Cosmological constraints from X-ray AGN clustering and Type Ia supernova data

S. Basilakos1* and M. Plionis1

1Institute of Astronomy & Astrophysics, National Observatory of Athens, I. Metaxa & V. Pavlou, Palaia Penteli, 15236 Athens, Greece
2Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Apartado Postal 51 y 216, 72000, Puebla, Pue., Mexico

Abstract

We put constraints on the main cosmological parameters of different spatially flat cosmological models by combining the recent clustering results of XMM–Newton soft (0.5–2 keV) X-ray sources, which have a redshift distribution with median redshift $z \sim 1.2$, and Type Ia supernova data. Using a likelihood procedure we find that the model that best reproduces the observational data and which is consistent with stellar ages is the concordance $\Lambda$ cold dark matter model with $\Omega_m \simeq 0.28$, $w \sim -1$, $H_0 \simeq 72$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_\Lambda \simeq 13.5$ Gyr, and has an X-ray active galactic nucleus clustering evolution which is constant in physical coordinates. For a different clustering evolution model (constant in comoving coordinates) we find another viable model, although less probable because of the smaller age of the universe, with $\Omega_m \simeq 0.38$, $w \sim -1.25$, $H_0 \simeq 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_\Lambda \simeq 12.9$ Gyr.

Key words: galaxies: clusters: general – cosmology: theory – large-scale structure of Universe – X-rays: general.

1 Introduction

Recent advances in observational cosmology, based on the analysis of a multitude of high-quality observational data (Type Ia supernovae (SNe Ia), cosmic microwave background (CMB), large-scale structure, age of globular clusters, high-redshift galaxies), have strongly indicated that we are living in a flat ($\Omega_{\text{tot}} = 1$) accelerating Universe containing a small baryonic component, non-baryonic cold dark matter (CDM) to explain the clustering of extragalactic sources and an extra component with negative pressure, usually named ‘dark energy’, to explain the present accelerated expansion of the Universe (e.g. Riess et al. 1998; Perlmutter et al. 1999; Efstathiou 2002; Percival et al. 2002; Spergel et al. 2003; Tonry et al. 2003; Schuecker et al. 2003; Riess et al. 2004; Tegmark et al. 2004).

In the last few years there has been much theoretical speculation regarding the nature of the exotic ‘dark energy’. Various candidates have been proposed in the literature, among which are the time-varying $\Lambda$-parameter (e.g. Ozer & Taha 1987), a scalar field having a self-interaction potential $V(\Phi)$ with the field energy density decreasing at a lower rate than the matter energy density [also dubbed ‘quintessence’ (e.g. Peebles & Ratra 2003, and references therein)] or an extra ‘matter’ component, which is described by an equation of state $p_\gamma = \omega \rho_\gamma$ with $w < -1/3$ [a redshift dependence of $w$ is also possible but present measurements are not precise enough to allow meaningful constraints (e.g. Dicus & Repko 2004)]. A particular case of ‘dark energy’ is the traditional $\Lambda$-model which corresponds to $w = -1$. Note that a variety of observations indicate that $w < -0.6$ for a flat geometry (e.g. Ettori, Tozzi & Rosati 2003; Tonry et al. 2003; Riess et al. 2004; Schuecker 2005).

In this Letter we put constraints on spatially flat cosmological models using the recently derived clustering properties of the XMM–Newton soft (0.5–2 keV) X-ray point sources (Basilakos et al. 2005), the SN Ia data (Tonry et al. 2003) and the age of globular clusters (e.g. Cayrel et al. 2001; Krauss 2003). Hereafter will use the normalized Hubble constant $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$.

