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Dark energy and cosmic sound

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Abstract

I describe how acoustic oscillations imprinted into the late-time correlations of galaxies by baryonic physics at the epoch of recombination can be used as a cosmological standard ruler. Measurements of this length scale by large galaxy surveys would allow us to compute the angular diameter distance to and Hubble parameter at the redshifts of the survey. This in turn offers a robust way to measure the acceleration of the universe. I briefly present calculations of the statistical performance from baseline surveys; full details of the methods and results are available in Seo and Eisenstein [ApJ, 598 (2003) 720]. I discuss the advantages and disadvantages of the acoustic oscillation method relative to other dark energy probes.

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1. General remarks

The unexpected late-time acceleration of the expansion of the universe (Riess et al., 1998; Perlmutter et al., 1999) ranks as one of the top problems in modern cosmology and physics. Sorting between the myriad proposed solutions will require observations of very high precision, as the differences under debate are typically at the percent level (see Fig. 1). The possibility of

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systematic error, due to the considerable level of precision required, the level of theoretical modeling for interpretation, and/or the need to compare observations at very different redshifts, leads us to seek multiple high precision probes of the cosmological expansion.

Baryonic acoustic oscillations imprinted into the galaxy power spectrum offer a new route to the measurement of dark energy (Eisenstein et al., 1998; Eisenstein, 2003; Blake and Glazebrook, 2003; Linder, 2003; Hu and Haiman, 2003; Seo and Eisenstein, 2003). Prior to the epoch of recombination, the enormous pressure of the cosmic microwave background (CMB) photons opposes cosmological collapse, leading to the establishment of acoustic modes (Peebles and Yu, 1970). When the baryons and electrons combine into atoms, the photons are released from the plasma, but both components are left in a perturbed state with a preferred length scale, namely the distance that a sound wave could travel in the age of the universe to that point. In the case of the photons, the acoustic mode history is manifested as the high-contrast Doppler peaks in today's temperature anisotropies (e.g., Bennett et al., 2003). However, the baryons are left in a similar state that, when mixed with the non-oscillating cold dark matter perturbations, leaves a small residual imprint in the clustering of matter at late times (see Eisenstein and Hu, 1998 for more discussion of this). Fig. 2 shows the resulting low-redshift power spectrum as a function of baryon fraction.

The preferred length scale of the acoustic oscillations, roughly 140 Mpc with overtones, depends only on the time scales of the early universe and the speed of sound in the baryon-photon plasma. Both of these can be measured to high precision from the details of the acoustic peaks in the CMB. With this, one can compute the length scale to better than 1% accuracy. The remaining problem is to measure it at low redshift.

In recent times, the oscillations appear as a faint set of wiggles in the power spectrum. The features are best measured at wavenumbers between $k = 0.05$ and $k = 0.30h\ \mathrm{Mpc}^{-1}$ Fig. 2. On smaller scales, the amplitude is sharply reduced due to Silk damping. Hence, one requires surveys that can measure structure on 50 Mpc scales to very high accuracy. This pushes one to surveys with sizes of order 1 Gpc^3 and a million galaxies (Eisenstein, 2003).

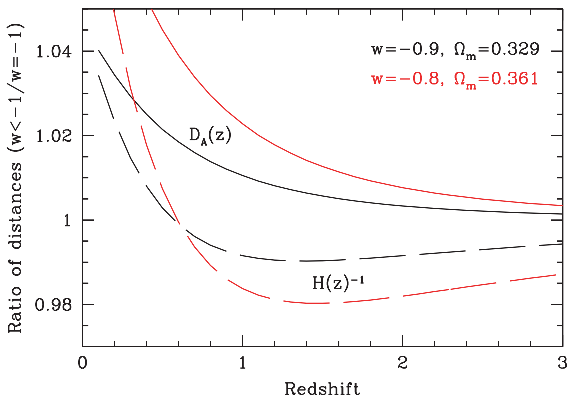

Fig. 1. The relative change in the angular diameter distance D_A and the Hubble parameter $H(z)$ for models with $w \neq -1$, as compared to one with $w = -1$. Here, we hold the quantities $\Omega_m h^2$ and the angular diameter distance to $z = 1000$ fixed, as these leave the CMB sky nearly unchanged. Distinguishing $w = -0.9$ from $w = -1$ requires percent-level precision. Note the considerable value that a very high precision measurement of H_0 would have!

