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Galaxies at the Detection Limits of Deep X-ray Surveys

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Abstract. The great sensitivities of the *Chandra* X-ray Observatory and XMM-Newton are allowing us to explore the X-ray emission from galaxies at moderate to high redshift. By using the stacking method, we show that we can detect the ensemble emission from normal elliptical, spiral and irregular galaxies out to redshifts approaching one. The average X-ray luminosity can then be compared with the results of models of the evolution in the numbers of X-ray binaries and can possibly be used to constrain models of star formation.

1. Introduction

Deep surveys in X-ray astronomy had the initial goal of solving the problem of the origin of the extragalactic X-ray background, and these surveys have now shown that the XRB is largely comprised of the evolving populations of AGN, some heavily absorbed (see Hasinger, this volume). There may be some disagreement between current models (Comastri et al.) and the best available recent data on the redshifts and luminosities of the contributing AGN, but the underlying But the deep surveys with the *Chandra* X-ray Observatory (CXO) have shown that normal galaxies are also detected, and the initial 1Ms survey of the Hubble Deep Field (HDF) North demonstrated that about a third of the X-ray sources were identified with galaxies (Horneschmeier et al. 2002).

We have thus entered a new era in X-ray astronomy, one in which we can begin to explore the evolution of extragalactic source populations in addition to the AGN.

2. Deep Surveys and Source Counts

The number counts in the HDF-N have been measured by Miyaji & Griffiths (2002), and extended to fluxes below 10^{-17} ergs cm^{-2} s^{-1} in the soft band (0.5 - 2 keV) and to 10^{-16} ergs cm^{-2} s^{-1} in the hard band (2 - 10 keV) by analysis of the fluctuations which remain after removal of the individual discrete source detections. Below this limit, the fluctuation analysis shows that the number counts continue to rise, as shown in Fig. 1, with a slope consistent with that between 10^{-15} and 10^{-16} ergs cm^{-2} s^{-1}. In vindication of this procedure, we have compared the fluctuations from a shorter sub-set of this data (the first 220 ks) with the actual number counts from the longer exposure and found excellent agreement in the number count slope. The same has been true when fluctuations

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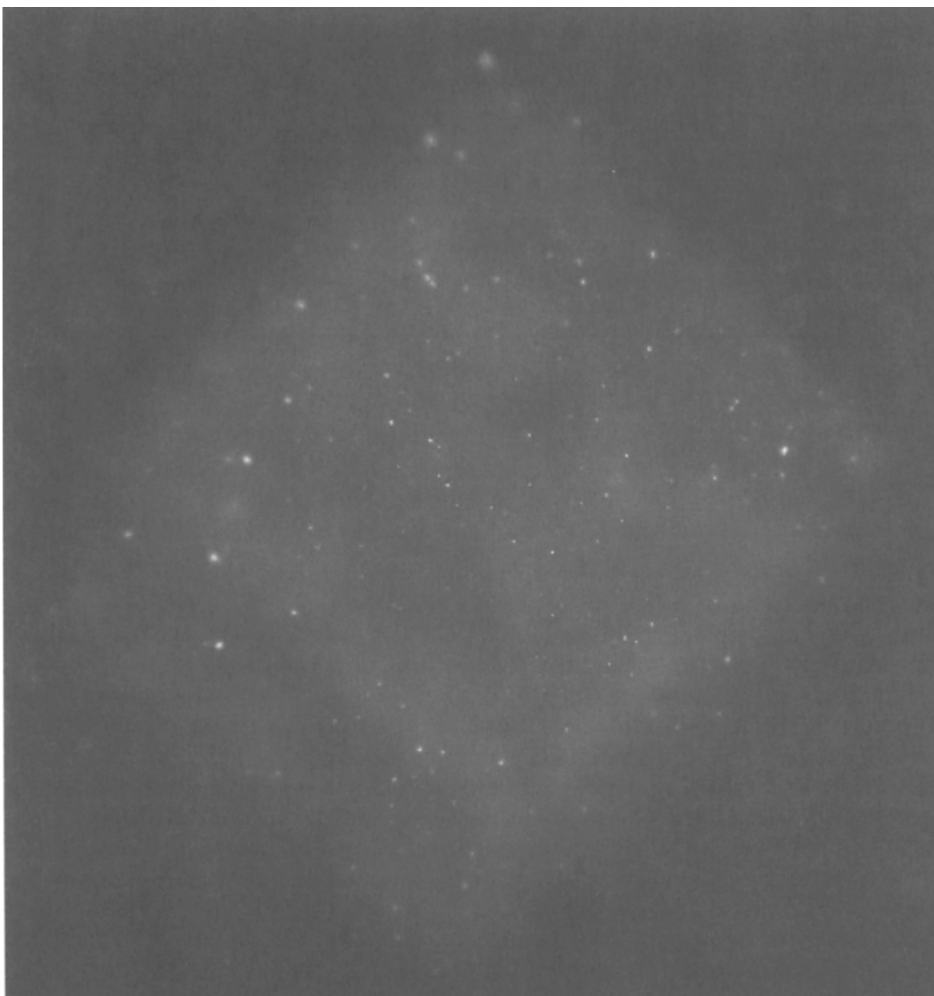

