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Research Note

The X-ray background-foreground galaxy cross-correlation: evidence for weak lensing?

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Abstract. A significant cross-correlation between the unresolved X-ray background (XRB) at soft energies (0.5 to 2 keV) and foreground bright galaxies has now been reported in several studies. This cross-correlation has been interpreted in terms of a low redshift and a low luminosity active galactic nuclei (AGN) population, clustered similar to optically bright galaxies, as responsible for the unresolved component of the XRB. In contrast to such a low redshift population, we suggest that a correlation between the unresolved XRB and bright optical galaxies can exist due to a high redshift population of X-ray emitting AGNs through weak lensing effects of low redshift large scale structure traced by foreground optical galaxies. We further investigate this possibility and suggest that a substantial fraction of the detected cross-correlation signal can arise from this scenario. The most likely explanation for the observed cross-correlation is that both a population of low redshift sources and a population of high redshift low luminous sources contribute through clustering and lensing effects, respectively. The exact weak gravitational lensing contribution to the detected signal can eventually be used to constrain cosmological parameters, foreground galaxy bias and, more importantly, models of high redshift X-ray emitting sources.

Key words: cosmology: large-scale structure of Universe – cosmology: gravitational lensing – galaxies: active – X-rays: galaxies – X-rays: general

1. Introduction

After many years of observational work and theoretical investigations, the nature and origin of the unresolved component of the cosmic X-ray background (XRB) still remains an unsolved problem. The deep X-ray imaging data, combined with optical spectroscopic observations, now suggest that up to $\sim$ 70% of the soft XRB observed with ROSAT in the 0.5 to 2.0 keV energy band is resolved to individual galaxies, mainly active galactic nuclei (AGN), out to redshifts of $\sim$ 4 and greater (e.g., Miyaji et al. 1998a; Hasinger 1999 contains a recent review). Other than various possibilities that have been suggested in the literature, the exact nature of the remaining contributors to the soft XRB has not been clearly established. The possibilities for candidates so far include a population of low-luminosity galaxies and AGNs, and an optically obscured population of moderate to high redshift and high luminosity galaxies and AGNs. The strong isotropy of the unresolved component of the XRB, as measured by its auto-correlation function, requires that most of the sources responsible are at high redshifts and constraints models involving a population of low redshift and low luminosity AGNs. Returning to an obscured population at optical wavelengths, the hard XRB requires a ratio of obscured to unobscured populations of AGNs that amount to a factor as high as $\sim$ 3; as discussed in Almaini et al. (1999), the implications for such an obscured population is wide ranging.

Recent experimental developments now allow some of these possibilities to be observationally tested. For example, the obscured population at optical wavelengths is expected to be visible at submm and far-infrared (FIR) wavelengths, through reemission of absorbed UV radiation by dust at longer wavelengths. Such sources should now be detected through deep observations with Submm Common User Bolometer Camera (SCUBA; Holland et al. 1998) on the James Clerk Maxwell Telescope. The current ongoing deep surveys with SCUBA will eventually test the exact fraction of obscured AGNs (see, Smail et al. 1999 for a recent review), with initial results suggesting that a dominant AGN fraction as high as 30% may be contributing to current SCUBA number counts (e.g., Cooray 1999a). At hard X-ray wavelengths, most of the Compton-thick AGNs which are absent at soft X-ray bands are expected to be present. Such populations have now been searched with ASCA and the Italian-Dutch BeppoSax satellite (Piro et al. 1995) in the 2 to 10 keV energy band. Contrary to expectations, however, these surveys are finding that all hard X-ray sources have soft X-ray counterparts (Hasinger 1999; however, see, Fiore et al. 1999). As most of these FIR/submm and hard X-ray observational programs are still ongoing, it is unlikely that an exact answer on the sources responsible for the unresolved component will soon be available.

Recently, the existence of a high redshift population of low luminous X-ray emitting sources has been suggested by Haiman & Loeb (1999). These sources are present in cosmological models of hierarchical structure formation and are associated with the first generation of quasars. The presence of a high redshift population of X-ray emitting sources is also suggested by the possibility that there is no clear evidence for a decline in X-ray AGN number counts beyond a redshift of 2.5 (e.g., Miyaji et al. 1998b), which is contrary to optical quasar surveys where a decline has been inferred at high redshifts (e.g., Schmidt et al. 1995). According to the expected number counts of high redshift AGNs from Haiman & Loeb (1999), the contribution to current unresolved XRB from a high redshift AGN population is greater than 90%. Thus, almost all of the present unresolved XRB can be explained with such a low X-ray luminous population and without invoking the presence of optically obscured or Compton-thick sources. In addition to analytical calculations presented in Haiman & Loeb (1999), a population of high redshift low luminous quasars is also present in Monte Carlo realizations of merger histories of dark matter halos based on extended Press-Schechter theory (see, e.g. Cole 1991; Kauffmann & White 1993; Somerville & Kolatt 1998) combined with semi-analytical models of galaxy and quasar formations (Cooray & Haiman, in preparation). Given that the direct detection of such low luminous AGNs at X-ray wavelengths is not likely to be possible with current observational programs, the evidence for such high redshift X-ray sources should be inferred through indirect methods. It is likely that this situation will soon change with upcoming X-ray satellites such as the Chandra X-ray Observatory (CXO)[1] and the X-ray Multiple Mirror (XMM) Telescope[2].

