The State of the Universe: Cosmological Parameters 2002 [?]

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Abstract. In the past decade, observational cosmology has had one of the most exciting periods in the past century. The precision with which we have been able to measure cosmological parameters has increased tremendously, while at the same time, we have been surprised beyond our wildest dreams by the results. I review here recent measurements of the expansion rate, geometry, age , matter content, and equation of state of the universe, and discuss the implications for our understanding of cosmology.

1 Introduction

As early as a decade ago, the uncertainties in the measurement of cosmological parameters was such that few definitive statements could be made regarding cosmological models. That situation has changed completely. Instead all cosmological observables have now converged on a single cosmological model. Unfortunately, or perhaps fortunately for theorists, the "standard model" of cosmology from the 1980's is now dead. Instead, the model that has survived the test of observation is completely inexplicable at the present time, producing many more questions than answers. At the very least, our vision of the future of the Universe has completely changed, and the long-tauted connection between geometry and destiny is now dead.

I have been asked here to review the current status of our knowledge of cosmological observables. Following previous reviews I have prepared, it seems reasonable to divide this into three subsections, Space, Time, and Matter. Specifically, I shall concentrate on the following observables:

Space:

Expansion Rate
Geometry

Time:

Age of the Universe

Matter:

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- Baryon Density
- Large Scale Structure
- Matter Density
- Equation of State

2 Space: The Final Frontier:

2.1 The Hubble Constant

Arguably the most important single parameter describing the physical universe today is the Hubble Constant. Since the discovery in 1929 that the Universe is expanding, the determination of the rate of expansion dominated observational cosmology for much of the rest of the 20th century. The expansion rate, given by the Hubble Constant, sets the overall scale for most other observables in cosmology.

The big news, if any, is that by the end of the 20th century, almost all measurements have converged on a single range for this all important quantity. (I say almost all, because to my knowledge Alan Sandage still believes the claimed limits are incorrect [4].)

Recently, the Hubble Space Telescope Key Project has announced its final results. This is the largest scale endeavor carried out over the past decade with a goal of achieving a 10 % absolute uncertainty in the Hubble constant. The goal of the project has been to use Cepheid luminosity distances to 25 different galaxies located within 25 Megaparsecs in order to calibrate a variety of secondary distance indicators, which in turn can be used to determine the distance to far further objects of known redshift. This in principle allows a measurement of the distance-redshift relation and thus the Hubble constant on scales where local peculiar velocities are insignificant. The five distance indicators so constrained are: (1) the Tully Fisher relation, appropriate for spirals, (2) the Fundamental plane, appropriate for ellipticals, (3) surface brightness fluctuations, and (4) Supernova Type 1a distance measures, and (5) Supernovae Type II distance measures.

The Cepheid distances obtained from the HST project include a larger LMC sample to calibrate the period-luminosity relation, a new photometric calibration, and correctdions for metallicity. As a result they determined a new LMC distance modulus, of $\mu_o = 18.50 \pm 0.10$ mag. The number of Cepheid calibrators used for the secondary measures include 21 for the Tully-Fisher relation, and 6 for each of the Type Ia and surface fluctuation measures.

The HST-Key project reported measurements for each of these methods is present below [1]. (While I shall adopt these as quoted, it is worth pointing out that some critics have stressed that this involves utilizing data obtained by other groups, who themselves sometimes report different values of H_0). The first quoted uncertainty is statistical, the second is systematic (coming from such things as LMC zero point measurements, photometry, metallicity uncertainties, and remnant bulk flows).

$$H_O^{TF} = 71 \pm 3 \pm 7$$

$$H_O^{FP} = 82 \quad 6 \quad 9$$

$$H_O^{SBF} = 70 \quad 5 \quad 6$$

$$H_O^{SN1a} = 71 \quad 2 \quad 6$$

$$H_O^{SNII} = 72 \quad 9 \quad 7$$

On the basis of these results, the Key Project reports a weighted average value:

$$H_O^{WA} = 72 \quad 3 \quad 7 \text{ km s}^{1}\text{Mpc}^{1} (1 \ )$$

and a nal combined average of

$$H_O^{WA} = 72 \quad 8 \text{ km s}^{1}\text{Mpc}^{1} (1 \ )$$

.

The Hubble Diagram obtained from the HST project [1] is reproduced here.

