AGN predictions for the Hubble Deep Field and the X-ray background

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ABSTRACT
We estimate the number of AGN among the galaxies in the Hubble Deep Field (HDF). The recent discovery of a class of X-ray luminous narrow emission-line galaxies has provided a possible explanation for the origin of the X-ray background (XRB), although the nature of the activity is still unresolved. By extrapolating the observed X-ray number count distribution to faint optical magnitudes we predict that this AGN population could account for a significant fraction, \( \sim 10 \) per cent, of the galaxies in the HDF. In contrast, normal broad line QSOs are expected to account for no more than \( \sim 0.1 \) per cent of the sources at these magnitudes.

Key words: galaxies: active – quasars: general - X-rays:general - X-rays: galaxies - diffuse radiation X-rays: general – galaxies: evolution

1 INTRODUCTION

Little is known about low luminosity or obscured (i.e. Seyfert 2) AGN other than in the very local universe. Deep optical observations such as the HDF (Williams et al. 1996) provide an opportunity to probe such objects at moderate to high redshift. Locally, a few percent of galaxies have active nuclei and if this holds true at \( z \approx 2 \) then there could be several tens of AGN in the HDF.

Low luminosity and/or obscured AGN are also prime candidates for explaining the origin of the XRB. In particular, it is becoming clear from deep ROSAT observations that a population of X-ray luminous narrow emission-line galaxies (NELGs) could dominate the source counts at faint X-ray fluxes (Boyle et al. 1995a, Roche et al. 1995, McHardy et al. 1995, Carballo et al. 1995, Griffiths et al. 1996). Following Hasinger (1996) we will refer to these X-ray loud objects as ‘narrow-line X-ray galaxies’ (NLXGs) in order to distinguish them from the other narrow emission-line galaxies found in increasing numbers in deep optical surveys (e.g. Tresse et al. 1996). The discovery of strong evolution in this new X-ray population (Boyle et al. 1995a, Griffiths et al. 1996, Almaini et al. 1997) can now allow us to make predictions for their contribution at faint X-ray fluxes and hence extrapolate to deep optical surveys. We make such predictions and find that NLXGs could outnumber ordinary broad line QSOs in the HDF by approximately two orders of magnitude and plausibly account for \( \sim 10 \) per cent of the galaxies in the HDF. We suggest that workers on the HDF should be aware of this possibility in accounting for any unusual properties of these faint galaxies. We assume \( q_0 = 0.5 \) and \( H_0 = 50 \) km s\(^{-1}\)Mpc\(^{-1}\) throughout.

2 THE X-RAY SOURCE SOURCE POPULATIONS

The origin of the X-ray background is still a major unsolved problem, but at soft energies (< 3.5 keV) great strides have been made following the launch of the Einstein and ROSAT satellites. By resolving as many sources as possible in the deepest ROSAT exposures, up to 70 per cent of the XRB can now be resolved into discrete sources. By optical spectroscopy at least half of the detected sources have been identified as broad-line QSOs, which directly account for \( \sim 30 \) per cent of the XRB at 1keV (Shanks et al 1991).

As larger samples of QSOs became established, studies of the X-ray luminosity function (Boyle et al. 1994) and the source number count distribution (Georgantopoulos et al. 1996a) have shown that QSOs are unlikely to contribute more than 50 per cent of the XRB at 1keV. This suggested the existence of another source population. A further problem in explaining the XRB with QSOs is the shape of their X-ray spectra. QSOs show relatively steep X-ray spectra with indices of \( \Gamma = 2.2 \pm 0.1 \) while the \( 1 - 10 \) keV XRB has a significantly flatter spectrum with \( \Gamma = 1.4 \) (Gendreau et al. 1995). Recent deep ASCA GIS observations in the harder \( 2 - 10 \) keV X-ray band have found a number count distribution roughly a factor of two above the ROSAT source counts (Georgantopoulos et al. 1996b, Inoue et al. 1996). This also suggests the presence of another population at hard energies, other than the broad-line AGN which dominate the bright ROSAT counts.