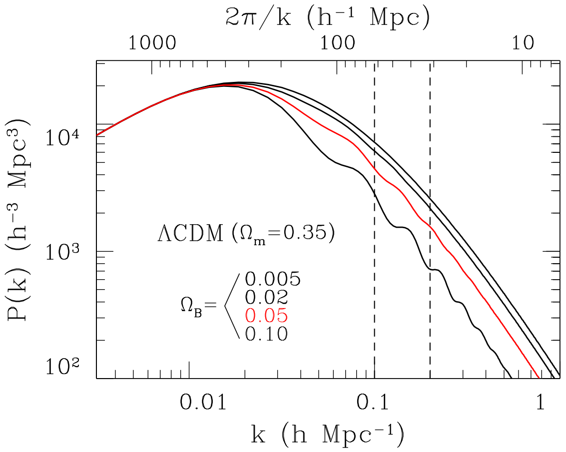

Fig. 2. The linear-regime matter power spectrum as a function of baryon fraction. Pure cold dark matter produce smooth power spectra, such as the top line. As baryons are added at fixed Ω_m, the strength of the acoustic oscillations increases and there is an overall suppression of power on small scales. From Eisenstein and Hu (1998).

One measures the oscillations along and across the line of sight as preferred scales in redshift and angular separations. Taking the ratio of these to the known physical scale allows one to measure the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$, respectively, where z is the redshift of the survey (Eisenstein, 2003). Unlike the Alcock and Paczynski (1979) method, we know the length of the standard ruler, and so we can measure these two quantities directly rather than merely the product $H^{-1}D_A$.

In Seo and Eisenstein (2003), we presented calculations of the statistical precision available to a set of fiducial galaxy redshift surveys. We considered the Sloan Digital Sky Survey luminous red galaxy (Eisenstein et al., 2001) sample at $z \approx 0.3$ and two hypothetical higher redshift surveys: 1000 square degrees over the range $0.5 < z < 1.3$ with 900,000 galaxies and 150 square degrees over the range $2.5 < z < 3.5$ with 500,000 galaxies. An example of the type of power spectra that could be extracted from such a survey is shown in Fig. 3; one sees that the acoustic oscillations are easily detected and their scale could plausibly be measured. The resulting fractional precisions on $H(z)$ and $D_A(z)$ for these surveys are shown in Fig. 4. We then propagated these measurements to constraints on a dark energy model with equation of state $w = w_0 + w_1 z$. These constraints and those from a representative next generation supernova experiment are shown in Fig. 5.

Further details and results are described in Seo and Eisenstein (2003). In addition Blake and Glazebrook (2003), Hu and Haiman (2003), and Linder (2003) present similar analyses. While these works differ in certain aspects of methodology and scope, I think that they are all essentially in agreement.

Like any method, one must be wary of systematic errors that could affect the measurements. In the case of galaxy clustering, the major astrophysical issues are non-linear structure formation, redshift distortions, and galaxy clustering bias. All of these affect the clustering of galaxies on very large scales. However, none of them are show-stoppers because the acoustic oscillations manifest themselves as a preferred scale or equivalently as a harmonic sequence in power. Non-linear structure, redshift distortions, and bias do not treat $100h^{-1}$ Mpc differently from 90 or 110; their natural scales are much smaller, e.g., the size of the