Figure 1. The CXO 2 Ms image of the HDF-N region

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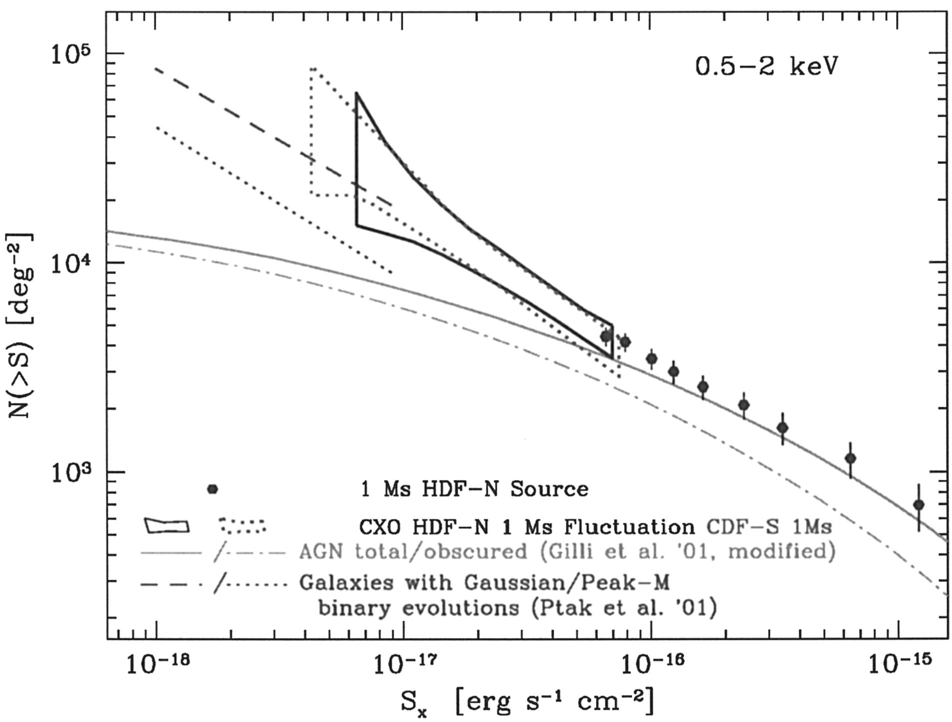

Figure 2. X-ray Number Counts from HDF-N

in the Einstein data were vindicated by the actual counts from ROSAT data, and when fluctuations in the deep ROSAT data were compared with the actual counts presented here and elsewhere. We therefore have a high level of confidence in the number count slope from the fluctuations presented here.

At X-ray fluxes between 10^{-15} and 10^{-16} ergs cm^{-2} s^{-1}, the optical identifications in the HDF-N (Horneschmeier et al. 2002) show that starburst and normal galaxies begin to dominate the number counts (0.5–8 keV). We infer that the number counts in the region explored with fluctuations (the boxed area in Fig. 1) are unlikely to be due to AGN. Furthermore, the current best models for the AGN contributions to the number counts fall well below the fluctuations.

