The Hubble Constant and Dark Energy1

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ABSTRACT. The Hubble constant measured from the anisotropy in the cosmic microwave background (CMB) is shown to be independent of small changes from the standard model of the redshift dependence of dark energy. Modifications of the Friedmann equation to include phantom power \((w < -1)\), textures \((w = -2/3)\), and curvature are considered, and constraints on these dark energy contributors from supernova observations are derived. Modified values for the density of matter inferred from cosmic density perturbations and from the CMB under these circumstances are also estimated, as exemplified by 2dF and SDSS.

Online material: color figures

1. INTRODUCTION

Turner (1999) coined the term “dark energy” to name the power source of the accelerating universe (Riess et al. 1998; Perlmutter et al. 1999).

For the first time, there was a plausible, complete accounting of matter and energy in the universe. Expressed as a fraction of the critical density, there are neutrinos (between 0.3% and 15%), stars (0.5%), baryons (total, 5%), matter (total, 40%), and smooth, dark energy (60%), adding up to the critical density. This accounting is consistent with the inflationary prediction of a flat universe and defines three dark matter problems: Where are the dark baryons? What is the nonbaryonic dark matter? What is the nature of the dark energy? The leading candidate for the (optically) dark baryons is diffuse hot gas; the leading candidates for the nonbaryonic dark matter were slowly moving elementary particles left over from the earliest moments (cold dark matter), such as axions or neutralinos; the leading candidates for the dark energy involve fundamental physics and include a cosmological constant (vacuum energy), a rolling scalar field (quintessence), and light, frustrated topological defects.

Gooding et al. (1992) considered a universe in which density fluctuations are produced in an initially smooth universe by the ordering dynamics of scalar fields following a symmetry breaking phase transition at the grand unified scale. Such transitions lead to the formation of an unstable topological defect known as “global texture.”

Carroll2 points out that for some purposes it is useful to pretend that the \(-ka^{-2}R_{0}^{2}\) term in the Friedmann equation represents an effective “energy density in curvature,” and to define \(\rho_{k} = (3k/8\pi GR_{0}^{2})a^{-2}\).

Caldwell (1999) remarks that most observations are consistent with models right up to the \(w = -1\) or cosmological constant limit, and so it is natural to ask what lies on the other side at \(w < -1\). He termed this “phantom energy.”

In this article we outline how a dark energy program will constrain these elements and, in particular, how they affect the measurement of the Hubble constant by means of the anisotropy in the cosmic microwave background. Section 2 extends the Friedmann equation; § 3 shows that supernova data are currently tolerant of small values of \(\Omega_{1}\) and \(\Omega_{2}\); § 4 explores the degeneracies in CMB data; § 5 examines how matter density experiments like 2dF (Peacock et al. 2001) are affected; and § 6 broadly explores the parameter space of \(\Omega_{n}\) as it applies to supernova (SN) and CMB data. Our conclusions are in the final section.

2. THE EXPANSION RATE

An observer confronted with data like those in Figure 1 might respond by fitting a polynomial to the expansion rate as a function of redshift. But a physical equation already exists, namely, the Friedmann equation:

\[
(H/H_{0})^{2} = \Sigma_{n} a^{-3n} \Omega_{n} = h^{2}. \tag{1}
\]

From the point of view of fitting the data the observer might be surprised at the emphasis placed by physics on the higher-order coefficients. This was not rectified until the discovery of dark energy, based on earlier versions of Figure 1 by the high-z supernova and supernova cosmology teams, although the zeroth-order coefficient was considered and discarded by Einstein.

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2 See http://ned.ipac.caltech.edu/level5/Carroll2/Carroll2_1.html.
According to Gooding et al. (1992) the textures source term is

$$S_T = 4\pi G (\rho_T + 3P_T) \tau_a^2 a^2 / (1 + a),$$

(2)

where $\tau$ is a time constant equal to $(8\pi G \rho_{eq}/3)^{-1/2}$ and the scale factor, $a$, is taken to be unity at the equality of matter and radiation. The quantities $\rho_T$ and $P_T$ are the density and pressure of textures, respectively. The time constant is just the age of the universe at equality. When $a \gg 1$, $S$ scales like $\rho a$, and textures will contribute to $\Omega_1$. When $a \ll 1$, $S$ scales like $\rho a^2$, and textures will contribute to $\Omega_2$.

