely low surface brightness galaxies. It again has very blue $g - r \approx 0$. It is the only one of our objects which has two separate X-ray sources (which we will refer to as a and b) probably associated with it. The first source is 7 arcsec (≈ 200 pc) south-west of the centre (as defined by the position at which the SDSS spectrum was taken). The second source lies 15 arcsec (450 pc) south of the centre. Note that due to its proximity, the overall galaxy diameter is around 2.6 arcmin so both sources are well within the optical image. (We consider the likelihood of contamination at the larger separation below.) The two sources are also reported by Kaaret et al. (2011) and Brorby, Kaaret & Prestwich (2014), as part of their study of X-ray-detected BCDs, with luminosities reasonably consistent with our values.

Galaxy 2386; SDSSJ122219.46+300341.4

Galaxy 2386 (UGC7438) is classified as an Sdm and is noted as an H I rich low surface brightness galaxy (LSBG) by O'Neil et al. (2004). It has strong emission lines (particularly H α and H β), though it has a fairly red $g - r \approx 0.6$, and the X-ray source confirms a detection in the CSC. The X-ray source is located within the central star-forming region, ~ 40 pc from the centre.

Galaxy 2508; SDSSJ101900.93+211656.2

Galaxy 2508 as a whole (PGC030133) is a largish low surface brightness object (Schombert & Bothun 1988), but containing or interacting with a very bright blue complex which matches the position of SDSSJ101900.93+211656.2, the SDSS spectrum showing strong H α and [O III] lines. About 2 arcsec (200 pc) from the SDSS position (about 9 arcsec off-centre of PGC030133), we find an X-ray source which appears not to have been detected previously.

Galaxy 2593; SDSSJ111746.30+174424.6

Finally, galaxy 2593 is an irregular looking, virtually unstudied galaxy which is again extremely blue ($g - r \simeq 0.0$) and has strong [O III] and H α lines. There are two *Chandra* observations of this galaxy, ObsID 4933 (20 ks) and ObsID 5836 (46 ks), with the SDSS position at an off-axis angle of 3.8–3.9 arcmin. From ObsID 4933, we confirm a detection in the CSC, coincident with the brightest knot in the image (the SDSS centre). The X-ray source is not formally detected in ObsID 5836, in a blind search of the area using *wavdetect*, despite its longer exposure time. There are excess counts at the same position as the ObsID 4933 detection, but at a much lower level (see Table 2). It thus appears that there may have been a significant change in flux over a period of about eight months. There is another CSC source 15 arcsec away which we also detect, but this appears to be outside the body of the galaxy; although the isophotal major axis a_{iso} is also 15 arcsec, the source is roughly in the minor axis direction, where b_{iso} is only 8 arcsec.⁹

3.4 Contamination

To test how likely our samples are to be contaminated by non-associated background sources (e.g. distant AGN), we have used two alternative approaches. First we use our ‘standard’ limit at $3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. To this depth, the X-ray number counts of Georgakakis et al. (2008) imply that $\simeq 1.5$ per cent and 5 per cent of random positions will have an X-ray source within 9 and 15 arcsec, respectively. This implies that over our total sample of target galaxies (allowing for the 70 per cent completeness to this flux level), we have an expected contamination of $\simeq 2$ sources in our list of 18 detections at radii less than 9 arcsec (see Tables 1 and 2). Moving the search area out to $\simeq 9$ –15 arcsec, the expected contamination in this range is about five sources. In total, during our searches we found six such sources, one within the body of a galaxy (so claimed as a likely genuine association) and five outside galaxies, in good agreement with the expected background numbers. The source at this separation which is clearly well within galaxy 2079 is included in our table of detections, but of course statistically could be another contaminant.

Secondly, we can compare with the detailed calculations by Prestwich et al. (2013) and Brorby et al. (2014), who show that for other samples of nearby dwarfs (with essentially equivalent data to ours) the probability of finding a background source inside the optical area of a typical dwarf is 1–2 per cent. From this, we would expect 2–4 contaminating X-ray sources in our sample, similar to the figure derived from the number counts.