In the weighted average quoted above, the dominant contribution to the 11% one sigma error comes from an overall uncertainty in the distance to the Large Magellanic Cloud. If the Cepheid Metallicity were shifted within its allowed 4% uncertainty range, the best t mean value for the Hubble Constant from the HST-Key project would shift downward to 68 6.

S-Z E ect:

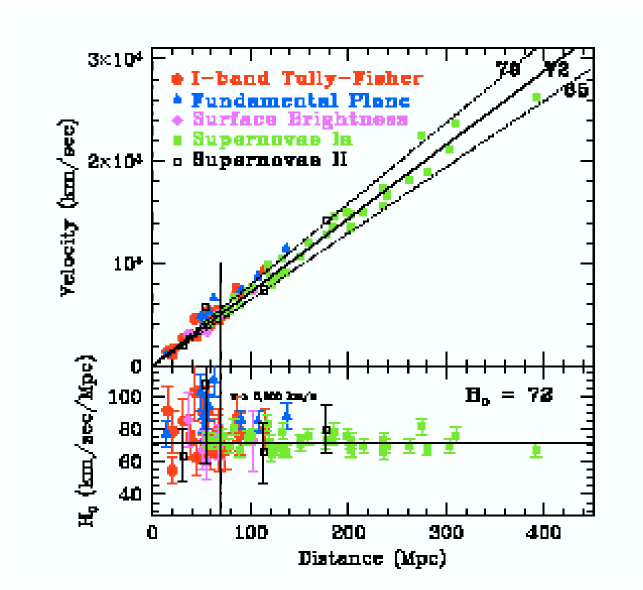

Fig. 1. HST Key Project Hubble Diagram

The Sunyaev-Zeldovich effect results from a shift in the spectrum of the Cosmic Microwave Background radiation due to scattering of the radiation by electgrons as the radiation passes through intervening galaxy clusters on the way to our receivers on Earth. Because the electron temperature in Clusters exceeds that in the CMB, the radiation is systematically shifted to higher frequencies, producing a deficit in the intensity below some characteristic frequency, and an excess above it. The amplitude of the effect depends upon the Thompson scattering scross section, and the electron density, integrated over the photon's path:

$$\Delta_{SZ} \propto \int \sigma_T n_e dl$$

At the same time the electrons in the hot gas that dominates the baryonic matter in galaxy clusters also emits X-Rays, and the overall X-Ray intensity is proportional to the square of the electron density integrated along the line of sight through the cluster:

$$\Delta_{X-Ray} \propto \int n_e^2 dl$$

Using models of the cluster density profile one can then use the the differing dependence on n_e in the two integrals above to extract the physical path-length through the cluster. Assuming the radial extension of the cluster is approximately equal to the extension across the line of sight one can compare the physical size of the cluster to the angular size to determine its distance. Clearly, since this assumption is only good in a statistical sense, the use of S-Z and X-Ray observations to determine the Hubble constant cannot be done reliably on the basis of a single cluster observation, but rather on an ensemble.

A recent preliminary analysis of several clusters [2] yields:

$$H_0^{SZ} = 60 \pm 10 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Type 1a SN (non-Key Project):

One of the HST Key Project distance estimators involves the use of Type 1a SN as standard candles. As previously emphasized, the Key Project does not perform direct measurements of Type 1a supernovae but rather uses data obtained by other gorpus. When these groups perform an independent analysis to derive a value for the Hubble constant they arrive at a smaller value than that quoted by the Key Project. Their most recent quoted value is [3]:

$$H_0^{1a} = 64^{+8}_{-6} \text{ km s}^{-1}\text{Mpc}^{-1}$$

At the same time, Sandage and collaborators have performed an independent analysis of SNe Ia distances and obtain [4]:

$$H_0^{1a} = 58 \pm 6 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Surface Brightness Fluctuations and The Galaxy Density Field:

Another recently used distance estimator involves the measurement of fluctuations in the galaxy surface brightness, which correspond to density fluctuations allowing an estimate of the physical size of a galaxy. This measure yields a slightly higher value for the Hubble constant [5]:

$$H_0^{SBF} = 74 \pm 4\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

Time Delays in Gravitational Lensing:

One of the most remarkable observations associated with observations of multiple images of distant quasars due to gravitational lensing intervening galaxies has been the measurement of the time delay in the two images of quasar Q0957 + 561. This time delay, measured quite accurately to be 417 ± 3 days is due to two factors: The path-length difference between the quasar and the earth for the light from the two different images, and the Shapiro gravitational time delay for the light rays traveling in slightly different gravitational potential wells. If it were not for this second factor, a measurement of the time delay could be directly used to determine the distance of the intervening galaxy. This latter factor however, implies that a model of both the galaxy, and the cluster in which it is embedded must be used to estimate the Shapiro time delay. This introduces an additional model-dependent uncertainty into the analysis. Two different analyses yield values [6]:

$$H_0^{TD1} = 69^{+18}_{-12}(1-\kappa)\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

$$H_0^{TD2} = 74^{+18}_{-10}(1-\kappa)\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

where κ is a parameter which accounts for a possible deviation in cluster parameters governing the overall induced gravitational time delay of the two signals from that assumed in the best fit. It is assumed in the analysis that κ is small.

Summary:

It is difficult to know how to best incorporate all of the quoted estimates into a single estimate, given their separate systematic and statistical uncertainties. Assuming large number statistics, where large here includes the quoted values presented here, I perform a simple weighted average of the individual estimates, and find an approximate average value:

$$H_0^{Av} \approx 70 \pm 5\,\mathrm{km\,s^{-1}Mpc^{-1}} \qquad (1)$$

2.2 Geometry:

Again, for much of the 20th century the effort to determine the geometry of the Universe involved a very indirect route. Einstein's Equations yield a relationship between the Hubble constant, the energy density, and the curvature of the Universe. By attempting to determine the first two quantities, one hoped to constrain the third. The problem is that until the past decade the uncertainty in the Hubble constant was at least 20-30 % and the uncertainty in the average energy density of the universe was even greater. As a result, almost any value for the net curvature of the universe remained viable.

It has remained a dream of observational cosmologists to be able to directly measure the geometry of space-time rather than infer the curvature of the universe by comparing the expansion rate to the mean mass density. While several such tests, based on measuring galaxy counts as a function of redshift, or the variation of angular diameter distance with redshift, have been attempted in the past, these have all been stymied by the achilles heel of many observational measurements in cosmology, evolutionary effects.

Recently, however, measurements of the cosmic microwave background have finally brought us to the threshold of a direct measurement of geometry, independent of traditional astrophysical uncertainties. The idea behind this measurement is, in principle, quite simple. The CMB originates from a spherical shell located at the surface of last scattering (SLS), at a redshift of roughly $z \approx 1000$):

If a fiducial length could unambigously be distinguished on this surface, then a determination of the angular size associated with this length would allow a determination of the intervening geometry:

Fortunately, nature has provided such a fiducial length, which corresponds roughly to the horizon size at the time the surface of last scattering existed (In this case the length is the "sound horizon", but since the medium in question is relativistic, the speed of sound is close to the speed of light.) The reason for this is also straightforward. This is the largest scale over which causal effects at the time of the creation of the surface of last scattering could have left an imprint. Density fluctuations on such scales would result in acoustic oscillations of the matter-radiation fluid, and the doppler motion of electrons moving along with this fluid which scatter on photons emerging from the SLS produces a characteristic peak in the power spectrum of fluctuations of the CMBR at a wavenumber corresponding to the angular scale spanned by this physical scale. These fluctuations should also be visually distinguishable in an image map of the CMB, provided a resolution on degree scales is possible.

Recently, a number of different ground-based balloon experiments, launched in places such Texas and Antarctica have resulted in maps with the required resolution [7,8,9,10]. Shown below is a comparison of the actual Boomerang map with several simulations based on a gaussian random spectrum of density fluctuations in a cold-dark matter universe, for open, closed, and flat cosmologies. Even at this qualitative level, it is clear that a flat universe provides better agreement to between the simulations and the data than either an open or closed universe.