The fluctuations analysis shows that the number counts are approximately 20,000 – 40,000 per sq. deg. at X-ray fluxes of 10^{-17} ergs cm^{-2} s^{-1}. Such number counts match those of the optical counts of galaxies at B = 24. We therefore explore the possibility of X-ray detection of faint galaxies in the HDF-N by using the stacking method.

3. Cosmic Variance in Deep X-ray Surveys

The published results on faint number counts in the CDF-S (Tozzi et al. 2001, Campana et al. 2001) are somewhat lower than those in the HDF-N. In order to confirm that such a result is due to cosmic variance, we have compared number counts in the HDF-N with those in the Groth-Westphal strip using deep survey data from XMM-Newton and the same analysis software. The results plotted here clearly show that a variance in number counts at the level of 30% in not unusual in number counts at $10^{-15} - -10^{-16}$ ergs cm^{-2} s^{-1}when measured over fields covering 0.5 degs. square.

4. Selection of Galaxies by Morphological Type and Luminosity

During the execution of the Medium Deep Survey using the Hubble Space Telescope, software was developed for the automated classification of galaxies into spirals (exponential disks), ellipticals ('de Vaucouleurs' profiles) and irregular galaxies which exhibited large residual images after the removal of disk or bulge profiles (Ratnatunga, Griffiths & Ostrander 1999). This survey showed, for example, that the fraction of irregulars rises from 12% locally to 30% at a redshift of 0.5.

We have applied this MDS software and analysis to the HST images of the HDF-N and other deep HST surveys. In those fields where we have deep CXO observations, we can then examine the X-ray images for the presence of X-rays from the galaxies of differing broad morphological type.

As well as this morphological information, unique to HST data, we also clearly need redshift information for as many of the field galaxies as possible, so that the HDF-N represents the first opportunity to explore the goal of examining the average X-ray luminosities of field galaxies as a function of their optical luminosity and redshift, using redshift information from the spectroscopy of Cohen et al. (2000) and the photometric reshifts of Fernandez-Soto, Lanzetta and Yahil (1999).

5. Results of 'Stacking'

Although the fluctuations analysis gives us an indication of the number counts of X-ray sources at the faintest flux levels currently accessible, they do not give us any indication of the nature of the sources contributing to the fluctuations. How do we find out the possible nature of these sources ? One method is that of 'stacking', i.e. the summation of sub-images centered on objects selected at another wavelength. This was first applied to X-ray telescope images by Anderson & Margon (1987) who used it to look for a signal from high-z qso's in Einstein data. More recently, Brandt et al. (2001) and Horneschmeier et al. (2002) have used this method on early CXO data of the HDF-N. In the HDF, we have the advantage of being able to use the HST images themselves to select various types of galaxies for the stacking process, using the software developed as part of the HST Medium Deep Survey (Ratnatunga, Griffiths and Ostrander 1999). We have now done this for elliptical, spiral and irregular galaxies, and some of the results are shown in figure 2.

