Observational Basis for the Big-Bang Model

1. The night sky is dark.

2. General relativity works on solar system scales.

3. Nearby galaxies recede from us with velocity proportional to their distance.

4. The observed universe is isotropic on very large scales.

5. The inferred ages of globular clusters is roughly $\sim 1/H_0$.

6. We observe isotropic microwave radiation with a blackbody spectrum of $T \sim 2.7$ K.

7. The Helium abundance of the lowest metallicity stars is $\sim 25\%$ (by mass).

8. Abundances of other light elements are $\sim 10^{-5}$ (D, $^3$He), $5 \times 10^{-10}$ ($^7$Li), to within a factor of 20.
• Original measurement from Hubble's 1929 paper.
• Off by a factor of 5 (invalid calibration).
• Only 9 years after Shapley-Curtis debate, regarding whether extragalactic objects even existed.

Figure 7 The 1929 Hubble Diagram Which Depicts Hubble's 'Law Of Redshifts'

This diagram contained in Hubble's January 1929 paper shows a somewhat linear correlation between the magnitude of observed galactic redshifts (shown as velocity for convenience) and their estimated distances from Earth. Several of the galactic light shifts closest to Earth are actually blueshifts, not redshifts.

Source: Hubble, January 1929, p. 172

Copyright © 09-19-11 Justin Manning Jacobs. The Day The Universe Stopped Expanding
70 years after Hubble's discovery

Freedman WL, Madore BF. 2010.
The Universe is Homogeneous?

CfA redshift survey, 1979+
The Universe is Homogeneous

SDSS-I/II
2000-2009
The Universe is Homogeneous
5. Ages of globular clusters $\sim 1/H_0$
We observe a nearly isotropic background of microwave radiation with a blackbody spectrum.

**COBE results (1990)**
The LCDM Model: Key Observations

9. The present day universe is clustered.

10. Dynamical studies imply that most of the universe is dark. The dark matter around galaxies is much more extended than the luminous matter.

11. Dynamical measurements of the average dark matter density imply that:
   9. It is 30% of the “critical density” required to make the universe flat.
   10. It is more than the allowed baryon density from big bang nucleosynthesis.

12. Star-forming galaxies and quasars are observed out to $z \sim 9$.

13. The CMB has temperature fluctuations that are $\Delta T/T \sim 10^{-5}$. (2006 Nobel Prize)

14. Best estimates of the Hubble constant are $\sim 70$ km/s/Mpc, with $1/H_0 \sim 14$ Gyr. Inferred ages of globular clusters are $\sim 1/H_0$, significantly older than $2/(3H_0)$.

15. Studies of distant supernovae, assumed to be “standard candles”, imply that cosmic expansion has accelerated over the last $\sim 5$ Gyr. (2011 Nobel Prize)
   9. This has been confirmed and strengthened with measurements of “standard rulers” in the clustering signal of galaxies.

16. The power spectrum of CMB anisotropies shows alternating peaks and troughs, starting with the first peak at $\theta \sim 1$ degrees. CMB fluctuations are Gaussian to high precision.

17. The amplitude of matter clustering, measured from galaxy clustering, weak lensing, and Lyman-alpha forest, is consistent with predictions of LCDM.
Accelerating universe from supernova Ia search

\[ \frac{\text{distance}}{\text{velocity}} \]

\[ m - M \text{ (mag)} \]

\[ \Delta (m - M) \text{ (mag)} \]

\[
\begin{align*}
\Omega_M &= 0.3, \quad \Omega_\Lambda = 0.7 \\
\Omega_M &= 0.3, \quad \Omega_\Lambda = 0.0 \\
\Omega_M &= 1.0, \quad \Omega_\Lambda = 0.0
\end{align*}
\]
Comparison to other results

Figure 35 compares our results from Table 3 (modeling approach) with other measurements from galaxy surveys, but must be interpreted with care. The UZC points may contain excess large-scale power due to selection function effects (Padmanabhan et al. 2000; THX02), and the angular SDSS points measured from the early data release sample are difficult to interpret because of their extremely broad window functions. Only the SDSS, APM and angular SDSS points can be interpreted as measuring the large-scale matter power spectrum with constant bias, since the others have not been corrected for the red-tilting effect of luminosity-dependent bias. The Percival et al. (2001) 2dFGRS analysis unfortunately cannot be directly plotted in the figure because of its complicated window functions.