On a more quantitative level, one can compare the inferred power spectra with predicted spectra [11]. Such comparisions for the most recent data [12] yields a constraint on the density parameter:

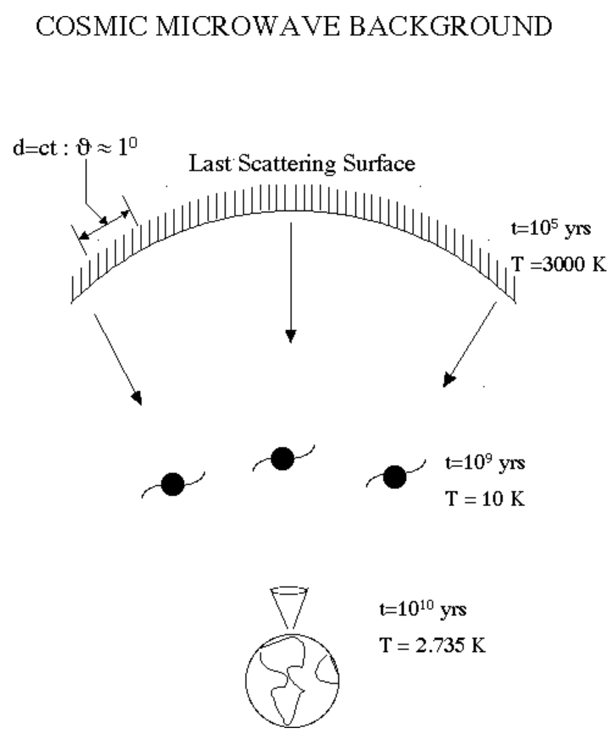

Fig. 2. A schematic diagram of the surface of last scattering, showing the distance traversed by CMB radiation.

$$\Omega = 1.03^{+.05}_{-.06} \ (68\% \ \mathrm{CL}) \qquad (2)$$

For the first time, it appears that the longstanding prejudice of theorists, namely that we live in a flat universe, may have been vindicated by observation! However, theorists can not be too self-satisfied by this result, because the source of this energy density appears to be completely unexpected, and largely inexplicable at the present time, as we will shortly see.

3 Time

3.1 Stellar Ages:

Ever since Kelvin and Helmholtz first estimated the age of the Sun to be less than 100 million years, assuming that gravitational contraction was its prime energy source, there has been a tension between stellar age estimates and estimates of the age of the universe. In the case of the Kelvin-Helmholtz case, the age of

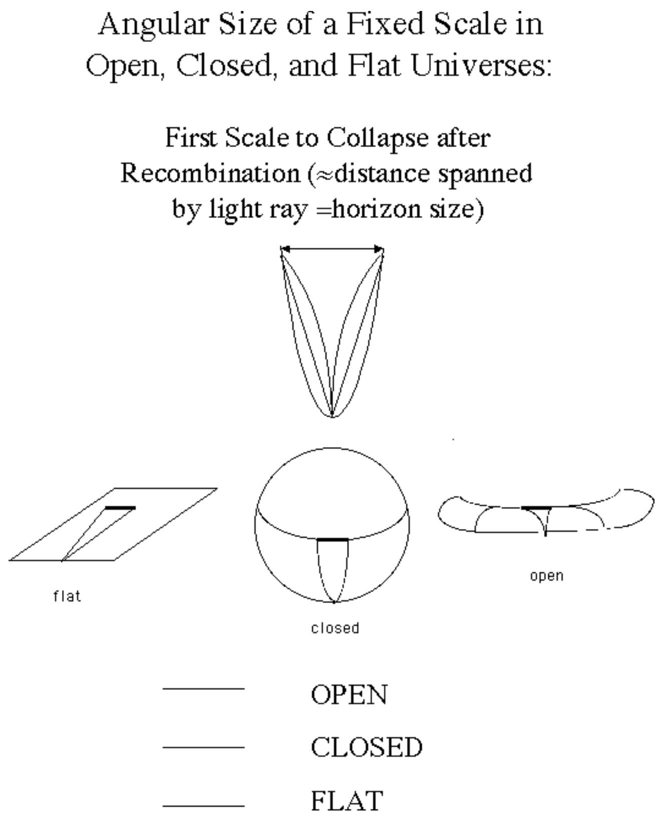

Fig. 3. The geometry of the Universe and ray trajectories for CMB radiation.

the sun appeared too short to accommodate an Earth which was several billion years old. Over much of the latter half of the 20th century, the opposite problem dominated the cosmological landscape. Stellar ages, based on nuclear reactions as measured in the laboratory, appeared to be too old to accommodate even an open universe, based on estimates of the Hubble parameter. Again, as I shall outline in the next section, the observed expansion rate gives an upper limit on the age of the Universe which depends, to some degree, upon the equation of state, and the overall energy density of the dominant matter in the Universe.