2 X-ray active galactic nucleus clustering

In a previous paper (Basilakos et al. 2005) we derived the angular correlation function of the soft (0.5–2 keV) XMM–Newton X-ray sources using a shallow (2–10 ks) wide-field survey ($\sim 2.3$ deg$^2$). A full description of the data reduction, source detection and flux estimation is presented by Georgakakis et al. (2004). Note that the survey contains 432 point sources within an effective area of $\sim 2.1$ deg$^2$ (for $f_\gamma \geq 2.7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$), while for $f_\gamma \geq 8.8 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ the effective area of the survey is $\sim 1.8$ deg$^2$. In Basilakos et al. (2005) we present the details of the correlation function estimation, the various biases that should be taken into account (the amplification bias and integral constraint), the survey luminosity and selection functions as well as issues related to possible stellar contamination. In particular, the redshift selection function of our X-ray sources, derived by using the soft-band luminosity function of Miyaji, Hasinger & Schmidt (2000),
and assuming the realistic luminosity-dependent density evolution of our sources, predicts a characteristic depth of $z \simeq 1.2$ for our sample (for details see Basilakos et al. 2005).

Our aim here is to compare the theoretical clustering predictions from different flat cosmological models with the actual observed angular clustering of distant X-ray AGNs. For the purpose of this study we use Limber’s formula which relates the angular, $u(\theta)$, and the spatial, $\xi(r)$, correlation functions. In the case of a spatially flat universe, Limber’s equation can be written as

$$u(\theta) = 2 \int_0^\infty \int_0^\infty x^2 \phi(x) \xi(r, z) \frac{dx}{E(x)} \frac{du}{\theta},$$

(1)

where $\phi(x)$ is the selection function (the probability that a source at a distance $x$ is detected in the survey) and $x$ is the coordinate distance related to the redshift through

$$x(z) = \frac{c}{H_0} \int_0^z \frac{dy}{E(y)},$$

(2)

with $E(z) = \Omega_m(1+z)^3 + (1 - \Omega_m)(1+z)^{(1/2)}$ and $\beta = 3(1+w)$. The number of objects within a shell $(z, z+dz)$ and in a given survey of solid angle $d\omega$ is

$$dN = \omega_s x^2 n_s \phi(x) \left( \frac{c}{H_0} \right) \frac{E^{-1}(z)}{E(y)},$$

(3)

where $n_s$ is the comoving number density at zero redshift. Combining the above system of equations we obtain

$$u(\theta) = 2 \frac{H_0}{c} \int_0^\infty \left( \frac{1}{N} \frac{dN}{dz} \right)^2 E(z)dz \int_0^\infty \xi(r, z) du,$$

(4)

where $r$ is the physical separation between two sources, having an angular separation, $\theta$, given by $r \simeq (1+z)^{-1} (x^2 + x^2 \theta^2)^{1/2}$ (small-angle approximation). Therefore, in order to estimate the expected $u(\theta)$ in a cosmological model we also need to determine the source redshift distribution $dN/dz$, which, as we said previously, is estimated by integrating the appropriate Miyaji et al. (2000) luminosity function.

2.1 The role and evolution of galaxy bias

It has been claimed that the large-scale clustering of different mass tracers (galaxies or clusters) is biased with respect to the matter distribution (cf. Kaiser 1984; Bardeen et al. 1986). It is also an essential ingredient for CDM models to reproduce the observed galaxy distribution (cf. Davis et al. 1985). Within the framework of linear biasing (cf. Kaiser 1984; Benson et al. 2000), the mass tracer and dark matter spatial correlations, at some redshift $z$, are related by

$$\xi(r, z) = \xi_{m}(r, z) b^2(z),$$

(5)

where $b(z)$ is the bias evolution function. This has been shown to be a monotonically increasing function of redshift (Mo & White 1996; Matzarresse et al. 1997; Basilakos & Plionis 2001, and references therein). Here we use the bias evolution model of Basilakos & Plionis (2001), Basilakos & Plionis (2003), which is based on linear perturbation theory and the Friedmann-Lemaître solutions of the cosmological field equations. We remind the reader that for the case of a spatially flat cosmological model our general bias evolution can be written as

$$b(z) = A E(z) + C E(z) \int_z^\infty \frac{(1+y)^3}{E^2(y)} dy + 1.$$

(6)

Note that our model gives a family of bias curves, due to the fact that it has two unknowns (the integration constants $A$ and $C$). In this paper, for simplicity, we fix the value of $C$ to $\pm 0.004$, as was determined by Basilakos & Plionis (2003) from the Two-degree Field (2dF) galaxy correlation function. We have tested the robustness of our results by increasing $C$ by a factor of 10 and 100 to find differences of only $\pm 5$ per cent in the fitted values of $\Omega_m$ and $h_0$. This behaviour can be explained from the fact that the dominant term on the right-hand side of equation (6) is the first term $[\alpha (1+z)^{3/2}]$, while the second term has a slower dependence on redshift $[\alpha (1+z)]$.