Figure 36 is the same as Figure 35, but restricted to a comparison of decorrelated power spectra, those for SDSS, 2dFGRS and PSCz. Because the power spectra are decorrelated, it is fair to do “chi-by-eye” when examining this Figure. The similarity in the bumps and wiggles between the three power spectra is intriguing.

Fig. 37.—Comparison of our results with other \( P(k) \) constraints. The location of CMB, cluster, lensing and Ly\( \alpha \) forest points in this plane depends on the cosmic matter budget (and, for the CMB, on the reionization optical depth \( \tau \)), so requiring consistency with SDSS constrains these cosmological parameters without assumptions about the primordial power spectrum. This figure is for the case of a “vanilla” flat scalar scale-invariant model with \( \Omega_m = 0.28 \), \( h = 0.72 \) and \( \Omega_b/\Omega_m = 0.16 \), \( \tau = 0.17 \) (Spergel et al. 2003; Verde et al. 2003, Tegmark et al. 2003b), assuming \( b^* = 0.92 \) for the SDSS galaxies.
BAO in SDSS-III BOSS galaxies

variations in the power observed in the different data sets, but the shapes of each are clearly consistent, suggesting that we should expect to recover consistent results for the BAO scale. Measurements of the clustering in the LOWZ sample are presented in Tojeiro et al. (2014).

The power is observed to increase with each data release, and similar behaviour is observed in the correlation function for $s < 70 h^{-1}$ Mpc. The difference in clustering amplitude can be explained by the tiling of the survey. In order to obtain the most complete sample, dense regions are observed using overlapping plates. Thus, as the survey progresses, a larger percentage of observations using overlapping plates are completed and the mean density of the survey increases. This increase in density occurs almost exclusively by adding overdense regions and thus increases the clustering amplitude. The measured increase in clustering amplitude is roughly the square of increase in density (4 per cent between DR9 and DR11, and 2 per cent between DR10 and DR11). As the survey nears completion, the issue naturally becomes less important. For DR11, it represents, at worst, a 1 per cent underestimate of the bias of the CMASS galaxies. Consistent trends are found in the LOWZ sample (Tojeiro et al. 2014).

Fig. 11 displays the best-fitting BAO model (solid curves) compared to the data for $\xi(s)$ (left-hand panels) and $P(k)$ (right-hand panels) for DR11 only. The pre-reconstruction measurements are displayed in the top panels, and the post-reconstruction ones in the bottom panels. The measurements are presented for our fiducial binning width and centring, and show a clear BAO feature in both $P(k)$ and $\xi(s)$, with the best-fitting models providing a good fit. The effect of reconstruction is clear for both the correlation function and power spectrum, with the BAO signature becoming more pronounced relative to the smooth shape of the measurements. Indeed, all of the BAO measurements, listed in Table 7, have improved post-reconstruction, in contrast to our DR9 results (Anderson et al. 2012). This behaviour is expected given the results of Section 4.2, which showed that, given the precision afforded by the DR11 volume coverage, reconstruction improved the results from all of our mock catalogues. Reconstruction is particularly striking in the power spectrum plot, showing a clear third peak in the post-reconstruction $P(k)$.

6.2 DR11 acoustic-scale measurements

Our BAO measurements are listed in Table 7. The mocks for DR10 and DR11 show significant improvement with reconstruction in most realizations, and we therefore adopt the reconstruction results as our default measurements. Our consensus value for the CMASS BAO measurement, $\alpha = 1.0144 \pm 0.0089$, is determined from a combination of $P(k)$ and $\xi(s)$ measurements, and in what follows, we describe the process of obtaining this value, and tests that validate it.

Post-reconstruction, the significance of the BAO detection in both the correlation function and the power spectrum are greater than 7σ for the reconstructed DR11 CMASS BAO measurements. The significance of detection is shown in Fig. 12, where we also...
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