There are several methods to attempt to determine stellar ages, but I will concentrate here on main sequence fitting techiniques, because those are the ones I have been involved in. For a more general review, see [13].

The basic idea behind main sequence fitting is simple. A stellar model is constructed by solving the basic equations of stellar structure, including conservation of mass and energy and the assumption of hydrostatic equilibrium, and the equations of energy transport. Boundary conditions at the center of the star

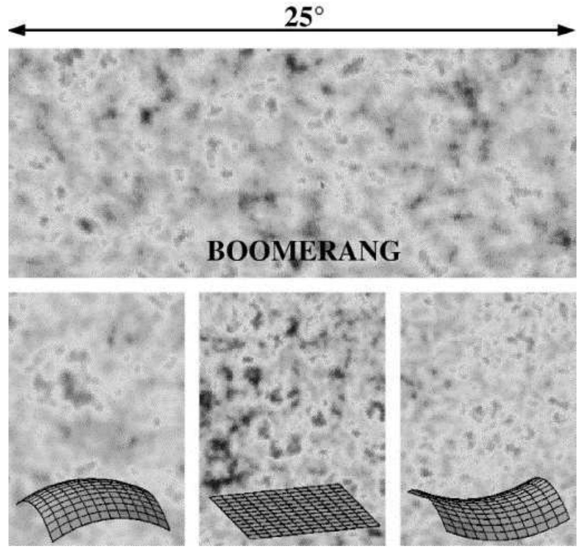

Fig. 4. Boomerang data visually compared to expectations for an open, closed, and flat CDM Universe.

and at the surface are then used, and combined with assumed equation of state equations, opacities, and nuclear reaction rates in order to evolve a star of given mass, and elemental composition.

Globular clusters are compact stellar systems containing up to 10^5 stars, with low heavy element abundance. Many are located in a spherical halo around the galactic center, suggesting they formed early in the history of our galaxy. By making a cut on those clusters with large halo velocities, and lowest metallicities (less than 1/100th the solar value), one attempts to observationally distinguish the oldest such systems. Because these systems are compact, one can safely assume that all the stars within them formed at approximately the same time.

Observers measure the color and luminosity of stars in such clusters, producing color-magnitude diagrams of the type shown in Figure 2 (based on data from [15].

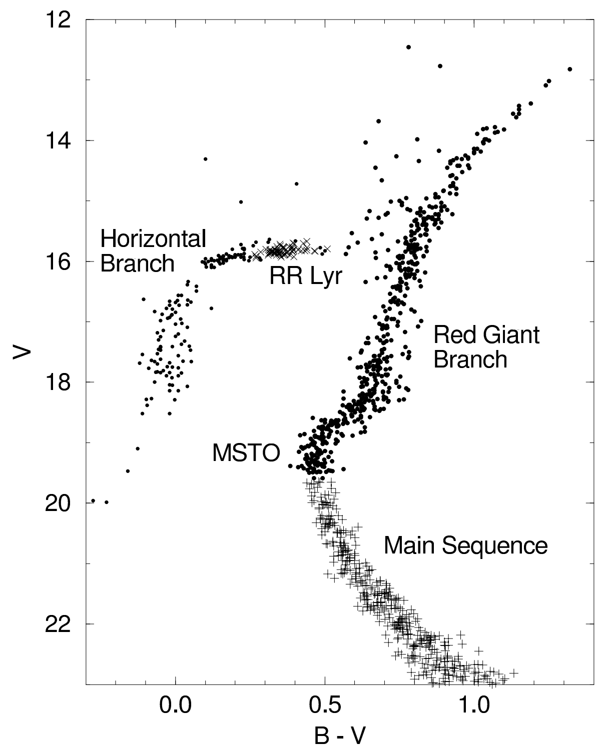

Fig. 5. Color-magnitude diagram for a typical globular cluster, M15. Vertical axis plots the magnitude (luminosity) of the stars in the V wavelength region and the horizontal axis plots the color (surface temperature) of the stars.