2.2 Clustering evolution

The redshift evolution of the spatial mass correlation function, $\xi_{m}(r, z)$, can be written as the Fourier transform of the spatial power spectrum $P(k)$. Using also equation (5) we have

$$\xi(r, z) = \frac{(1+z)^{3(1+\gamma)/2}(z)}{2\pi^2} \int_0^\infty k P(k) \frac{\sin(kr)}{kr} dk,$$

(7)

where $k$ is the comoving wavenumber. Note that the parameter $\gamma$ parametrizes the type of clustering evolution (e.g. de Zotti et al. 1990). If $\gamma = 3$ (with $\gamma$ the slope of the spatial correlation function; $\gamma = 1.8$) the clustering is constant in comoving coordinates, while if $\gamma = -3$ the clustering is constant in physical coordinates.

The power spectrum of our CDM models is given by $P(k) \propto k^3 \xi^{2}(k)$ with scale-invariant $(n = 1)$ primeval inflationary fluctuations and $T(k)$ the CDM transfer function. In particular, we use the transfer function parametrization as in Bardeen et al. (1986), with the corrections given approximately by Sugiyama (1995) while the normalization of the power spectrum is given by $\sigma_8 = 0.5 \Omega_m^{0.25}$ with $\gamma = 0.30 - 0.35$ for $m + 0.33 \Omega_m$ (Wang & Steinhardt 1998). We caution that this fit, based on the rich cluster abundances, has been derived for $w > -1$. In this work we assume that the fit is valid also for $w < -1$. Note that we also use the non-linear corrections introduced by Peacock & Dodds (1994).

3 COSMOLOGICAL CONSTRAINTS

3.1 X-ray AGN clustering likelihood

It has been shown that the application of the correlation function analysis on samples of high-redshift galaxies can be a useful tool for cosmological studies (e.g. Matsubara 2004). In our case, to constrain the cosmological parameters we utilize a standard $\chi^2$ likelihood procedure to compare the observed XMM–Newton angular correlation function, $w_{\text{obs}}(\theta)$ (Basilakos et al. 2005) with the prediction of different spatially flat cosmological models. In particular, we define the likelihood estimator 1 as $L_{\text{AGN}}(e) \propto \exp[-\chi^2_{\text{AGN}}(e)/2]$, with

$$\chi^2_{\text{AGN}}(e) = \sum_{i=1}^n \left[ \frac{w(\theta_i, e) - w_{\text{obs}}(\theta_i)}{\sigma_i} \right]^2,$$

(8)

where $e$ is a vector containing the cosmological parameters that we want to fit, and $\sigma_i$ is the observed angular correlation function uncertainty. Here we work within the framework of a flat ($\Omega_{\text{tot}} = 1$) cosmology with primordial adiabatic fluctuations and baryonic density of $\Omega_b h^2 \simeq 0.022$ (e.g. Kirkman et al. 2003). In this case the corresponding vector is $e \equiv (\Omega_m, w, h, b_0)$. We sample the

1 Likelihoods are normalized to their maximum values.

© 2005 RAS, MNRAS 360, L35–L38
step function of 0.02; and the X-ray sources bias at the present time. The contours are plotted where $-2 \ln \mathcal{L}_\text{max}$ is equal to 2.30, 6.16 and 11.83, corresponding to $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels. The cross represents the ΛCDM case ($w = -1$).