4 SUMMARY AND DISCUSSION

4.1 Virgo dwarfs

As described in Section 3.2, only nine of the 119 Virgo dwarfs which lie in areas which have been observed by *Chandra* have significant

X-ray detections. As above, the likelihood of a background source falling within 9 arcsec of a given target is $\simeq 1.5$ per cent at the relevant depths ($\sim 3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$), so we may expect about one accidental match from 119 targets, given that 70 per cent of them are observed to this depth.

If we allow for a relative positional uncertainty in the matching of 0.6 arcsec, from above, then up to five of the sources are consistent with being at the centre of the host galaxy, while at least three are well away from the centre (by ~ 2 to 9 arcsec, or about 150 to 700 pc). There is no evidence of emission lines in the spectra of any of the detected objects, either with central or off-centre X-ray sources. (The faintest object currently lacks spectral information.) Hence, despite the proximity of several of the sources to their host galaxy nucleus, we suggest that in fact none (at most one) have AGN (or central star formation). All the galaxies with near central sources do have stellar nuclei, however, in line with Ferrarese et al. (2006b) finding central star clusters rather than SMBH in most early-type dwarfs. This would suggest that less than or of the order of 1 per cent of (early-type) dwarfs at these magnitudes have active AGN, a similar fraction to the ~ 0.5 per cent found by Reines et al. (2013).

In the galaxies with non-central X-ray sources, based on them being passive early types, we are almost certainly seeing LMXBs associated with their old stellar populations; the X-ray luminosities are typically $\sim 10^{38} \text{ erg s}^{-1}$ (though rising to $10^{39} \text{ erg s}^{-1}$ in one case) consistent with this picture. From the lack of evidence for AGN, we assume that the same is true for the near central sources, too. There is no obvious correlation between X-ray flux and galaxy luminosity, which is what would be expected for single LMXBs of similar luminosity being found stochastically.

VCC 1779 is an interesting individual case as it may be a transitional dIrr/dE galaxy with fairly recently ended star formation. It may host an LMXB, like the other Virgo objects, but its high luminosity, near the upper cut-off for LMXBs (Kim & Fabbiano 2004; Gilfanov 2004), may hint at an HMXB instead, as these have a more extended tail to high luminosities (e.g. Grimm et al. 2003). Nevertheless, in the calculations below we will assume that all the detected sources are LMXBs.

The detection rate for bright LMXBs ($L_X > 10^{38} \text{ erg s}^{-1}$) is then evidently 7/119 (two of our sources are below this level), or about 6 per cent of our dwarf galaxies. Most of the galaxies detected in X-rays have $M_r \sim -16.5$ to -17.5 , corresponding to around 3 – $8 \times 10^8 L_\odot$, but many of the overall sample (not detected) are considerably fainter. The total luminosity of our dwarfs (excluding the handful of Im or BCD galaxies, for consistency) is approximately $1.1 \times 10^{10} L_\odot$, or $\sim 3.3 \times 10^{10} M_\odot$ for a typical stellar mass-to-light ratio $\sim 3 M_\odot/L_\odot$. This gives, overall, one bright LMXB per $5 \times 10^9 M_\odot$. Although not very precise, this estimate is entirely consistent with that for individual giant ellipticals, also around one bright LMXB per $5 \times 10^9 M_\odot$ of stars (e.g. Boroson et al. 2011).

As discussed earlier, not all of our sample galaxies are equally deeply imaged in X-rays, due to different exposure times and position-dependent sensitivities on the chip. In our seven bright detections, four meet the higher limit $2 \times 10^{38} \text{ erg s}^{-1}$, where we are almost complete, with the other three above the standard $10^{38} \text{ erg s}^{-1}$ cut-off. Given that only 73 per cent of the target objects could have revealed sources at the lower flux level, we can roughly estimate that we have missed one other source between $10^{38} \text{ erg s}^{-1}$ and $2 \times 10^{38} \text{ erg s}^{-1}$, giving a total of eight. If we expect one contaminating source, this reduces back to seven. The detection fraction is therefore not very sensitive to such issues and is clearly dominated by the small number statistics.