The number count distribution of X-ray sources in the ROSAT band can be well fitted by a Euclidean power law (\( \gamma = 2.5 \)) at bright X-ray fluxes but turns over to a flat-
ter power law slope of $\gamma \sim 1.5$ below $S(0.5 - 2.0\ \text{keV}) \simeq 2 \times 10^{-14}\ \text{erg s}^{-1}\text{cm}^{-2}$ (Hasinger et al. 1993, Branduardi-Raymont et al. 1994, Vikhlinin et al. 1995). Separating QSOs from this population, their fractional contribution appears to fall below this limit as they turn over to an even flatter power law slope of $\gamma \sim 1$ (Georgantopoulos et al. 1996a). This is confirmed by a detailed analysis of the X-ray luminosity function (Boyle et al. 1993, 1994) where the total QSO contribution was found to lie in the range $34 - 53$ per cent, with the main uncertainty depending on the faint end slope.

There is now very strong evidence that the 'new' X-ray source population consists of unusually X-ray luminous galaxies, typically $10 - 100$ times brighter than normal field galaxies, which could account for the remainder of the XRB (Boyle et al. 1995a, Roche et al. 1995, Carballo et al. 1995, Griffiths et al. 1996, McHardy et al. 1997). The discovery that these galaxies have hard X-ray spectra (Carballo et al. 1995, Griffiths et al. 1996, McHardy et al. 1997) lends further weight to hypothesis.

Preliminary estimates of luminosity functions at the bright end of the NLXG population have shown evidence for strong evolution, parameterized by the form $L_X \propto (1 + z)^3$ (Boyle et al. 1995b, Griffiths et al. 1996). Evidence for strong evolution in the fainter population has recently been obtained by Almaini et al. (1997) by cross-correlating the unresolved XRB in deep ROSAT exposures with faint galaxy catalogues. By using the optical magnitude of the catalogue galaxies as probes of their redshift distribution, evidence for strong evolution was found of the form $L_X \propto (1 + z)^{3.2 \pm 1}$ (Almaini et al. 1997).

We will now estimate the likely contribution of X-ray luminous galaxies to the HDF. We use the faintest luminosity function available to date, by Griffiths et al. (1996), who collated a sample of 32 NLXGs from both ROSAT and Einstein surveys. They find a best fitting local ($z = 0$) luminosity function modelled by a broken power law of the form:

$$ \Phi(L_z) = \begin{cases} K_1 L_z^{-\gamma_1} & L_z(z = 0) < L_z^* \\ K_2 L_z^{-\gamma_2} & L_z(z = 0) > L_z^* \end{cases} $$

(1)

where $K_1$, $\gamma_1$ and $\gamma_2$ represent the normalization, faint and bright end slopes of the XLF respectively. The best fitting values were found to be $\gamma_1 = 1.85 \pm 0.25$, $\gamma_2 = 3.83 \pm 0.20$ and $K_1 = 1.3 \times 10^{-7}\text{Mpc}^{-2}(10^{44}\text{erg}^{-1})$. The 'break' luminosity, $L_z^*$, was found to evolve with the form:

$$ L_z^* \propto (1 + z)^{3.35 \pm 0.25}. $$

(2)

This is in good agreement with the evolution found in fainter NLXGs by Almaini et al. (1997). We use this luminosity function to calculate the predicted NLXG number-flux relation to very faint limits. We integrate this model out to $z = 4$, with no evolution beyond $z_{\text{max}} = 2$, as observed for broad-line AGN (eg. Boyle et al 1994). We use a local luminosity function defined over the range $10^{39} - 10^{45}\text{erg s}^{-1}$. We ignore NLXGs with X-ray luminosities below $10^{39}\text{erg s}^{-1}$ since these appear to have more ‘normal’ X-ray to optical ratios (eg. Della-Ceca et al. 1996) and are therefore less likely to be AGN. A correction was made to convert to the 0.5 - 2keV ROSAT band by assuming an X-ray spectral index of $\Gamma = 1.4$, as required if these objects are to explain the XRB. This also modifies the evolution to the form $L_z^* \propto (1 + z)^{2.75 \pm 0.25}$.