We use the sample of 172 supernovae of Tonry et al. (2003) in order to constrain $\Omega_m$ and the equation of state in the framework of a flat geometry ($\Omega_{\text{tot}} = 1$). In this case, the corresponding vector $e$ is $e = (\Omega_m, w)$ and the likelihood function can be written as $\mathcal{L}_\text{SNe Ia}(e) \propto \exp[-\chi^2_{\text{SNe Ia}}(e)/2]$ with

$$\chi_{\text{SNe Ia}}^2(e) = \frac{1}{\sigma_i} \sum_{i=1}^{172} \left[ \log D_L(z_i, e) - \log D_L^{\text{obs}}(z_i) \right]^2,$$

where $D_L(z)$ is the dimensionless luminosity distance, $D_L(z) = H_0(1 + z)\chi(z)$ and $z_i$ is the observed redshift. The green lines in Fig. 2 represent the $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels in the $(\Omega_m, w)$ plane. We find that the best-fitting solution is $\Omega_m = 0.30 \pm 0.04$ for $w > -1$, in complete agreement with previous SN Ia studies (Tonry et al. 2003; Riess et al. 2004).

### 3.3 The joined likelihoods

In order to combine the X-ray AGN clustering properties with the SN Ia data, we perform a joint likelihood analysis and, marginalizing the X-ray clustering results over $h$ and $b_0$, which are not constrained by the value of $w$ (see Fig. 1), we obtain $\mathcal{L}_{\text{joint}}(\Omega_m, w) = \mathcal{L}_{\text{AGN}} \times \mathcal{L}_{\text{SNe Ia}}$. Also taking the age limit into account (the yellow area in Fig. 2), the likelihood for the $e = -1.2$ clustering evolution model peaks at $\Omega_m = 0.28 \pm 0.02$ with $w = -1.05^{+0.10}_{-0.20}$ (corresponding to $t_0 = 13.5$ Gyr) which is in excellent agreement with the WMAP results of Spergel et al. (2003) and the REFLEX X-ray clusters + SNe Ia results of Schuecker et al. (2003). For the $e = -3$ clustering

The result for the joined analysis is consistent with $\Omega_{\text{tot}} = 1$, and the corresponding vector $e$ is $e = (\Omega_m, w)$ and the likelihood function can be written as $\mathcal{L}_{\text{joint}}(e) \propto \exp[-\chi^2_{\text{joint}}(e)/2]$ with

$$\chi_{\text{joint}}^2(e) = \frac{1}{\sigma_i} \sum_{i=1}^{172} \left[ \log D_L(z_i, e) - \log D_L^{\text{obs}}(z_i) \right]^2,$$

## Table 1

Cosmological parameters from the likelihood analysis. The first column indicates the data used (the last two rows correspond to the joint likelihood analysis). Errors of the fitted parameters represent $\sigma$ uncertainties (‘uncon.’ means ‘unconstrained’). Note that for the joined analysis the corresponding results are marginalized over the Hubble constant and the bias factor at the present time, for which we use the values indicated.

| Data                      | $\Omega_m$    | $w$          | $h$          | $b_0$         | $t_0$         | $\chi^2$/d.o.f. |
|---------------------------|---------------|--------------|--------------|---------------|---------------|-----------------|
| XMM–Newton ($e = -1.2$)   | 0.31$^{+0.16}_{-0.08}$ | uncon. (w = -1) | 0.72$^{+0.02}_{-0.03}$ | 2.30$^{+0.70}_{-0.20}$ | 13.0          | 0.82            |
| XMM–Newton ($e = -3.0$)   | 0.38$^{+0.02}_{-0.14}$ | uncon. (w = -1) | 0.70$^{+0.04}_{-0.16}$ | 12.0$^{+0.60}_{-0.30}$ | 12.6          | 0.84            |
| XMM–Newton ($e = -1.2$)/SNe Ia | 0.28 ± 0.02   | -1.05$^{+0.10}_{-0.20}$ | 0.72          | 2.30          | 13.5          | 0.87            |
| XMM–Newton ($e = -3.0$)/SNe Ia | 0.38 ± 0.03   | -1.25$^{+0.10}_{-0.25}$ | 0.70          | 1.20          | 12.9          | 0.85            |

### Figure 1

Likelihood contours in the ($w$, $h$) plane (left-hand panel) and the ($w$, $b_0$) plane (right-hand panel) for $e = -1.2$ (a similar degeneracy is true also for the $e = -3$ clustering evolution model). The contours are plotted where $-2 \ln \mathcal{L}/\mathcal{L}_{\text{max}}$ is equal to 2.30, 6.16 and 11.83, corresponding to $1\sigma$, $2\sigma$ and $3\sigma$ confidence levels.