⁹ As for the Virgo dwarfs, we can note two other cases where X-ray sources were found close to but outside the optical extent of dwarf field galaxies. Galaxy 1178, SDSSJ114929.60+560154.1, has a (known CSC) source at separation 15 arcsec, compared to an isophotal size $12 \text{ arcsec} \times 8 \text{ arcsec}$. This galaxy is a faint ($M_r \simeq -13.5$) member of the Ursa Major group, close to NGC 3898. Galaxy 245, SDSSJ145840.88+022023.5, has a source at separation 14.6 arcsec but an isophotal radius of only 9 arcsec. Like galaxy 236, it is a member of the NGC 5846 group.

VCC 914 is particularly intriguing because of its very low optical luminosity, $M_r \simeq -12.8$, or only $\sim 10^7 L_\odot$. (The close match of the optical centre and the X-ray source make it highly unlikely that this is a chance superposition of a background source, at this flux level.) If the overall rate is around 1 per $1.5 \times 10^9 L_\odot$ then evidently this is a 1 in 150 chance for an individual $M_r \simeq -12.8$ galaxy, but such a detection is feasible given a total of ~ 35 similarly low-luminosity objects in our overall sample.

Phillipps et al. (2013) previously studied X-ray sources in compact dwarf galaxies in the Fornax cluster and derived a detection rate of order 1 per $10^8 M_\odot$. Although low compared to globular clusters (which are not much fainter than the lowest luminosity objects in their sample), this is considerably higher than we find here, perhaps supporting the idea that high stellar density (as well as the total number of stars) is important in the production of LMXBs (e.g. Jordan et al. 2007; Peacock et al. 2010). This might also be responsible for the preponderance of sources at very small radii, where, obviously, the density is highest.

4.2 Field dwarfs

Interestingly, our detection rate for field dwarfs ($M_r > -16$) is not too dissimilar, with nine out of 98 revealing X-ray sources. Each has a source with flux above $3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ within 9 arcsec of the centre, and from our earlier calculation, given our flux limits, we can again expect about one contaminating source. A second source in one of the same galaxies, which lies at separation 14.8 arcsec though well within the extent of the galaxy, could also be a contaminant (see Section 3.4).

Since they are limited by the SDSS spectroscopic depth (and our definition of a dwarf galaxy), the input ‘Northern hemisphere’ sample galaxies are all within a distance of $\simeq 50$ Mpc. However, with our additional X-ray flux limits, all the matched sources actually lie at distances less than 30 Mpc. Thus the X-ray luminosity limits are similar for the field and Virgo cluster samples. Seven of the 10 would count as ‘bright’, i.e. above $10^{38} \text{ erg s}^{-1}$; the three fainter ones are, unsurprisingly, in the two nearest galaxies, less than 10 Mpc away. Four sources are slightly above $10^{39} \text{ erg s}^{-1}$, so might nominally be considered ULX sources (Prestwich et al. 2013). However, Walton et al. (2011) argue that ULXs in star-forming galaxies are just bright HMXBs, so we do not separate the two here. A detailed calculation based on the individual flux limits and distances demonstrates that we could have detected $10^{38} \text{ erg s}^{-1}$ sources in $\simeq 50$ per cent of our input sample galaxies and a $10^{39} \text{ erg s}^{-1}$ source in over 90 per cent of them. (Such sources are detectable out to 11 and 37 Mpc, respectively, at the X-ray flux limit at which we are effectively complete, $\sim 6 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$; at the lower flux limit, $\sim 3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$, where we are $\simeq 70$ per cent complete, these distances are a factor 1.5 larger).

Of the 10 detections, one is a known Seyfert 2 AGN, but which has not previously been identified with an X-ray source. It can therefore be added to the small number of known X-ray AGN in dwarf galaxies (Gallo et al. 2008; Seth et al. 2008; Reines et al. 2014), extending these down to $M_r \simeq -15.3$ (i.e. total galaxy luminosity $10^8 L_\odot$).