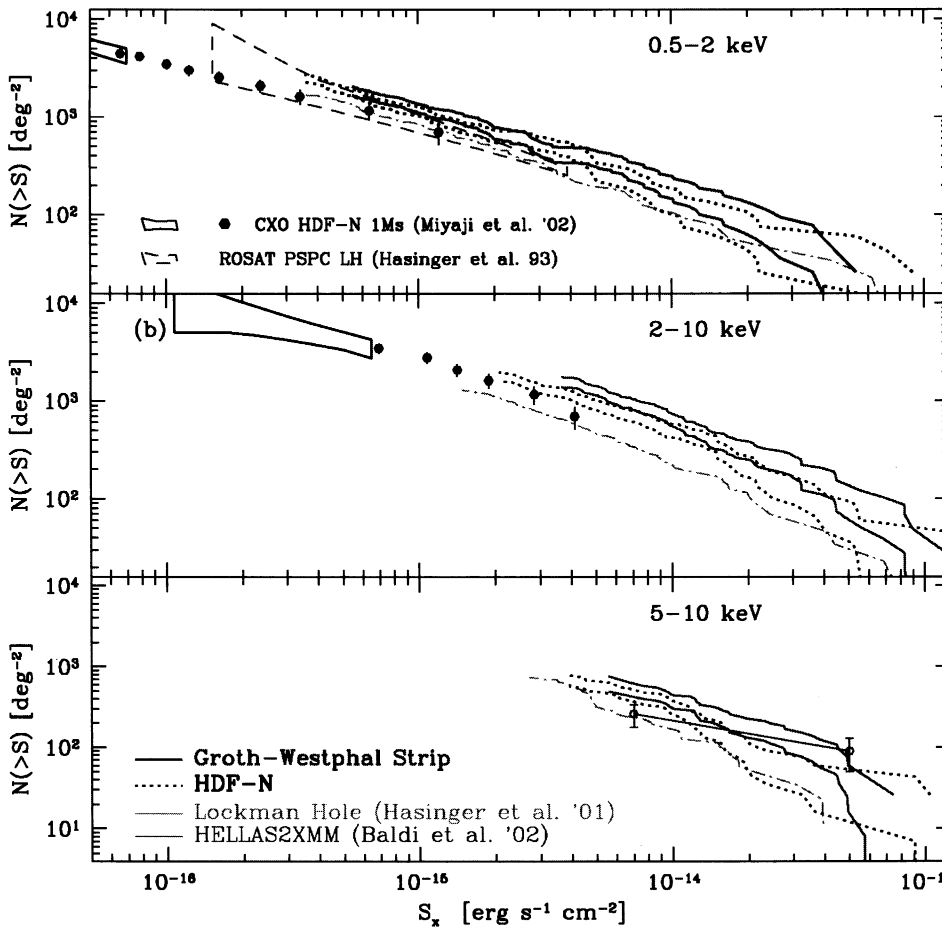

Figure 3. Variance in deep X-ray number counts

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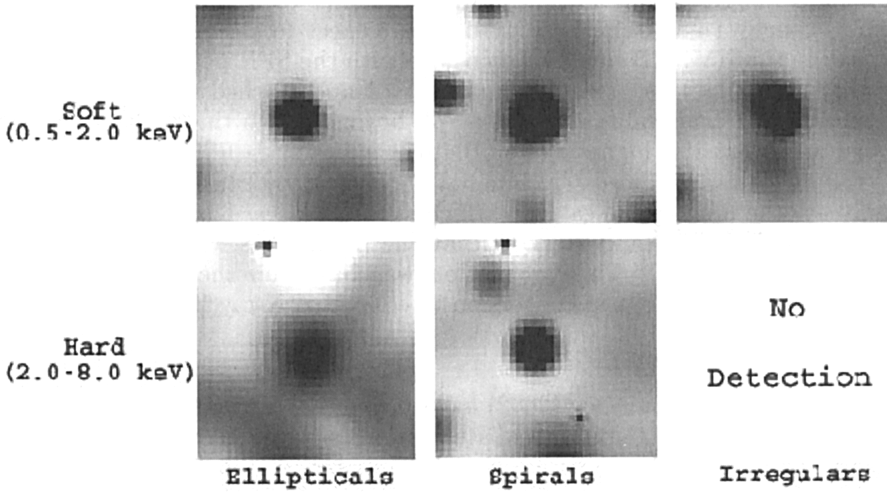

Figure 4. Stacked X-ray images of ensembles of galaxies

As the figure shows, the spiral and elliptical galaxies are detected at high confidence in both the soft and hard energy bands, but the irregular galaxies are detected in the soft band only. The median redshifts are 0.87 for the 27 ellipticals, 0.49 for the 54 spirals and 1.55 for the 57 irregulars in these stacked images. Monte Carlo simulations have been used to verify the statistical confidence in these results. In such simulations the stacking is done on 'null' candidates, i.e. positions where there are no optical sources but where the background level is similar to that around the actual optical sources. This Monte Carlo procedure is repeated 10^5 times in order to understand the distribution of false detections (Gaussian).

