SLAC-PUB-12037
August 2006

PROBING DARK ENERGY WITH CONSTELLATION-X

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Constellation-X (Con-X) will carry out two powerful and independent sets of tests of dark energy based on X-ray observations of galaxy clusters, providing comparable accuracy to other leading dark energy probes. The first group of tests will measure the absolute distances to clusters, primarily using measurements of the X-ray gas mass fraction in the largest, dynamically relaxed clusters, but with additional constraining power provided by follow-up observations of the Sunyaev-Zel'dovich (SZ) effect. As with supernovae studies, such data determine the transformation between redshift and true distance, $d(z)$, allowing cosmic acceleration to be measured directly. The second, independent group of tests will use the exquisite spectroscopic capabilities of Con-X to determine scaling relations between X-ray observables and mass. Together with forthcoming X-ray and SZ cluster surveys, these data will help to constrain the growth of structure, which is also a strong function of cosmological parameters.

1 Introduction

The late-time accelerated expansion of the Universe is now a well measured fact [17,2,19]. However, the underlying cause of this cosmic acceleration remains unknown. Assuming general relativity, a new energy component of the Universe, so-called dark energy, is required. In order to pin down its nature, a number of powerful future experiments are planned.

Con-X [a] data will constrain dark energy with comparable accuracy and in a beautifully complementary manner to the best other techniques available circa 2018. Using a modest $\sim 10-15\%$ (10-15Ms) investment of the available observing time over the first 5 years of the Con-X mission, we will be able to measure the X-ray gas mass fraction (or predict the Compton y-parameter) to 5% or 3.5% accuracy, corresponding to 3.3% or 2.3% in distance, for 500 or 250 clusters, respectively, with a median redshift $z \sim 1$. When combined with CMB data or suitable priors, the predicted dark energy constraints from Con-X X-ray data are comparable to those projected by e.g. future supernovae, weak lensing and baryon oscillation experiments. Only by combining such independent and complementary methods can a rigorous and precise understanding of the nature of dark energy be achieved.

2 Gas mass fraction, $f_{\rm gas}$, in X-ray galaxy clusters

The matter content of the largest, dynamically relaxed galaxy clusters is expected to provide an almost fair sample of the matter content of the Universe, $\Omega_{\rm m}$ [22,23,6]. The ratio of baryonic to total mass in such clusters should closely match the ratio of the cosmological parameters $\Omega_{\rm b}/\Omega_{\rm m}$ (where $\Omega_{\rm b}$ is the mean baryonic matter density of the Universe in units of the critical density).

[a] http://constellation.gsfc.nasa.gov/

Contributed to XLIst Rencontres de Moriond "Contents and Structures of the Universe, 3/18/2006-3/25/2006, La Thuille, Italy
Work supported in part by DOE Contract No. DE-AC02-76SF00515

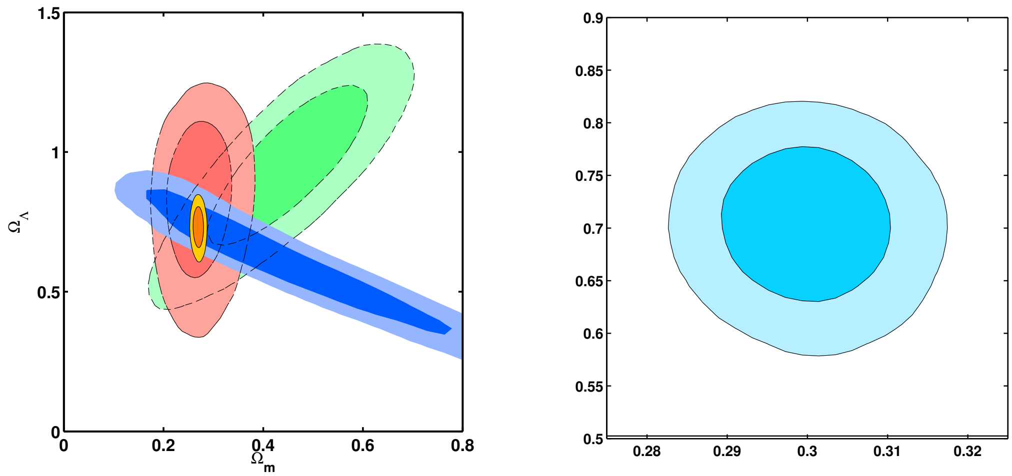

Figure 1: (left panel) The joint 1 and 2 σ contours on $\Omega_{\rm m}$ and Ω_Λ from the current Chandra $f_{\rm gas}(z)$ data (red; Allen et. al 2006, in preparation). Also shown are the constraints from SNIa (green; Riess et al. 2004) and CMB studies (blue; 1st year WMAP+CBI+ACBAR). The same contours from the analysis of the simulated Con-X $f_{\rm gas}$ data set of Fig. 2 are shown in orange. These constraints are also shown alone in the right panel of this figure.