In Almaini et al. (1997), a cross-correlation between the unresolved XRB at soft X-ray energies, based on three ~ 50 ksec ROSAT deep wide-field deep observations, and foreground bright galaxies, down to B-band magnitude of 23, has been presented. Such a correlation has been previously investigated in various studies involving the nature of XRB and sources responsible for it (e.g., Lahav et al. 1993; Miyaji et al. 1994; Carrera et al. 1995; Roche et al. 1996; Refregier et al. 1997; Soltan et al. 1997). The cross-correlation showed a highly significant signal and has been interpreted as evidence for a population of low redshift sources, traced by bright optical galaxies, as contributors to the unresolved XRB. Such an interpretation is based on the fact that detected cross-correlation is due to clustering between sources responsible for the unresolved component of the XRB and optical galaxies. If clustering were not to be present, in a case in which sources responsible for the XRB and optical galaxies were physically distinct in redshift space - or at least at scales greater than ~ 100 Mpc - one would not normally expect any cross-correlation signal to be present. Apart from clustering, however, physically distinct populations can produce detectable cross-correlation if the flux-limited number counts and/or spatial distribution of one population was affected by the other. A well known possibility is that gravitational lensing by foreground sources modifies the distribution and number counts of background sources. Thus, an alternative possibility for the unresolved XRB is a population of sources at high redshifts provided that their X-ray emission is gravitationally lensed through foreground large scale structure. The cross-correlation between such sources and foreground optical galaxies results from the fact that foreground galaxies are a biased tracer of the large scale structure. The presented cross-correlation effect here is similar to the one involving high redshift optical quasars and foreground galaxies as discussed in Bartelmann (1995) and Dolag & Bartelmann (1997). A more general treatment of the cross-correlation between foreground and background samples due to weak gravitational lensing could be found in Sanz et al. (1997) and Moessner & Jain (1998). In both these studies, cross-correlation between two distinct populations in redshift was suggested as a probe of weak lensing due to large scale structure. In Sect. 2, we further investigate this possibility by modeling the X-ray emission from background sources and considering weak lensing effects of X-ray number counts. We use recent results from Haiman & Loeb (1999) to describe the background X-ray population. The general framework for the weak lensing calculation follows Cooray (1999b). We refer the reader to Mellier (1998) for a recent review on weak gravitational lensing, its applications and observations. We follow the conventions that the Hubble constant, H_0, is 100 h km s^{-1} Mpc^{-1} and Ω_i is the fraction of the critical density contributed by the ith energy component: b baryons, ν neutrinos, m all matter species (including baryons and neutrinos) and Λ cosmological constant.

[1] http://asc.harvard.edu
[2] http://astro.estec.esa.nl/XMM/

2. The x-ray background – foreground galaxy cross-correlation

Here, we briefly describe the expected signal between a foreground galaxy population with number density n_g and X-ray sources responsible for the unresolved XRB, n_x. The angular cross-correlation function between the two samples is:

$$w(\theta) = \langle \delta n_g(\hat{\phi}) \delta n_x(\hat{\phi}') \rangle \tag{1}$$

where δn is the excess fluctuations at a given line of sight. The cross-correlation between two physically distinctive samples contain four terms (Moessner & Jain 1998):

$$\begin{aligned} w(\theta) = \quad & \langle \delta n_g^c(\hat{\phi}) \delta n_x^c(\hat{\phi}') \rangle + \langle \delta n_g^c(\hat{\phi}) \delta n_x^\mu(\hat{\phi}') \rangle \\ & + \langle \delta n_g^\mu(\hat{\phi}) \delta n_x^c(\hat{\phi}') \rangle + \langle \delta n_g^\mu(\hat{\phi}) \delta n_x^\mu(\hat{\phi}') \rangle, \end{aligned} \tag{2}$$

where δn^c is the fluctuations due to clustering of the sources while δn^μ is fluctuations due to gravitational lensing. These two terms can be written as,