Next, using stellar models, one can attempt to evolve stars of di ering mass for the metallicities appropriate to a given cluster, in order to t observations. A point which is often conveniently chosen is the so-called main sequence-turno (MSTO) point, the point in which hydrogen burning (main sequence) stars have exhausted their supply of hydrogen in the core. After the MSTO, the stars quickly expand, become brighter, and are referred to as Red Giant Branch (RGB) stars. Higher mass stars develop a helium core that is so hot and dense that helium fusion begins. These form along the horizontal branch. Some stars along this branch are unstable to radial pulsations, the so-called RR Lyrae stars mentioned earlier, which are important distance indicators. While one in principle could attempt to fit theoretical isochrones (the locus of points on the predicted CM curve corresponding to different mass stars which have evolved to a specified age), to observations at any point, the main sequence turnoff is both sensitive to age, and involves minimal (though just how minimal remains to be seen) theoretical uncertainties.

Dimensional analysis tells us that the main sequence turnoff should be a sensitive function of age. The luminosity of upper main sequence stars is very roughly proportional to the third power of solar mass. Hence the time it takes to burn the hydrogen fuel is proportional to the total amount of fuel (proportional to the mass M), divided by the Luminosity — proportional to M^3. Hence the lifetime of stars on the main sequence is roughly proportional to the inverse square of the stellar mass.

Of course the ability to go beyond this rough approximation depends completely on the on the confidence one has in one's stellar models. What is most important for the comparison of cosmological predictions with inferred age estimates is the uncertainties in stellar model parameters, and not merely their best fit values.

Over the course of the past several years, I and my collaborators have tried to incorporate stellar model uncertainties, along with observational uncertainties into a self consistent Monte Carlo analysis which might allow one to estimate a reliable range of globular cluster ages. Others have carried out independent, but similar studies, and at the present time, rough agreement has been obtained between the different groups (i.e. see [8]).

I will not belabor the detailed history of all such efforts here. The most crucial insight has been that stellar model uncertainties are small in comparison to an overall observational uncertainty inherent in fitting predicted main sequence luminosities to observed turnoff magnitudes. This matching depends crucially on a determination of the distance to globular clusters. The uncertainty in this distance scale produces by far the largest uncertainty in the quoted age estimates.

In many studies, the distance to globular clusters can be parametrized in terms of the inferred magnitude of the horizontal branch stars. This magnitude can, in turn, be presented in terms of the inferred absolute magnitude, M_v(RR) of RR Lyrae variable stars located on the horizontal branch.

In 1997, the Hipparcos satellite produced its catalogue of parallaxes of nearby stars, causing an apparent revision in distance estimates. The Hipparcos parallaxes seemed to be systematically smaller, for the smallest measured parallaxes, than previous terrestrially determined parallaxes. Could this represent the unanticipated systematic uncertainty that David has suspected? Since all the detailed analyses had been pre-Hipparcos, several groups scrambled to incorporate the Hipparcos catalogue into their analyses. The immediate result was a generally lower mean age estimate, reducing the mean value to 11.5–12 Gyr, and allowing ages of the oldest globular clusters as low as 9.5 Gyr. However, what is also clear is that there is now an explicit systematic uncertainty in the RR Lyrae distance modulus which dominates the results. Different measurements are no longer consistent. Depending upon which distance estimator is correct, and there is now better evidence that the distance estimators which disagree with Hipparcos-based main sequence tting should not be dismissed out of hand, the best- t globular cluster estimate could shift up perhaps 1 , or about 1.5 Gyr, to about 13 Gyr.

Within the past two years, Brian Chaboyer and I have reanalyzed globular cluster ages, incorporating new nuclear reaction rates, cosmological estimates of the ^{4}He abundance, and most importantly, several new estimates of M_v(RR), shown below.