The resulting predicted faint source counts are displayed in Figure 1. The dominant uncertainty in the extrapolation is the slope of the faint end of the luminosity function. The dotted lines in Figure 1 show the effect of varying this parameter within its 1$\sigma$ error. Integrating this distribution to the faintest limits ($10^{-20}\text{erg s}^{-1}\text{cm}^{-2}$) we obtain an NLXG contribution of $\sim 25 \pm 13$ of the XRB at 1keV (the upper limit formally diverges and saturates the residual XRB at $\sim 10^{-17}\text{erg s}^{-1}\text{cm}^{-2}$). Throughout this paper we assume that the intensity of the XRB at 1keV is 12.0 keV cm$^{-2}\text{sr}^{-1}\text{keV}^{-1}$ (Georgantopoulos et al. 1996a). The solid line represents the predicted number-flux relation for broad-line QSOs, based on Model U in Boyle et al. (1994). This model predicts that QSOs account for $\sim 40 \pm 10$ per cent of the XRB at 1keV, although for clarity we have not plotted the uncertainties in the expected source counts.

It is clear that extrapolating the Griffiths et al. luminosity function gives very uncertain faint source predictions. Fainter observations are required. In addition, as described in Griffiths et al. (1996), a possible source of error is the incompleteness of the ROSAT survey which defines
the faint end of their sample. In many cases source confusion hindered the unambiguous identification of the faintest X-ray sources and so a first order correction was applied following Boyle et al. (1993). Recent measurements of the number of NLXGs at fainter limits than those probed by Griffiths et al. can allow us to constrain the predicted number-flux relation more tightly. Almaini et al. (1997) used a statistical method to overcome confusion problems directly. By cross-correlating the X-ray sources not firmly identified with QSOs or stars with faint optical galaxy catalogues they obtained a significant positive signal, the amplitude of which implies a surface density of $48 \pm 17$ X-ray galaxies deg$^{-2}$ at a flux of $4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. With the improved resolution of the ROSAT HRI, the confusion problems are considerably reduced. Recent ultra-deep HRI observations by Hasinger (1996) have measured the NLXG number density to a limiting flux of $2 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. Both of these measurements are plotted on Figure 1, in good agreement with the predictions of the Griffiths et al. model, but suggesting tighter constraints on the upper and lower bounds.

To constrain the NLXG contribution further we vary the faint end slope of the luminosity function to obtain an X-ray number-flux relation giving a best fit through the two fainter measurements of Almaini et al. (1997) and Hasinger (1996) (see Figure 1). The revised 1σ error bounds are displayed as the shaded area in Figure 1. By integration of the predicted distribution to $10^{-20}$ erg s$^{-1}$ cm$^{-2}$ these error bounds correspond to 28 – 55 per cent of the XRB at 1keV. The revised upper limits now do not over-predict the XRB at 1keV. In the next section we convert these predictions into optical number counts.

3 THE PREDICTED OPTICAL NUMBER-MAGNITUDE RELATION

To convert the X-ray number counts into the optical band we use the X-ray to optical ratio of NLXGs from the Deep ROSAT Survey of Shanks et al. (1997):

$$f_{\nu}(2\text{keV})/f_{\nu}(4000\text{Å}) = 10^{4.7 \pm 0.8}.$$  

where the error quoted represents the dispersion in X-ray to optical ratios rather than the error on the mean. We adopt an optical spectral index of $\alpha_o = 1$, which assumes that these are predominantly late-type/Irr galaxies similar to those of Tresse et al. (1996). Locally observed Seyfert 2 galaxies have similar optical/UV spectra (Kinney et al. 1991, Heckman et al. 1995).