$$\delta n^c(\hat{\phi}) = \int_0^{\chi_H} d\chi \, b(r(\chi)\hat{\phi}, \chi) W(\chi) \delta(r(\chi)\hat{\phi}, \chi) \tag{3}$$

and,

$$\delta n^\mu(\hat{\phi}) = 3(\alpha - 1)\Omega_m \int_0^{\chi_H} d\chi \, g(\chi) \delta(r(\chi)\hat{\phi}, \chi), \tag{4}$$

respectively. Here, χ_H is the comoving distance to the horizon, $W(\chi)$ is the radial distribution of sources, α is the slope of number counts of these sources, $n \propto S^{-\alpha}$ with flux S, $b(r(\chi)\hat{\phi}, \chi)$

is the source bias with respect to matter distribution, assuming to be both scale and time dependent, and $g(\chi)$ is a weight function:

$$g(\chi) = r(\chi) \int_{\chi}^{\chi_H} \frac{r(\chi' - \chi)}{r(\chi')} W(\chi') d\chi'. \quad (5)$$

In Eqs. (3), (4) and (5), $r(\chi)$ is the comoving angular diameter distance written as $r(\chi) = 1/\sqrt{-K} \sin \sqrt{-K}\chi$, χ, $1/\sqrt{K} \sinh \sqrt{K}\chi$ for closed, flat and open models respectively with $K = (1 - \Omega_{\rm tot}) H_0^2/c^2$ and χ is the radial comoving distance related to redshift z through:

$$\chi(z) = \frac{c}{H_0} \int_0^z dz' \times \left[\Omega_m (1+z')^3 + \Omega_k (1+z')^2 + \Omega_\Lambda\right]^{-1/2}. \quad (6)$$

The lensing term in the cross-correlation is due to the fact that number counts of lensed background sources are affected in two ways: magnification by a factor μ so that lensed counts reach a fainter flux level (S/μ) and distortion of the observed area such that solid angle observed is reduced by a factor $1/\mu$. Thus, lensed number counts change to $n' \propto \mu^{\alpha-1} S^{-\alpha}$ from unlensed counts of $n \propto S^{-\alpha}$. In the weak lensing limit, magnification $\mu = 1 + 2\kappa$, where κ is the convergence and is equivalent to a weighted projection, via $g(\chi)$, of the matter distribution along the line of sight to background sources (see, e.g., Jain & Seljak 1997; Kaiser 1998; Schneider et al. 1998).

The four terms in the cross-correlation are respectively: (1) clustering of sources in the two samples, when their redshift distributions overlap (2) lensing of background sources by large scale structure front of them traced by foreground galaxies (3) lensing of foreground sources by large scale structure traced by background galaxies; this term is non-zero only if there is an overlap in redshift distribution between the two samples, and (4) lensing of both foreground and background sources by large scale structure.

When there is no overlap in redshift between the two samples, terms (1) and (3) are zero, while the last term can be ignored as its contribution is an order of magnitude lower than the 2nd term involving lensing of background sources by foreground large scale structure. The gravitational lensing effect results from two effects: (1) magnification due to lensing such that sources too faint to be included due to flux limit are now introduced and (2) modification of the observed solid angle, or volume, such that number counts are diluted. Considering these two well known effects, finally, the cross-correlation between two samples separated in redshift space can be written in the weak lensing limit as:

$$w_{gx}(\theta) = 3 b_g \Omega_m (\alpha_x - 1) \int_0^{\chi_H} W_g(\chi) \frac{g_x(\chi)}{a(\chi)} \int_0^\infty \frac{dk\, k}{2\pi} P(k,\chi) J_0\left[k r(\chi) \theta\right] \quad (7)$$

where $W_g(\chi)$ and $W_x(\chi)$ are the radial distributions of foreground galaxies and background X-ray sources, α_x is the slope of number counts of background X-ray emitting sources at the limit of the unresolved background, and b_g is the galaxy bias, assuming a linear bias independent of scale and time. The detailed derivation of Eq. (7), can be found in Bartelmann (1995) for an Einstein-de Sitter Universe with an extension to general cosmologies and nonlinear evolution of the power spectrum in Dolag & Bartelmann (1997), Sanz et al. (1997) and Moessner & Jain (1998). Here, we have introduced slope of the number counts, α_x, for background X-ray sources, while, for example, in Moessner & Jain (1998) background sources were considered to be galaxies with a logarithmic number count slope of s in magnitudes.