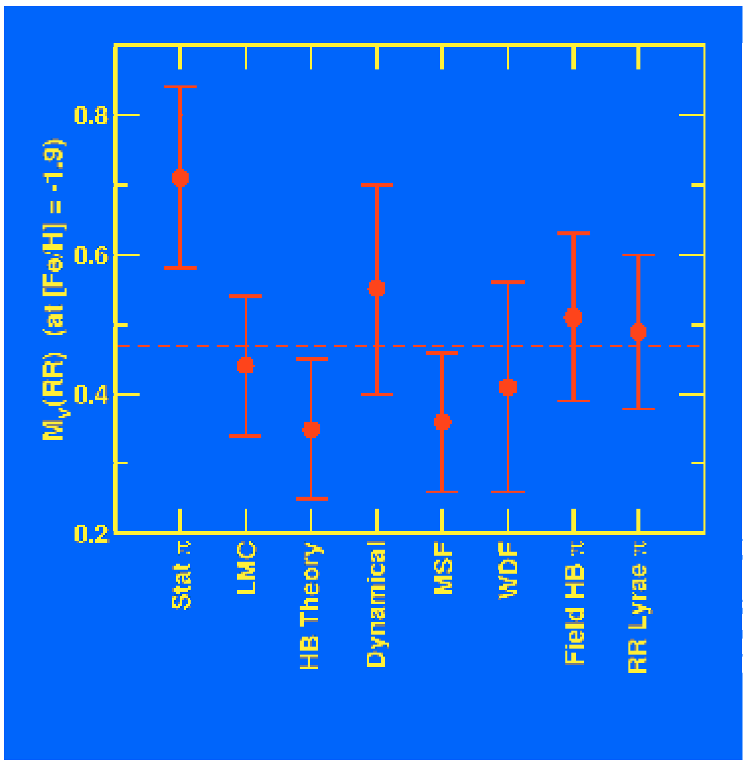

Fig. 6. Di erent estimates of the inferred magnitude of horizontal branch RR Lyrae stars, with uncertainties

The result is that while systematic uncertainties clearly still dominate, we argue that the best t age of globular clusters is now $12.6^{+3.4}_{\ 2.4}$ (95%) Gyr, with a 95% con dence range of about 11-16 Gyr [3].

If we are to turn this result into a lower limit on the age of the Universe we must add to this estimate the time after the Big Bang that it took for the rst globular clusters in our galaxy to form. Here there is great uncertainty. However a robust lower limit comes from observations of structure formation

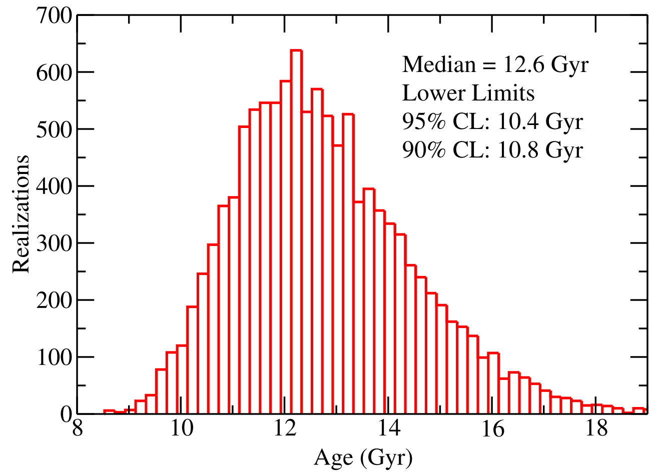

Fig. 7. Histogram showing range of age fits to old globular clusters using Monte Carlo analysis

in the Universe, which suggest that the first galaxies could not have formed much before a redshift of 6–7. Turning this redshift into an age depends upon the equation of state of the dominant energy density at that time (see below). However, one can show that at such high redshifts, the effects of a possible dark energy component are minimal, leading to a minimum age of globular cluster formation of about .8 Gyr. The maximum age is much less certain, as it is possible for galaxies to form at redshifts as low as 1–2. Thus, one must add an age of perhaps 3.5–4 Gyr to the globular age estimate above to get an upper limit on the age of the Universe. Putting these factors together, one derives a 95% confidence age range for the Universe of 11.2–20 Gyr.

3.2 Hubble Age:

As alluded to earlier, in a Friedman-Robertson-Walker Universe, the age of the Universe is directly related to both the overall density of energy, and to the equation of state of the dominant component of this energy density. The equation of state is parameterized by the ratio $\omega = p/\rho$, where p stands for pressure and ρ for energy density. It is this ratio which enters into the second order Friedman equation describing the change in Hubble parameter with time, which in turn determines the age of the Universe for a specific net total energy density.

The fact that this depends on two independent parameters has meant that one could reconcile possible conflicts with globular cluster age estimates by altering either the energy density, or the equation of state. An open universe, for example, is older for a given Hubble Constant, than is a flat universe, while a flat universe dominated by a cosmological constant can be older than an open matter dominated universe.