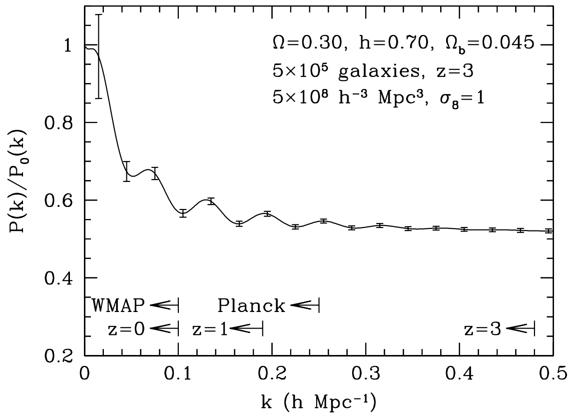

Fig. 3. The matter power spectrum for an $\Omega_m = 0.3$, $\Omega_b = 0.045$, $h = 0.7$ cosmology divided by the power spectrum for the same model but with $\Omega_b = 0$. The acoustic oscillations are clearly visible. Overplotted are the predicted statistical errors (Tegmark, 1997) for a redshift survey at $z = 3$ covering 150 square degrees and $5 \times 10^8 h^{-3}$ MPc^3 with 500,000 galaxies. The resulting number density of such galaxies is comparable to that of the Steidel et al. (1996) sample. At the bottom is the linear regime reach for galaxy surveys at different redshifts, along with the CMB satellites WMAP and Planck.

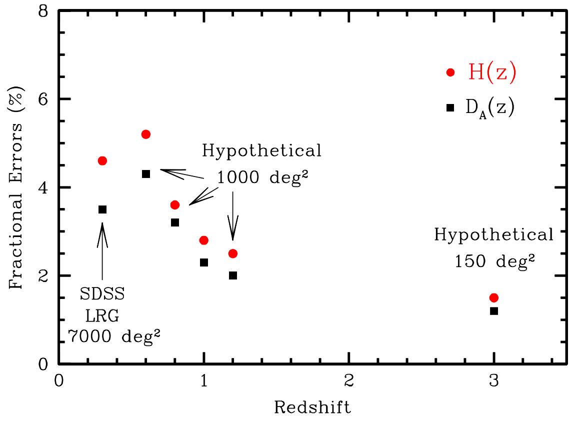

Fig. 4. The predicted 1–σ fractional errors on the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ from the fiducial surveys. The improvement as one goes to larger redshift is a combination of being able to use higher harmonics of the acoustic oscillations because of the receding non-linear structure scale and the variations in the assumed survey volumes. The key point is that high precision is possible, given large enough surveys. From Seo and Eisenstein (2003).

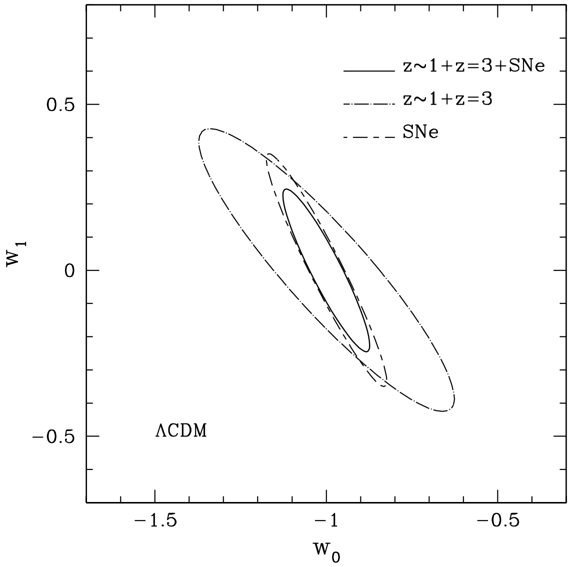

Fig. 5. The constraints on the dark energy equation of state model $w_0 + w_1 z$ when perturbing around a fiducial model of a cosmological constant. Shown are the results from the galaxy surveys (also including a Planck-style CMB experiment), from a supernova experiment, and from a combination of all. The supernova experiment was assumed to produce 1% errors in D_A for 16 independent redshift bins from $z = 0.05$ to 1.7, with a 5% overall uncertainty in the distance scale (i.e., H_0). Given that this reflects a relative calibration between low and high redshift of better than 0.01 mag, we feel that this is a good representation of a SNAP-level supernova experiment (Aldering et al., 2002). For the cosmological constant fiducial model, the supernova measurements are outperforming the galaxy surveys, although the combination is helpful. Fiducial models with $w > -1$ produce smaller errors for both experiments, with a more favorable outcome for the galaxy survey. From Seo and Eisenstein (2003).

largest halos and infall regions. Therefore they will affect the amplitude of the large-scale power spectrum, probably in a mildly scale-dependent way, but they do not create or shift the oscillations. This point was investigated numerically at $z = 0$ by Meiksin et al. (1999) and we are now studying higher redshifts (Seo and Eisenstein, 2004).