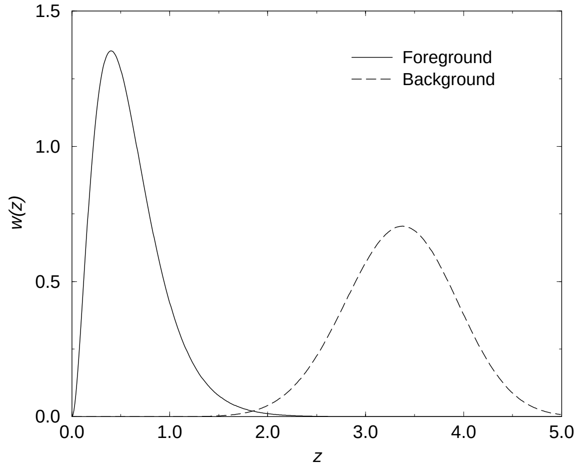

Fig. 1. The redshift distribution of foreground galaxy and background X-ray sources.

2.1. *Expected contribution from weak lensing*

In order to estimate the expected level of contribution from weak lensing effects, we describe the background X-ray sources following calculations presented in Haiman & Loeb (1999). The foreground sources are described following Almaini et al. (1997), with a redshift distribution that peaks at a redshift of ~ 0.5 and decreases to zero by redshift around ~ 2.0. Such a redshift distribution for galaxies down to a magnitude limit of 23 in B-band is consistent with observations. We assume that galaxies are biased such that $b_g = 1/\sigma_8$, which should adequate for the present calculation. Since most of the galaxies are at low redshifts, our predictions are insensitive to the exact redshift distribution of background sources as long as their redshifts are greater than 2.0. For the purpose of this calculation, we consider a background redshift distribution in which X-ray sources are distributed around a mean redshift of ~ 3.5. In Fig. 1, we show the two foreground and background redshift distributions. There is a slight overlap in redshift between the two distributions, but we have ignored it for the purpose of this calculation.

Our input dark matter power spectrum and its non-linear evolution is calculated following Cooray (1999b) using the fitting formulae given in Hu & Eisenstein (1998) to obtain the transfer function and Peacock & Dodds (1996) to obtain the non-linear evolution. We consider cosmologies in which $\Omega_b = 0.05$, $\Omega_\nu = 0.0$, $h = 0.65$. The power spectrum is normalized to

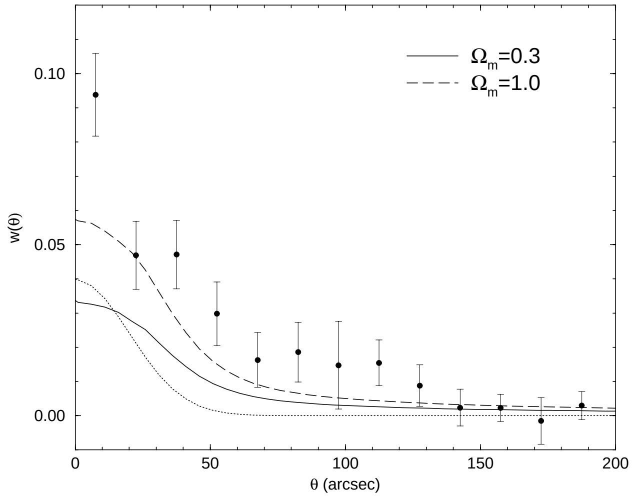

Fig. 2. The observed cross-correlation between the XRB and foreground galaxies. Data are from Almaini et al. (1997). The two curves show the expected weak lensing contribution for two cosmological models involving $\Omega_m = 1.0$ (dashed line) and $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ (solid line). The dotted line is the expected Poisson noise contribution to the cross-correlation (see text).

$\sigma_8(= 0.56\Omega_m^{-0.47})$ as determined by number density of galaxy clusters (Viana & Liddle 1996). Following calculations presented in Haiman & Loeb (1999), we determined the slope of X-ray number counts, α, at the limit of the unresolved XRB to be ~ 1.2. This number, however, is not well determined and is highly sensitive to how one models the X-ray emission from high redshift low luminous sources and number counts of such sources, as derived based on the Press-Schechter theory. We note that a value for $\alpha < 1.0$ produces a cross-correlation which is negative, while $\alpha = 1.0$ produces no contribution to cross-correlation from weak lensing.