Since the galaxies in the HDF are believed to be mostly at high redshift ($z > 1$) we choose to convert the X-ray number counts into optical predictions for the I band, corresponding to rest-frame wavelengths in the optical/ultraviolet region. To include the effect of this dispersion in the X-ray to optical spectral index we assume a Gaussian distribution in the log of the flux ratio given above with a dispersion $\sigma = 0.8$ and distribute the optical counts accordingly. The resulting number-magnitude relations are shown in Figure 2, with 1σ error bounds given by the shaded region. Thus in the F814 HDF image, with an approximate magnitude limit of $I = 28$, we predict $\sim 10^3$ QSOs deg$^{-2}$ but a considerably larger number of NLXGs ($\sim 10^2 \pm 0.2$ deg$^{-2}$). With a more conservative lower limit of $\sim 10^{0.8}$ erg s$^{-1}$ (rather than $10^{3.9}$ erg s$^{-1}$) in the X-ray luminosity function, the predicted counts are reduced so that the centre of the shaded region will lie on the dashed line in Figure 2.

4 SUMMARY AND CONCLUSIONS

There is now very strong evidence that a population of X-ray luminous narrow emission-line galaxies could account for the origin of the cosmic X-ray background. We use the latest measurements of the X-ray luminosity function for NLXGs, combined with their number density at the faintest X-ray fluxes, to predict the number of objects expected in deep optical images such as the HDF. Using measurements of the X-ray to optical luminosity ratio, we estimate that this new class of AGN could outnumber broad-line QSOs by two orders of magnitude at a limit of $I \sim 28$, accounting for $\sim 10$ per cent of the faint galaxies in the HDF. We note that if a significant fraction of these galaxies have since merged then the percentage of present day quiescent galaxies which have at one time hosted an X-ray luminous AGN could be much higher.

With current technology we cannot expect to identify the faintest HDF objects by spectroscopy, but even by...
\( I = 22 \) we expect \( \sim 10^3 \) NLXGs deg\(^{-2}\), i.e. a few percent of all galaxies at this magnitude. The brighter X-ray luminous NLXGs identified so far are formally classified as a mixture of starburst and Seyfert 2 galaxies on the basis of standard emission-line ratios (Boyle et al. 1995a). In terms of their optical magnitudes, X-ray properties and redshift distributions, however, the two populations cannot be distinguished. As noted by Boyle et al. (1995a), it seems likely that one underlying physical mechanism is at work. Faint optical redshift surveys (e.g. Tresse et al. 1996) have shown that a large fraction (\( \sim 50 \) per cent) of all faint field galaxies show only emission line features. Differentiating potentially X-ray luminous NLXGs from the field population may therefore be difficult without supporting high resolution X-ray observations. Further work is clearly required to establish a reliable diagnostic method for identifying this ‘new’ class of active galaxies.

Previous predictions of faint X-ray and optical source populations have been made by Treyer & Silk (1993) on the assumption of a population of evolving starbursting dwarf galaxies powered by short lived, massive stars. Such models have difficulty in explaining the XRB however, since ASCA observations of starburst galaxies have revealed soft X-ray spectra which cannot contribute significantly to the hard XRB (e.g. Dela-Ceca et al 1996).

Near infra-red spectroscopy of local NLXGs may provide a conclusive test of the obscured AGN hypothesis by allowing us to see through any obscuring dust to detect broad emission lines in moderately obscured AGN. If the nuclei are heavily obscured then the near infra-red emission may also be obliterated, but in this scenario it is difficult to produce the soft X-ray flux we observe with ROSAT without a very large (\( \sim 10 \) per cent) scattered component. The advection dominated accretion flow model of Di Matteo & Fabian (1997) should also be tested by searching for the inverted radio spectra predicted at short radio wavelengths.

We suggest that future workers on the HDF should be aware that \( \sim 10 \) per cent of the objects are potentially X-ray active and may contain AGN. Obscured QSOs and/or advection dominated accretion models are currently the most likely explanations for these unusual galaxies. If the latter model is correct, we predict that compact radio sources may be coincident with the more active NLXGs in the HDF. Given the subarcsecond resolution of the forthcoming AXAF X-ray satellite, a deep (\( \sim 1 \)Ms) observation of the HDF will be able to identify these X-ray sources to a flux limit of \( \sim 3 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \) (0.5 – 2 keV) and hence test the predicted number-flux relation displayed in Figure 1. Making use of the follow up work already achieved on HDF, we anticipate that such an observation will rapidly establish the true nature of the XRB.

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