### Figure 2

Likelihood contours in the ($\Omega_m$, $w$) plane. The contours correspond to $1\sigma$ (2.30), $2\sigma$ (6.16) and $3\sigma$ (11.83) confidence levels, using the two different clustering behaviours (left-hand panel for $e = -3$ and right-hand panel for $e = -1.2$). Note that the black and the green lines correspond to the X-ray clustering results over $\epsilon = 1.2$ and $\epsilon = 0.72$, for $h = 0.72$ and $h = 0.7$ for $e = -3$.

---

© 2005 RAS, MNRAS 360, L35–L38

---

2 Hereafter, when we marginalize over the Hubble constant we will use $h = 0.72$ for $e = -1.2$ and $h = 0.7$ for $e = -3$. 

3 The joined likelihoods

In order to combine the X-ray AGN clustering properties with the SN Ia data, we perform a joint likelihood analysis and, marginalizing the X-ray clustering results over $h$ and $b_0$, which are not constrained by the value of $w$ (see Fig. 1), we obtain $\mathcal{L}_{\text{joint}}(\Omega_m, w) = \mathcal{L}_{\text{AGN}} \times \mathcal{L}_{\text{SNe Ia}}$. Also taking the age limit into account (the yellow area in Fig. 2), the likelihood for the $e = -1.2$ clustering evolution model peaks at $\Omega_m = 0.28 \pm 0.02$ with $w = -1.05^{+0.10}_{-0.20}$ (corresponding to $t_0 = 13.5$ Gyr) which is in excellent agreement with the WMAP results of Spergel et al. (2003) and the REFLEX X-ray clusters + SNe Ia results of Schuecker et al. (2003). For the $e = -3$ clustering
evolution model we obtain \( \Omega_m = 0.38 \pm 0.03 \) with \( w = -1.25^{+0.10}_{-0.25} \) (which corresponds to \( t_0 = 12.9 \) Gyr). The latter model appears to be marginally ruled out by the stellar ages. Note that the normalization of the power spectrum that corresponds to these models is \( \sigma_8 \simeq 0.98 \) and \( 0.90 \), respectively.

It is evident that the combined likelihood analysis puts strong constraints on the value of \( w \), and once including stellar ages it appears to favour the standard concordance \( \Lambda \)CDM (\( \Omega_m \simeq 0.3, w \simeq -1 \)) cosmological model as well as a comoving AGN clustering model (\( \epsilon = -1.2 \)). However, the model with \( w \simeq -1.25, \Omega_m \simeq 0.38 \) and \( \epsilon = -3 \) cannot be ruled out at any significant level.

Many other recent analyses utilizing different combinations of data seem to agree with the former cosmological model. For example, Tegmark et al. (2004) used the WMAP CMB anisotropies in combination with the Sloan Digital Sky Survey galaxy power spectrum and found a good \( \Lambda \)CDM fit with \( \Omega_m = 0.30 \pm 0.04 \) and \( h = 0.70^{+0.04}_{-0.03} \) (see also Percival et al. 2002; Spergel et al. 2003; Schuecker et al. 2003). Also combining the gas fraction in relaxed X-ray-luminous clusters with the CMB and SNe Ia has provided stringent constraints on the value of \( w \), and once including stellar ages it cannot be excluded at any significant level.