Measurements of the ratio of X-ray gas mass-to-total mass ratio in clusters as a function of redshift, $f_{\rm gas}(z)$, can also be used to measure cosmic acceleration directly [17,2,16].

Current Chandra X-ray Observatory $f_{\rm gas}(z)$ data for 41 hot ($kT > 5$keV), X-ray luminous ($L_{\rm X} > 10^{45} h_{70}^{-2}$ erg/s), dynamically relaxed clusters spanning the redshift range $0.06 < z < 1.07$, provide a tight constraint on $\Omega_{\rm m} = 0.27 \pm 0.04$ and a $> 99.99\%$ significant detection of the effects of dark energy (cosmic acceleration) on the distances to the clusters [3] (Figure 1: red contours). These selection criteria, especially the restriction to the most relaxed systems, are essential to minimize systematic scatter in the experiment [2]. (Using these selection criteria, systematic scatter is undetected in the present Chandra data, for which the unweighted rms $f_{\rm gas}$ measurement errors are $\sim$ 10%, corresponding to $\sim$ 7% in distance.) Rapetti *et al* (2005a,b) discuss the complementary nature of $f_{\rm gas}$, CMB and type Ia supernovae experiments and the impressive combined degeneracy-breaking power of the data for dark energy studies. Measurements of the growth of structure through X-ray and SZ cluster surveys, weak lensing measurements and baryon oscillation experiments also offer powerful avenues of investigation.

The observed $f_{\rm gas}(z)$ values for a chosen reference (eg ΛCDM) cosmology can be fitted with a model that accounts for the expected apparent variation in $f_{\rm gas}(z)$ as the true, underlying cosmology is varied

$$f_{\rm gas}^{\Lambda{\rm CDM}}(z) = \frac{b\,\Omega_{\rm b}}{\left(1+0.19\sqrt{h}\right)\Omega_{\rm m}} \left[\frac{d_{\rm A}^{\Lambda{\rm CDM}}(z)}{d_{\rm A}^{\rm de}(z)}\right]^{1.5} , \qquad (1)$$

where $d_{\rm A}^{\rm de}(z)$ and $d_{\rm A}^{\Lambda{\rm CDM}}(z)$ are the angular diameter distances ($d_{\rm A} = d_{\rm L}/(1+z)^2$) to the clusters for a given dark energy (*de*) model and the reference ΛCDM cosmology, respectively. $H_0 = 100\,h\,{\rm km\,sec^{-1}\,Mpc^{-1}}$ is the present Hubble parameter and b is the 'bias' factor by which the baryon fraction is depleted with respect to the universal mean (a small amount of gas is expelled by shocks when the cluster forms). In present work, the optically luminous baryonic mass in clusters is assumed to scale as $0.19h^{0.5}$ times the X-ray gas mass [7,1] .

The expected value of b at a given mean enclosed mass overdensity in a cluster can be calibrated by numerical simulations (being one of the more straightforward quantities for such simulations to predict). Current simulations suggest that a Gaussian prior on $b = 0.824 \pm 0.089$ may be appropriate for relaxed clusters in the very high mass/luminosity/temperature range