The $\Omega$ coefficients are normalized by the Friedmann equation, so that

$$\Sigma_{n=-1}^4 \Omega_n = 1,$$

(3)

where

$$n = 3(1 + w_n)$$

(4)

specifies the equation of state for matter and radiation components, etc.

3. FITTING THE SUPERNOVA OBSERVATIONS

The current supernova data (Conley et al. 2011) are shown in Figure 1. A value of $\Omega_k = 0.05$ does not violate the data. GRB data are also shown in Figure 1 (Schaefer 2007). The data are reproduced in Figure 2. Assuming $\Omega_{-1} = \Omega_2 = 0$, a value of $\Omega_1 = 0.1$ does not violate the data. The data are reproduced again in Figure 3, where we consider the case $w = -4/3$. Assuming $\Omega_1 = \Omega_2 = 0$, a value of $\Omega_{-1} = 0.1$ does not violate the data. Larger doses of textures, curvature, and phantom power would violate the data. We revisit these data to place firm constraints in § 6.

4. FITTING THE CMB

Some constraints on $\Omega_{-1}$ and $\Omega_2$ are imposed by the small-scale anisotropy of the cosmic microwave background. Komatsu et al. (2009) deduced $-0.0179 < \Omega_k < 0.0081$ (95% confidence).

We can derive similar constraints on $\Omega_n$, generally by requiring that the acoustic scale and shift parameter, $R$ (Komatsu et al. 2011), are conserved. We also invoke equation (3). For small values of the textures and curvature contributions, writing $\delta R = \Sigma \partial R / \partial \Omega_n \delta \Omega_n$ and a similar expression for the acoustic scale,
TABLE 1

| Equation of State Components | \(\Omega_n\) | \(n\) | \(w_n\) | \(c_n\) | \(f_n\) | \(g_n\) |
|-----------------------------|-------------|-------|--------|--------|--------|--------|
| Phantom                     | \(-1\)      | \(-4/3\) | 4.6    | 0.307  | \(-0.401\) |
| Vacuum                      | 0           | \(-1\)  | \(-0.815\) | 0.662 | 0.552 |
| Textures                    | 1           | \(-2/3\) | 1      | 0.964  | 0.824 |
| Curvature                   | 2           | \(-1/3\) | \(-0.815\) | 2.294 | 1.368 |
| Matter                      | 3           | 0      | 0      | \(\ldots\) | 2.677 |
| Radiation                   | 4           | \(+1/3\) | \(\ldots\) | \(\ldots\) | \(\ldots\) |

\[ \sum_{n=0}^{2} f_n \delta \Omega_n = 0, \quad \delta \Omega_3 = 0, \quad \Sigma_{n=0}^{2} \delta \Omega_n = 0, \quad (5) \]

where:

\[ f_n = \int_0^z (1 + z')^n h^{-3}(z') dz'. \quad (6) \]

The acoustic scale and shift parameter are conserved when introducing \(\Omega_1 = \delta\) to the WMAP model provided \(\delta \Omega_n = c_n \delta\), where \(c_n\) are coefficients of order unity and \(c_1 = 1, c_3 = 0, c_0 = (f_1 - f_2)/(f_2 - f_0), \) and \(c_2 = -(f_1 - f_0)/(f_2 - f_0)\) are computed in a simple numerical integration. Values are given in Table 1. For example, if \(\Omega_1 = 0.1\), then \(\Omega_0 = 0.73 - 0.08 = 0.65\), and \(\Omega_2 = -0.02\). Similar equations can be written for \(\Omega_{-1}\) if we adopt \(\Omega_1 = 0\). The change in the Hubble constant deduced by WMAP is proportional to \(\Sigma f_n c_n\), which is zero.