### 4 CONCLUSIONS

We have combined for the first time the clustering properties of distant X-ray AGNs, identified as soft (0.5–2 keV) point sources in a shallow \( \sim 2.3 \) deg\(^2\) XMM–Newton survey, which have a \( z \)-distribution that peaks at \( z \simeq 1.2 \), with SN Ia data. From the X-ray AGN clustering likelihood analysis alone we constrain \( h \simeq 0.72 \pm 0.03 \) (where the uncertainty is found after marginalizing over \( w \) and \( b_0 \)). From the joined likelihood analysis and taking into account stellar ages, we constrain the matter density and the equation-of-state parameters. The best model appears to be one with \( \Omega_m \simeq 0.28, w \simeq -1 \) and a stable in comoving coordinates X-ray AGN clustering model. However, the model with \( \Omega_m \simeq 0.38, w \simeq -1.25 \) and constant in physical coordinates (\( \epsilon = -3 \)) X-ray AGN clustering, of which the predicted age is marginally consistent with stellar ages, cannot be excluded at any significant level by our analysis.

### ACKNOWLEDGMENTS

We would like to thank the referee, Peter Schuecker, for useful suggestions.

**REFERENCES**

Allen S. W., Schmidt R. W., Ebeling H., Fabian A. C., Speysbroeck L., 2004, MNRAS, 353, 457

Bardeen J. M., Bond J. R., Kaiser N., Szalay A. S., 1986, ApJ, 304, 15

Basilakos S., Plionis M., 2001, ApJ, 550, 522

Basilakos S., Plionis M., 2003, ApJ, 593, L61

Basilakos S., Plionis M., Georgantopoulos I., Georgakakis A., 2005, MNRAS, 356, 183

Benson A. J., Cole S., Frenk C. S., Baugh M. C., Lacey G. C., 2000, MNRAS, 311, 793

Caldwell R. R., 2002, Phys. Lett. B, 545, 23

Cayrel R. et al., 2001, Nat, 409, 691

Corasaniti P. S., Kunz M., Parkinson D., Copeland E. J., Basset B. A., 2004, Phys. Rev. Lett., 80, 3006

Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371

de Zotti G., Persic M., Franceschini A., Danese L., Palumbo G. G. C., Boldt E. A., Marshall F. E., 1990, ApJ, 351, 22

Dicus D. A., Repko W. W., 2004, Phys. Rev. D, 70, 3527

Efstathiou G., 2002, MNRAS, 330, L29

Ettori S., Tozzi P., Rosati P., 2003, A&A, 398, 879

Freedman W. L. et al., 2001, ApJ, 553, 47

Georgakakis A. et al., 2004, MNRAS, 349, 135

Kaiser N., 1984, ApJ, 284, L9

Kirkman D., Tytler D., Suzuki N., O’Meara J. M., Lubin D., 2003, ApJS, 149, 1

Krauss L. M., 2003, ApJ, 596, L1

Matarrese S., Coles P., Luccin F., Moscardini L., 1997, MNRAS, 286, 115

Matsubara T., 2004, ApJ, 615, 573

Miyaji T., Hasinger G., Schmidt M., 2000, A&A, 353, 25

Mo H. J., White S. D. M., 1996, MNRAS, 282, 347

Ozer M., Taha O., 1987, Nucl. Phys. B, 287, 776

Peacock A. J., Dodds S. J., 1994, MNRAS, 267, 1020

Perlmutter S. et al., 1999, ApJ, 517, 565

Riess A. G. et al., 1998, AJ, 116, 1009

Riess A. G. et al., 2004, ApJ, 607, 665

Schuecker P., 2005, astro-ph/0502234

Schuecker P., Caldwell R. R., Böringer H., Collins C. A., Guzzo L., Weinberg N. N., 2003, A&A, 402, 53

Spergel D. N. et al., 2003, ApJS, 148, 175

Sugiyama N., 1995, ApJS, 100, 221

Tegmark M. et al., 2004, Phys. Rev. D, 69, 3501

Tonry J. et al., 2003, ApJ, 594, 1

Wang L., Steinhardt P. J., 1998, ApJ, 508, 483

This paper has been typeset from a TeX/LaTeX file prepared by the author.