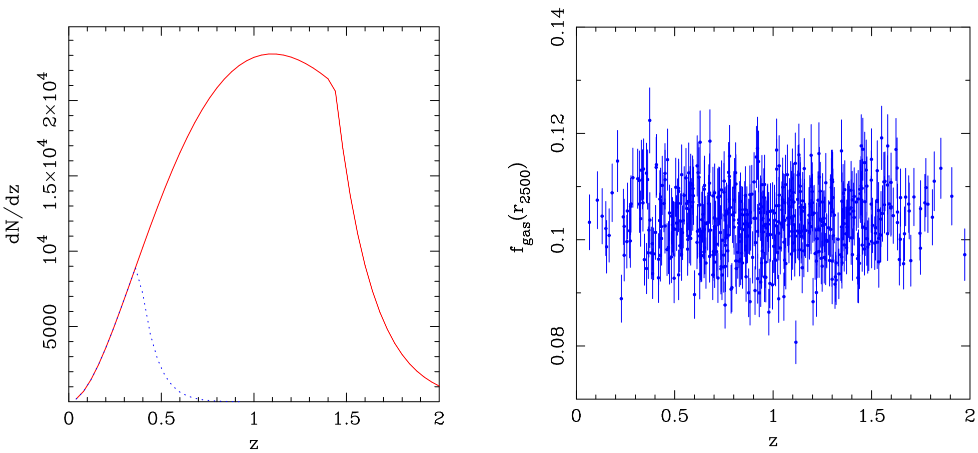

Figure 2: (left panel) The predicted number density of clusters with (bolometric) X-ray luminosities $L_{\rm X} > 10^{45} h_{70}^{-2}$erg/s for a cluster survey flux limit of 5×10^{-14}erg cm^{-2}s^{-1} in the $0.1-2.4$keV band (red, solid curve). The blue, dotted curve shows the results for the same luminosity limit but a $0.1-2.4$keV flux limit of 10^{-12}erg cm^{-2}s^{-1}, appropriate for the ROSAT All-Sky Survey. For illustration purposes, zero scatter in the mass-luminosity relation and negligible flux errors are assumed. The predictions are normalized to observations at lower redshifts (Ebeling et al. 1998, 2001). (right panel) Projected $f_{\rm gas}(z)$ values for a possible Con-X survey of 500 clusters with individual $f_{\rm gas}$ measurement uncertainties of 5%. A systematic scatter of 4% due to cluster-cluster variations is included.

studied [2]. This includes a combined 10% allowance for systematic uncertainties in the overall normalization from various contributing sources. Systematic evolution in the baryonic mass fraction with redshift is a potential source of systematic uncertainty. Such evolution must be understood at the few % level if the full power of future X-ray data is to be extracted. Efforts to provide improved numerical simulations for large samples of the largest, dynamically relaxed clusters, are underway. Efforts to obtain precise, direct measurements of the optically luminous baryonic mass in clusters and its evolution using deep ground-based imaging are also ongoing.

3 Dark energy constraints from Con-X

A possible Con-X $f_{\rm gas}$ study could involve a modest 10-15Ms investment of observing time (approximately 10 per cent of the available observing time over the first 5 years of the mission). Using existing (at that time) X-ray and SZ cluster catalogs, one could initially carry out short (5-10ks) Con-X snapshot exposures and/or high resolution SZ observations of several thousand suitably luminous/massive systems. Based on these initial results, one could identify the 250-500 largest, relaxed clusters and re-observe these for a further 10Ms total, with typical Con-X exposure times of 20 or 40 ks, leading to individual statistical error bars in $f_{\rm gas}$ measurements of 5 or 3.5%. (This gives a precision in the individual distance measurements to the clusters of 3.3 or 2.3%.) Figure 2 shows the projected $f_{\rm gas}$ sample. We include a (possibly conservative) 4% systematic scatter in $f_{\rm gas}$ from cluster to cluster. (Current Chandra data suggest the weighted mean systematic scatter to be $< 5\%$ [3].) We analyze this simulated Con-X $f_{\rm gas}$ data set either alone (imposing 2% Gaussian 1σ width priors on $\Omega_{\rm b}h^2$ and h; Fig. 1, orange contours) or combined with a simulated CMB data set (in this case 8 years of WMAP data) as shown in Figure 3. We intitially use a 2% Gaussian prior on b and assume, in the first instance, negligible systematic evolution in the cluster baryonic mass content with redshift. We employ a full MCMC analysis in order to properly explore the degeneracy breaking power. For the evolving dark energy case of Fig. 3 we obtain comparable results to those projected by supernovae [9] and baryon oscillation experiments [10]. Allowing for unknown linear evolution in the baryonic mass content of clusters at the 2% level over the redshift range $0 < z < 2$ has little effect on the results, increasing only the uncertainity on w' by $\sim 15\%$. Doubling the uncertainty in the