Imaging surveys using photometric redshift can recover a portion of the acoustic oscillation signature (Seo and Eisenstein, 2003). Redshift precision of only $\sigma_z = 0.04(1 + z)\,(1 - \sigma)$ is sufficient to keep the acoustic oscillations in phase from the front of a photo-z slice to the back. That means that one can measure the angular diameter distance. However, the errors per solid angle of sky are larger, so one must cover 10–20 times more sky than the spectroscopic equivalent. Of course, such surveys are within the reach and aspirations of facilities such as Pan-STARRS (http://pan-starrs.ifa.hawaii.edu) and LSST (http://www.lssto.org). Redshift precision of $\sigma_z = 0.003(1 + z)$ is required to resolve the acoustic peaks along the line of sight, so $H(z)$ cannot be measured directly with photometric redshift surveys, although a grism could reach this level of redshift precision. Cooray et al. (2001) discuss the use of photometric redshift surveys to constrain $D_A(z)$ by other signatures in the angular power spectrum.

2. Sound in space?

As this was a meeting on wide-field imaging from space, the question of whether the acoustic oscillation method requires space is apropos. Of course, at many redshifts, imaging (for the purpose of detection and colors, not morphology) and spectroscopy from the ground are straightforward.

However, there are some ways in which a space mission could be of great benefit. Most obviously, the redshift range between 1.4 and 2.0 is spectroscopically challenging from the ground due to the lack of strong features in the optical window. Recent ground-based work has had success at these redshift (e.g., Steidel et al., 2004; Abraham et al., 2004), but given that one needs of order a million redshifts, the integration times might be prohibitive.

Less obvious, the spectroscopic demands are large enough that preselection by photometric redshifts may be required to select the rare high-redshift luminous galaxies from the more numerous lower redshift galaxies. For the redshift range between 1.2 and 2.0, this may require near-infrared imaging data as the 4000 Å break shifts out beyond 1 μm. Getting the requisite deep IR imaging over 1000s of square degrees would certainly be easier in space.

One sees here that the advantage of space is particularly in the $1.4 < z < 2.0$ redshift range. The acoustic oscillation method, however, does not require continuous redshift coverage. Whether or not this redshift range is essential to the separation of plausible dark energy models is an open question. As the acoustic oscillation method is reaching full form by $z \approx 1.5$, as the non-linear scale is finally small enough to allow us to recover several peaks, and dark energy is growing ever more subtle at higher redshifts, it is possible that a concerted effort at $z = 2$ is in fact the redshift of choice.

Slitless spectroscopy in space offers the possibility of huge multiplexing. Karl Glazebrook's talk at this conference described an ambitious plan in this regard. With ground-based programs discussing 1000 square degrees as a difficult goal for the next 10 years, the idea of going to 10,000 square degrees with a simple space mission may be compelling.

If one abandons spectroscopy in favor of photometric redshifts, near-infrared data is likely invaluable for the redshift range between 1.2 and 2.5 if one is to reach the required 4% goal. The panoramic option within the SNAP mission would be phenominal for acoustic oscillation science, as it would have complete photometric redshift coverage and sufficient depth to recover the oscillations out to $z \approx 4$. A ground-based survey such as LSST would have the depth, but it is not clear that photometric redshift accuracy would be sufficient over the full redshift range.

All of these comparisons of ground and space require detailed assessments of the ground-based prospects and the reach of particular surveys in the dark energy model spaces. This is on-going work.

3. Pros and cons

More generally, it is worth reviewing the advantages and disadvantages of the acoustic oscillation method relative to other methods. First, on the plus side, the acoustic oscillation method is a geometrical large-angle standard ruler test; it is not sensitive to dust or any form of small angle aberration. The ruler itself is based on clean linear-regime physics from the recombination epoch, which is very sensitively probed by the CMB. It is difficult to imagine astrophysical systematic effects on these scales that could confuse the measurement.