The median X-ray luminosities are $x \times 10^{-17}$ ergs cm^{-2} s^{-1}for the ellipticals, $x \times 10^{-17}$ ergs cm^{-2} s^{-1}for the spirals and $x \times 10^{-17}$ ergs cm^{-2} s^{-1}for the irregulars, consistent with their B-band luminosities and the average values for L_X/L_B for the galaxy types.

6. X-ray Evolution of Galaxies

There are several problems which need to be solved or investigated in support of the interpretation of these results: (i) the evolution of low-mass X-ray binaries (LMXRB), (ii) the evolution of high-mass X-ray binaries (HMXRB), (iii) the evolution in the number of ultraluminous X-ray (ULX) objects and (iv) SNR and hot gas components.

Ghosh & White (2001) have made predictions of the numbers of LMXRBs which may have been present at moderate redshifts, based on the supposition that they are the progenitors of millisecond radio pulsars. Starting with the cosmological evolution in the global star formation rate, they estimate the numbers of HMXRB and LMXRB, wtih a peak in the LMXRB numbers at $z \sim 1$ and in the numbers of HMXRB at slightly higher z closer to 2. The evolution in the number counts of LMXRBs is delayed with respect to the SFR peak, whereas the peak in the HMXRB numbers coincides with the SFR peak. The SFR itself was about ten times its present value at $z \sim 1$ and reached a peak about 10 – 100 times the current value at $z \sim 2 - -3$, beyond which the SFR was roughly flat or else declined to higher z (e.g. Blain et al. ....).

The estimates of Ghosh & White have been used by Ptak & Griffiths (2001) to estimate the numbers of galaxies which should be near the detection limit in the CXO HDF-N field and to show that the predictions were consistent with the observed numbers. This calculation was based on the observed B-band luminosities in the HDF and conversion to estimated X-ray fluxes.

6.1. HMXB and the SFR

Grimm, Gilfanov and Sunyaev (2002) have shown that HMXB can be used effectively as an indicator of the SFR in distant galaxies. Using recent data on nearby galaxies, these authors have shown that the number or collective L_X of HMXB exhibits a linear relationship with the SFR for a sufficiently high SFR (greater than about $4M_\odot$ per year. Furthermore, using *Chandra* observations of the L_X of several galaxies in the HDF-N, the predicted SFRs are in broad agreement with the estimates based on other methods such as 1.4 GHz luminosity.

This important result, that the integrated emission of HMXB is an indication of the global SFR in galaxies, could arise from the plausible supposition that the formation of neutron stars and black holes in star forming regions is both rapid and efficient. There seems to be a universal luminosity function for the HMXB in nearby galaxies, for which the normalisation is proportional to the SFR in that galaxy. This result may not have much dependence on metallicity, and may therefore apply to at least moderately high redshift.

Although the LF for HMXB seems to cut off at 10^{40} ergs s^{-1}, this cut-off will depend on the presence or absence of ultraluminous X-ray sources. In principle, such sources could skew the distribution and intermediate-mass black-hole objects could have much higher luminosities than this cut-off. This possible effect does not seem to have had any major impact on the conclusions of Grimm, Gilfanov & Sunyaev for nearby galaxies, but there is currently no knowledge of the number or evolution of such sources in galaxies at moderate redshift. The other major problem with the integrated luminosity from HMXB in galaxies at moderate redshift is, of course, that they may harbour AGN. These can be excluded using CXO in nearby galaxies (although not with XMM-Newton), but not in galaxies at redshifts exceeding 0.0x.

7. Conclusions

Results from the stacking analysis of normal galaxy populations applied to the CXO deep survey of the HDF-N show that normal galaxy populations are observable in these stacks out to redshifts of ~ 1. The average X-ray fluxes observed in these stacks are consistent with the numbers and fluxes inferred from the fluctuation analysis of the CXO data. We conclude that the fluctuations are therefore caused primarily by normal galaxy populations and that such deep X-ray surveys will eventually allow us to constrain the evolution of the binary source populations within these galaxies, using the relationship between HMXB numbers and the SFR of nearby galaxies.

Acknowledgements

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