5. DENSITY PERTURBATIONS

Density perturbations in the universe evolve as

\[ \delta \Omega_{\text{grow}} \propto H \int_0^a \frac{da}{\dot{a}^3}. \quad (7) \]

By requiring changes in \(\delta \Omega_{\text{grow}}\) relative to those detected by 2dF and SDSS to be zero in response to \(\delta \Omega_a\), we can follow the formalism of the previous section to obtain

\[ \Sigma_{n=0}^{3} g_n \delta \Omega_n = 0, \quad \Sigma_{n=0}^{3} \delta \Omega_n = 0, \quad (8) \]

where

\[ g_n = \int_{0.001}^{1} a^{-n+3} h^{-5}(a) da. \quad (9) \]

Calculating the \(g_n\) values numerically (see Table 1), we find that the growth factor is conserved when \(\delta \Omega_1\) and \(\delta \Omega_2\) are introduced to the 2dF/SDSS model, provided

\[ \delta \Omega_1 = -0.127 \delta \Omega_1 - 0.384 \delta \Omega_2. \quad (10) \]

So perturbing the standard model by 0.1 in \(\Omega_1\), one would perturb the matter density measurement by only \(-0.01\). And perturbing the standard model by 0.1 in \(\Omega_2\), one would perturb the density measurement by \(-0.04\). This would be a significant change. Similar equations can be written for \(\Omega_{-1}\) if we adopt \(\Omega_1 = 0\).

6. CONSTRAINING \(\Omega_{0.12}\) IN A DARK ENERGY PROGRAM

6.1. Combined SN and CMB Constraints

From WMAP7 we formed the data vector \((l_A, R, z_s)\) and calculated \(\chi^2\) for a full grid of values of \(\Omega_n\). For SNe \(\chi^2\) was calculated directly from the data shown in Figure 1. Marginalizing over \(\Omega_n\), we can calculate probability in the \((\Omega_{+1}, \Omega_{-2})\) plane given the SN data in Figure 1 and the WMAP7 yr data. The results are in Figures 4 and 5. We confirm what we found in § 4, that the Hubble constant and the density of matter do not constrain these parameters.

6.2. The Expansion Rate at Larger Redshifts

A polynomial approach to dark energy in the Friedmann equation may actually lead to physical insights. Because unknown physical processes may be classified by how they scale with \(1 + z\), they can at least be ranked by our approach. Quintessence is beyond the scope of the present work.
6.3. Dark Energy Surveys

Experiments such as the Dark Energy Survey (Frieman et al. 2005) and WiggleZ (Blake et al. 2011) are aimed at determination of the equation of state $P = \rho w$. Measurement of $\Omega_1$ and $\Omega_0$ are also within their scope (Komatsu et al. 2009; eq [80]):

$$\alpha^{3(1+w_\text{eff})} = \Omega_{\Lambda}/(\Omega_0 + \Omega_1/\alpha).$$

(11)

For small $z$ and $w_{\text{eff}} \approx -1$,

$$3w'_{\text{eff}} + 2 = 0$$

(12)

where $w' = dw/da$.

Coefficients in the Friedmann equation are related to $w$ by equation (4) and are identified in Table 1.

7. CONCLUSIONS

Our primary conclusion is that introducing $\Omega_1$ or $\Omega_{-1}$ does not change WMAP values of $H_0$ or $\Omega_m$. It is easy to show that this conclusion extends to phantom energy generally for $w < -1$ with $\Sigma a^{-n} \Omega_0 + a^{-3} \Omega_\Lambda = h^2$ and $x < 0$. Using the supernova data alone, it is not possible to determine all the $\Omega$‘s because of degeneracies. But in combination with CMB data, the degeneracies are broken. Second, we find that $\Omega_1 < 0.2$ and $\Omega_{-1} < 0.1$ with 95% confidence. Stricter limits will follow from dark energy program. Third, $\Omega_2 \approx -0.2 \Omega_1$ for $\Omega_1 < 1$. If $\Omega_2 = \epsilon$ (say, $10^{-6}$) due to inflation, $\Omega_1 < 0.018/(1 - f_0) = 0.06$.

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