The acoustic oscillation method does not require highly precise measurements. Doing basic galaxy photometry and spectroscopy is a well-understood process, even at the required redshifts; we need only do it in a highly multiplexed, wide-field manner. It is not necessary to work with L^* galaxies; one need only reach densities 3–10% of this, and so one can choose to work with brighter or otherwise more convenient galaxies. Heroic levels of relative photometry, e.g., sub-percent, are not required for a spectroscopic sample, although a photometric redshift approach would stress the photometric accuracy more. Compared to the photometric precision required of supernovae and the image fidelity required of weak lensing, the acoustic oscillation method is straightforward.

However, one does need a large number of these "simple" observations over a large amount of sky. Existing instrumentation on 8-m class telescopes is not well-positioned to perform 1000 square degrees of spectroscopy. New instrumentation and a significant investment of telescope time would be required. An instrument such as KAOS (see http://www.noao.edu/kaos for an extensive description), with ~4000 fibers over a 1.5° field, would bring such surveys within reach. Of course, such surveys would have other science applications of their data, but in addition one should consider multiplexing multiple independent science programs on the same part of sky. It is likely that telescope pointings, not raw numbers of spectroscopic targets, are the limiting resource.

Because the method does depend upon calibration of the sound horizon standard ruler with the CMB anisotropies, there is some model dependence. However, these possibilities are more limited than one might think (Eisenstein and White, in press), partly because the CMB is so sensitive to anomalies at $z > 1000$ and partly because of the structure of the degeneracies.

The acoustic oscillation method works better at $z > 1$ and can carry distance measurements out to $z \sim 3$ or higher. It can directly measure $H(z)$, which is one derivative closer to $w(z)$ than D_A and the luminosity distance. These aspects mean that the acoustic oscillation method could be sensitive to unexpected properties of dark energy. On the other hand, the reduced performance at $z < 1$ is a disadvantage if the dark energy is close to the standard cosmological constant, because in these cases nearly all of the anomalous behavior is at low redshift. If the dark energy is close to a cosmological constant, then methods involving weak lensing, cluster counting, and supernovae, all of which can or must place their attention at $z < 1$, are at a numerical advantage. As we have been surprised by the acceleration once and have no good theory for the dark energy, I regard the reach to $z = 3$ as an important advantage of the acoustic oscillation method, but of course the universe may turn out to be more boring.

In conclusion, the acoustic oscillation method is a robust method offering precision comparable to that of other methods. The simplicity of the physics and the individual measurements as well as the ability to measure the expansion of the universe at higher redshift are key advantages. The primary hurdle at present is the development of new wide-field, high multiplex spectroscopic facilities.

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References

Alcock, C., Paczynski, B., 1979. Nature 281, 358.

Abraham, R.G. et al., 2004. AJ 127, 2455.

Aldering, G., et al., 2002, SPIE, 4835, in press [astro-ph/0209550].

Bennett, C. et al., 2003. ApJS 148, 1.

Blake, C., Glazebrook, K., 2003. ApJ 594, 665.

Cooray, A., Hu, W., Huterer, D., Joffre, M., 2001. ApJ 557, L7.

Eisenstein, D.J., Hu, W., 1998. ApJ 496, 605.

Eisenstein, D.J., Hu, W., Tegmark, M., 1998. ApJ 504, L57.

Eisenstein, D.J. et al., 2001. AJ 122, 2267.

Eisenstein, D.J., 2003, in: Dey, A. (Ed.), Wide-field Multi-Object Spectroscopy, ASP Conference Series.

Eisenstein, D.J., White, M., in press.

Hu, W., Haiman, Z., 2003. PRD 68, 3004.

Linder, E.V., 2003. PRD 68, 3504.

Meiksin, A., White, M., Peacock, J.A., 1999. MNRAS 304, 851.

Peebles, P.J.E., Yu, J.T., 1970. ApJ 162, 815.

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

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

Seo, H., Eisenstein, D.J., 2003. ApJ 598, 720.

Seo, H., Eisenstein, D.J. 2004, in: Sidney Wolff, (Ed.), Observing Dark Energy, ASP Conference Series.

Steidel, C.C., Giavalisco, M., Pettini, M., Dickinson, M., Adelberger, K.L., 1996. ApJ 462, L17.

Steidel, C.C., Shapley, A.E., Pettini, M., Adelberger, K.L., Erb, D.K., Reddy, N.A., Hunt, M.P., 2004. ApJ 604, 534.

Tegmark, M., 1997. PRL 79, 3806.