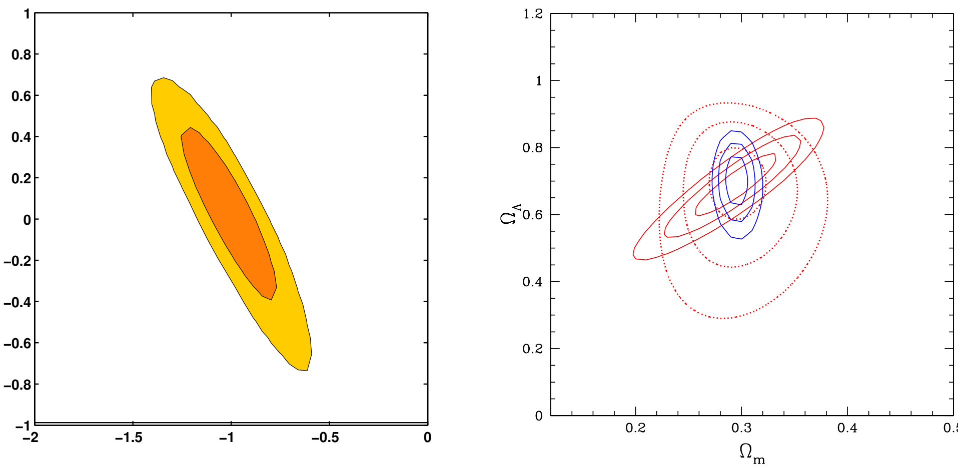

Figure 3: (left panel) Results from the Markov Chain Monte Carlo (MCMC) analysis of simulated Con-X $f_{\rm gas}$+CMB data. The CMB data are WMAP TT data only, appropriate for 8 years of that mission (Upadhye et al 2005). The 68.3 and 95.4 per cent uncertainties in the (w_0, w') plane for a $w(a) = w_0 + 2w'(1-a)$ model are shown. A 2% Gaussian prior on b is assumed. No priors on $\Omega_{\rm b}h^2$, h or $\Omega_{\rm k}$ are required. Similar constraints are achievable from the $f_{\rm gas}$ data alone, given 2% priors on $\Omega_{\rm b}h^2$, h and assuming flatness. Doubling the uncertainty in b and/or allowing for systematic evolution with redshift at the $\leq 4\%$ level does not worsen the plotted constraints significantly (see text for details). (right panel) The 1, 2 and 3 σ constraints for the Con-X X-ray+SZ experiment for the 500 cluster sample of Fig. 2 with 5% statistical errors in the predicted Compton y-values. The blue curve shows the result from the $f_{\rm gas}$ experiment, as in Fig. 1 (orange). The dotted red curve shows the results assuming a combined overall 2% systematic uncertainty in the normalization of the X-ray and SZ y-values and the solid red curve when the systematic uncertainty in this and h (combined) is reduced to 0.1%.

evolution to 4% still has a negligible effect on w_0 but increases the uncertainty on w' by a further $\sim 25\%$. Relaxing the prior on b (the normalization) by a factor 2 (4% Gaussian 1σ width) has little effect on w_0 but weakens the constraints on w' and $\Omega_{\rm m}$ by ~ 15 and $\sim 30\%$, respectively.

The combination of X-ray and Sunyaev-Zel'dovich (SZ) data provides a second, independent method by which to measure absolute distances to clusters. The observed SZ flux can be expressed in terms of the Compton y-parameter. This same Compton y-parameter can be predicted from the X-ray data ($y_{\rm mod} \propto \int n_e T dl$), with the predicted value depending on the assumed cosmology. For the correct cosmology, the observed and predicted y-parameters should agree [12,13,18]. The right panel of Figure 3 shows the projected constraints for a standard ΛCDM cosmology using the same 500 cluster Con-X sample and two illustrative SZ scenarios.

Clusters of galaxies are sensitive probes of the rate at which cosmic structure evolves. Their number density at a fixed mass is exponentially sensitive to the amplitude of linear matter density perturbations. Measurements of the cluster mass function at different redshifts constrains the perturbation growth parameter, which is a second crucial dark energy observable. Statistically, detailed studies of a sample of 1000 clusters can constrain the growth factor to better than 0.5%, leading to constraints on w_0 to $\pm 0.06 - 0.08$ [11,21,8]. The primary contribution of Con-X to this work will be the precise calibration of cluster mass measurements.

4 Closing comments

In probing cosmology via direct distance measurements, Con-X will offer a powerful complement to SNIa studies, giving comparable precision, but using different techniques and assumptions. Features to note include (i) that large relaxed galaxy clusters can, in principle, be well modelled by simulations, although improvements in this and other areas will be required to make full use of Con-X data; (ii) clusters are (in human terms) steady sources and can be revisited to build up signal-to-noise on individual targets and explore systematic issues; (iii) the $f_{\rm gas}$ technique includes inbuilt complementary constraints on $\Omega_{\rm m}$ from both the normalization and shape of the $f_{\rm gas}$ curve; (*iv*) the combination of $f_{\rm gas}$+CMB data breaks additional, key cosmological parameter degeneracies in a remarkably effective manner [14,16]; (*v*) The systematic scatter in the $f_{\rm gas}(z)$ data is small (undetected in current Chandra data) once an appropriate restriction to large, relaxed clusters is employed; (*vi*) direct checks on assumptions like the form of $b(z)$ are possible via combination with SZ data; this combination also provides important extra cosmological information; (vii) the $f_{\rm gas}$ and X-ray+SZ experiments complement 'cluster counting' experiments in that they do not require complete samples (one can simply 'cherry pick' the easiest clusters to work with) and do not rely on calibration relations to link observables to mass.

Acknowledgments

This work was supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

Note in press

A preprint by E. Linder (arXiv:astro-ph/0606602) appears to significantly underestimate the precision of individual Con-X $f_{\rm gas}$ measurements and their degeneracy breaking power, as measured in full MCMC simulations. Our results will be discussed in more detail in a future paper.

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