Finally, in order to account for the finite point spread function (PSF) of the PSPC detector, we convolve the expected lensing contribution with a parametric form of the PSF given by Hasinger et al. (1992). In Fig. 2, we show the expected contribution from weak lensing to be observed cross-correlation. The data and associated errors are from Almaini et al. (1997). The two curves show the expected contribution for two cosmological models involving $\Omega_m = 1.0$ and $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

3. Discussion and summary

As shown in Fig. 2, the weak lensing contribution to the observed cross-correlation between the XRB and foreground bright galaxies is substantial. The fractional contribution in the simple model considered here amount up to and more than 50%. Ignoring such a contribution is likely to produce biased estimates on the amplitude of clustering or the luminosity density of X-ray sources. In this respect, we note that previous estimates on the number density and luminosities of sources responsible for the unresolved XRB, using the cross-correlation, is certainly overestimated. In addition to changing cosmological parameters, we can increase the lensing contribution by increasing the foreground galaxy bias or increasing the slope of the X-ray number counts at the limit of the unresolved XRB. Currently, both these quantities, more importantly the slope of the number counts, are unknown. Therefore, it is premature to consider detailed models to explain the XRB using weak lensing effects completely. Since galaxy bias, however, is not expected to be much larger than $1/\sigma_8$, especially at low redshifts considered here, and that the slope of number counts is not likely to be very steep, it is unlikely that weak lensing alone can be used to fully explain the observed cross-correlation signal.

As shown in Fig. 2, weak gravitational lensing and Poisson fluctuations can easily account for almost all of the detected cross-correlation. However, we note that, in addition to weak lensing by large scale structure, strong lensing by individual galaxies and clusters of galaxies can contribute to the observed signal at small lag angles. Such a contribution is likely to be smaller than the weak lensing effect; still, it is likely that we have underestimated the complete lensing contribution to cross-correlation between the unresolved XRB and foreground galaxies by only considering weak lensing effects.

The most likely scenario is that the observed cross-correlation is both due to clustering, from a low redshift population overlapping with the galaxy distribution and weak lensing effects of a high redshift population. The isotropy of the XRB, from its auto-correlation function, requires that bulk of the sources are at redshifts greater than 1. The clustering analysis of the observed XRB-galaxy cross-correlation suggests that up to ~ 40% of the unresolved XRB is due to faint low-redshift X-ray sources (e.g., Almaini et al. 1997; Roche et al. 1996; Soltan et al. 1997). The additional contribution could arise from the high redshift X-ray emitting sources, however, we note that intracluster medium of galaxy clusters and groups as well $\sim 10^6$ Kelvin gas in outskirts of galaxies, where most of the baryons at low redshifts are now believed to be present (Cen & Ostriker 1999), can contribute to the unresolved XRB.

In addition to clustering and lensing terms, an additional term is present in the cross-correlation at zero lag or when $\theta = 0$ due to the Poisson behavior of the background. Even though this term only arises for $\theta = 0$, the finite PSF produces a substantial contribution at angular separations out to ~ 30 arcsecs; the contribution is proportional to the integrated luminosity density of X-ray sources. Following Almaini et al. (1997) and using the Miyaji et al. (1998a) luminosity function for X-ray AGNs at a redshift of ~ 3.5, we have estimated such a Poisson noise contribution to the cross-correlation. In Fig. 2, we show this term with a dotted line. A Poisson fluctuation contribution level similar to the one calculated and a weak lensing contribution similar to the one calculated for $\Omega_m = 1.0$, when added, can easily explain the observed cross-correlation signal. As stated earlier, given that we have no reliable knowledge on the number counts and foreground galaxy bias, such a fit to the observed data is meaningless. We leave the task of a detailed comparison between the observed XRB and galaxy cross-correlation and various models involving lensing, clustering and Poisson contributions to a later paper. In fact, if the contribution to cross-correlation from latter two terms can be independently determined, then the lensing contribution can be used as a probe of the high redshift low luminosity X-ray source population, in addition to possibilities as a cosmological probe and a method to determine foreground galaxy bias. For now, we strongly suggest that there is adequate evidence for a weak lensing contribution to the observed unresolved XRB - foreground galaxy cross-correlation.

Here, we have presented a hypothesis for the observed cross-correlation between the unresolved XRB and foreground bright galaxies using a population of high redshift X-ray sources. The upcoming surveys with CXO and XMM will allow the detection of such high redshift low luminosity sources, as discussed in Haiman & Loeb (1999) for the case of CXO. The followup observations of such deep and planned X-ray imaging of wide fields will eventually test the presence of such a population. In fact, the planned Guaranteed Time Observations (GTO) of several deep fields with CXO, such as the Hubble Deep Field (HDF; Williams et al. 1996), can easily be used to test the hypothesis whether remaining contributors to the unresolved XRB are a low redshift or high redshift population. The possibility that whether the cross-correlation is due to clustering of low redshift sources or lensing of high redshift sources can then be statistically studied based on the observed redshift distribution and luminosity function of X-ray emitting sources.

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