The nine other detections arise in eight dwarfs with $M_r \simeq -14$ to -16 , i.e. a range of a factor $\simeq 6$ in luminosity. They include four BCDs, two of them in close interacting systems (we do not count Galaxy 1631 as interacting). The BCDs (which include the archetypal IZw18) are all extremely metal poor (see also Prestwich et al. 2013; Brorby et al. 2014). The other four galaxies are low surface brightness irregulars or very late type spirals. Unsurprisingly

given their classifications, all eight galaxies are strongly star forming (though individual star formation rates cannot be obtained reliably for our sources as they are very irregular and much larger than the aperture in which SDSS line widths are measured). Seven of the eight are very blue, six have $g - r < 0.2$.

We can therefore reasonably assume that we are seeing X-ray emission from HMXBs (Bartlett et al. 2012; Mineo et al. 2012a) and that these hosts are preferentially picked out because of their high SFR compared to other dwarfs. Recall that we expect about one bright HMXB for an SFR of $0.3 M_\odot \text{ yr}^{-1}$. While low in itself, for our dwarfs this corresponds to a specific SFR (sSFR, i.e. SFR per unit stellar mass) $\sim 3 \times 10^{-9} \text{ yr}^{-1}$ (assuming a mass-to-light ratio ~ 1 for these objects), in line with the values seen for low mass irregulars with relatively high SFR in the Galaxy And Mass Assembly (GAMA) survey (also based on SDSS galaxies) by Mahajan et al. (2015). Mahajan et al. (2015) also see numerous low-mass galaxies with sSFR a factor 10 lower than this, so it would be unexpected to see HMXBs in these, purely on statistical grounds. Overall, our sample of 98 field dwarfs will have a stellar mass $\sim 1 \times 10^{10} M_\odot$, so we would expect a combined SFR $\sim 3 M_\odot \text{ yr}^{-1}$ (from the median sSFR for low-mass galaxies, $\sim 3 \times 10^{-10} \text{ yr}^{-1}$ in Mahajan et al. 2015) and therefore, with the conversion factor used before, ~ 10 HMXBs.

Given the small number statistics and the broad ranges of individual SFRs that are expected, this is compatible with our nine detections, six of these being ‘bright’. (Recall that galaxy 2079 has two sources but we are ignoring the Seyfert). In more detail, since sources at $10^{38} \text{ erg s}^{-1}$ would only be detected in about half of our galaxies, but any above $10^{39} \text{ erg s}^{-1}$ could be seen in almost any of them, this increases the six actual detections of ‘bright’ sources to a predicted eight sources, in good agreement with the expectation from our ‘scaled down’ star-forming galaxy model.

If we use the Gilfanov (2004) normalization to estimate the relative total luminosity in LMXBs compared to HMXBs in star-forming galaxies, and take this as an estimate of the relative numbers (since individual luminosities of the two classes are similar), then we find LMXB:HMXB $\simeq 0.13/10^{10} \text{ sSFR} \sim 0.04$ for our star-forming galaxies, so we would not expect any LMXBs in a sample of 10. (Obviously if the sSFR were smaller, as for *average*, rather than strongly star-forming, low-mass galaxies, the LMXB fraction would be higher.) Thus, we conclude that HMXBs continue to trace star formation in the same, or at least a similar, way in dwarfs as they do in giants.

On the other hand, except inasmuch as high-current SFR correlates with lack of previous processing, it is not obvious that we should expect as many as half of our X-ray detected dwarfs to be extreme low metallicity IZw18-like objects, which comprise only a small fraction of the global dwarf population. (Morales-Luis et al. (2011) find less than 1 per cent of local SDSS emission line galaxies are in this class.) This provides support for a link between metallicity and HMXB production as discussed recently by Brorby et al. (2014, and references therein). This may be due to differences in the stellar evolution prior to the supernova which produces the compact remnant in the binary (see e.g. Dray 2006; Bartlett et al. 2012). Prestwich et al. (2013) have also found that ULX sources in starburst galaxies occur preferentially in low-metallicity galaxies, perhaps because of differences in black hole growth.

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