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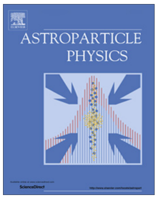

Distance probes of dark energy

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ABSTRACT

This document presents the results from the Distances subgroup of the Cosmic Frontier Community Planning Study (Snowmass 2013). We summarize the current state of the field as well as future prospects and challenges. In addition to the established probes using Type Ia supernovae and baryon acoustic oscillations, we also consider prospective methods based on clusters, active galactic nuclei, gravitational wave sirens and strong lensing time delays.

1. Executive summary

A basic paradigm of physics is that if one measures the distance to an object as a function of time, one can determine its velocity and acceleration. Add dynamics and one can find the forces, either from $F = ma$ or $G_{\mu\nu} = 8\pi T_{\mu\nu}$, and from these one can determine the

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nature of the underlying matter. Already distance measurements have shown that the cosmological constant, long disowned as being no more than theoretically allowable, is in fact a necessity. What remains to be seen is whether the Universe is pervaded by a uniform and never-changing energy density, an energy density that varies in time and perhaps position, or whether describing the Universe as a whole by General Relativity fails. Whatever future experiments reveal, the simple plot of the distance scale of the Universe as a function of time will be one of the primary icons of physical science. As the Copernican picture of the solar system removed our privileged perspective at the center of the Universe, the cosmological distance plot shows that the baryons, the matter that composes our physical essence, represent a minority fraction of the energy content of the Universe.

The data for this plot so far come primarily from measurements of Type Ia supernovae (SNe Ia) and baryon acoustic oscillations (BAO) and these will be the sources of streams of data in coming years. The Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST) will provide an essentially limitless supply of supernova, thousands, then hundreds of thousands. The challenge is to make measurements thoroughly enough to mitigate systematic uncertainties, especially those that are functions of redshift. Detailed studies of nearby supernovae are beginning to provide clues for how to do this. Much would be gained if observations could be made from space, but some of the gain could be achieved if we could make ground-based observations that avoid the atmospheric lines in the near infrared.

The subtle pattern of anisotropy in the cosmic microwave background, just one part in 10^5, is just the two dimensional boundary of a three-dimensional feature, the fluctuations in matter density throughout space. The counterpart of the oscillations in the CMB power spectrum is a peak in the correlation between the densities at points separated by 150 Mpc, left behind by baryon acoustic oscillations in the early Universe. This very large meter stick can be observed at redshifts out as far as $z = 1.6$ using galaxies as traces of matter density, and even out to $z = 3$ using light from quasars. The current experiment, the Baryon Oscillation Spectroscopic Survey (BOSS) [1], is likely to report a distance measurement soon at 1% accuracy and ultimately will provide two or perhaps three. The successor BAO experiment, Dark Energy Spectroscopic Instrument (DESI), should provide more than a dozen independent distance measurements.

If our basic understanding is correct, the supernova and BAO measurements should be in absolute agreement. The distance-versus-time curve of the Universe is so fundamental that exploring it with completely different techniques is essential. A basic disagreement would challenge our current picture, just as the discovery of the accelerating Universe upset the earlier picture. Provided the measurements agree, we can go on to see that they are consistent with expectations for a Universe containing 30% matter and 70% nearly-constant energy density. Finally, we will ask whether the nearly constant part is really constant. How well can data exclude a cosmological constant?

To measure progress in determining the expansion history of the Universe a simple quantitative characterization was proposed by the 2006 Dark Energy Task Force. The equation of state of the dark energy, $w = p/\rho$, which is -1 for the cosmological constant can be expanded as $w = w_0 + (1 - a)w_a$, where $a = 1/(1 + z)$ is the size-scale of the Universe relative to its size today, when $a = 1$ and $z = 0$. The DETF figure-of-merit is simply the reciprocal of the area of the error ellipse in the $w_0 - w_a$ plane, suitably normalized. This figure-of-merit is calculated using input from projections from the full Planck survey and from existing or projected results from the various dark energy experiments.

The cosmic expansion history is a fundamental element of the physics of our Universe. Ideally we would map it accurately at all redshifts. Within a cosmological model such as cold dark matter plus dynamical dark energy, the precision on the dark energy equation of state $w(z) = w_0 + w_a z/(1 + z)$ starts to plateau for measurements beyond $z \approx 1.5 - 2$. However, even within a cosmological constant model the dark energy contributes nearly 10% of the cosmic energy density at $z = 2$ and alters the deceleration parameter by 25%. Surprises could certainly await as we probe to these redshifts and beyond. Thus next generation experiments aim to map cosmic distances to $z \approx 2$, as outlined in the Rocky III report, while keeping in mind potential techniques to improve our understanding further.

Anticipated progress in direct distance measurements is shown in Fig. 1. Today, 580 SNe Ia lead to 1% precision measurements at the lowest redshifts, with uncertainties climbing to roughly 5% over the redshift interval $1 < z < 1.5$. DES will lower uncertainties in the 2015–2020 timeframe, while LSST and WFIRST will have a larger impact in the longer-term. Measurements of the BAO feature in the Lyman-α forest with BOSS confirm deceleration at $z = 2.4$. In the next 5 years, eBOSS will provide three new 1–2% precision measurements over the interval $0.6 < z < 2$, while the combination of Prime Focus Spectrograph (PFS) and Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) will offer nine measurements at $\sim 2\%$ precision at fairly uniform spacing over the interval $0.8 < z < 3.5$. More generally, the future experiments DESI, WFIRST, and Euclid are expected to fill in the entire expansion history of the Universe from deceleration to acceleration.

While supernovae and BAO are established techniques, other distance probes could provide independent reduction of statistical uncertainty, check of systematic bias, and different sensitivity to dark energy parameters. Galaxy clusters, gravitational lensing time delays, reverberation mapping of AGNs, and gravitational wave sirens have been identified as having the potential to be developed into competitive probes in the future, and could drive the field in the post-LSST era.

2. Galaxy redshift surveys: baryon acoustic oscillations and Alcock–Paczynski effect

2.1. Executive summary

Sound waves propagating in the first 400,000 years after the Big Bang imprint a characteristic scale in the clustering of matter in the Universe. The baryon acoustic oscillations produce a reasonably sharp peak in the correlation function of galaxies and other cosmic tracers at a comoving scale of 150 Mpc [2–9]. The length scale of this feature can be accurately predicted from the simple physics of the early Universe and the measurements of the CMB anisotropies. Using this standard ruler, we can measure the angular diameter distance and the Hubble parameter as functions of redshift [10–18]. The method was extensively described in the recent Weinberg et al. review [19].

The BAO method has several important advantages. First, the simplicity of the physics and the very large physical scale involved make the method highly robust. Current theory suggests that the measurements at $z < 3$ can be made to the cosmic variance limit without being limited by systematic uncertainties. Second, the method affords a high level of statistical precision, particularly at $z > 0.5$. Third, the method allows a direct probe of $H(z)$, further increasing the leverage at $z > 1$. Fourth, the method allows a direct connection to the angular acoustic scale of the CMB, placing strong constraints on the spatial curvature of the Universe.

The primary challenge of the BAO method is the need for large redshift surveys. Surveys to $z = 2$ aimed at extracting most of the BAO information require of order 50 million galaxies. At $z > 2$, it is likely that Lyman-α forest methods are more advantageous (e.g. [20]). The BOSS experiment is presently measuring the BAO from 1/4 of the sky at $z < 0.7$, as well as conducting first