If, however, we incorporate the recent geometric determination which suggests we live in a flat Universe into our analysis, then our constraints on the possible equation of state on the dominant energy density of the universe become more severe. If, for existence, we allow for a diffuse component to the total energy density with the equation of state of a cosmological constant ($\omega = -1$), then the age of the Universe for various combinations of matter and cosmological constant is given by:

$$H_0 t_0 = \int_0^\infty \frac{dz}{(1+z)[(\Omega_m)(1+z)^3 + (\Omega_X)(1+z)^{3(1+w)}]^{1/2}} \qquad (3)$$

This leads to ages as shown in the table below.

Table 1. Hubble Ages for a Flat Universe, $H_0 = 70 \pm 8$,

Ω_M	Ω_x	t_0
1	0	9.7 ± 1
0.2	0.8	15.3 ± 1.5
0.3	0.7	13.7 ± 1.4
0.35	0.65	12.9 ± 1.3

The existing limits on the age of the universe from globular clusters are thus already are incompatible with a flat matter dominated universe. This is a very important result, as it implies that now all three classic tests of cosmology, including geometry, large scale structure, and age of the Universe now support the same cosmological model, which involves a universe dominated by dark energy. We can provide limits on the equation of state for dark energy as well. Shown in Figure 8, is the constraint on w, assuming a Hubble constant of 72 [13].

At the same time, it is worth noting that unfortunately the upper limit on the age of the universe coming from globular cluster ages cannot provide a useful limit on the equation of state parameter w, because there is an upper limit on the Hubble Age, independent of w, if the contribution of matter to the total density is greater than 20% [14].

4 Matter

Having indirectly probed the nature of matter in the Universe using the previous estimates, it is now time to turn to direct constraints that have been derived in the past decade.

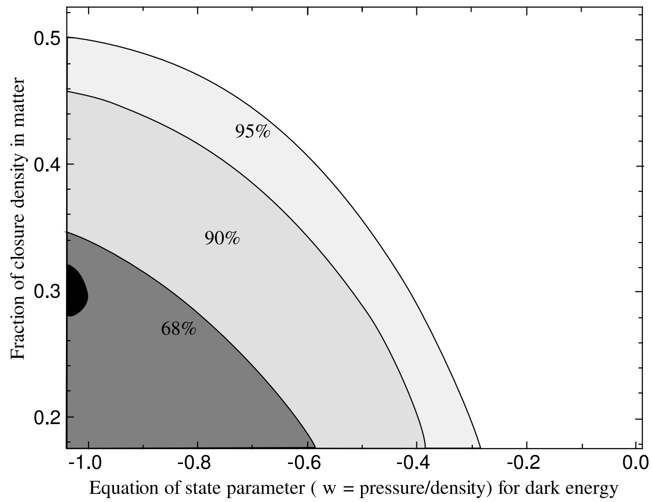

Fig. 8. Constraint on the equation of state parameter for dark energy as a function of the fraction of closure density in matter resulting from age constraint described here.

4.1 The Baryon Density: a re-occuring crisis?:

The success of Big Bang Nucleosynthesis in predicting in the cosmic abundances of the light elements has been much heralded. Nevertheless, the finer the ability to empirically infer the primordial abundances on the basis of observations, the greater the ability to uncover some small deviation from the predictions. Over the past five years, two different sets of observations have threatened, at least in some people's minds, to overturn the simplest BBN model predictions. I believe it is fair to say that most people have accepted that the first threat was overblown. The concerns about the second have only recently subsided.

i. Primordial Deuterium: The production of primordial deuterium during BBN is a monotonically decreasing function of the baryon density simply because the greater this density the more efficiently protons and neutrons get processed to helium, and deuterium, as an intermediary in this reactions set, is thus also more efficiently processed at the same time. The problem with inferring the primordial deuterium abundance by using present day measurements of deuterium abundances in the solar system, for example, is that deuterium is highly processed (i.e. destroyed) in stars, and no one has a good enough model for galactic chemical evolution to work backwards from the observed abundances in order to adequately constrain deuterium at a level where this constraint could significantly test BBN estimates.

Five years ago, the situation regarding deuterium as a probe of BBN changed dramatically, when David Tytler and Scott Burles convincingly measured the deuterium fraction in high redshift hydrogen clouds that absorb light from even higher redshift quasars. Because these clouds are at high redshift, before significant star formation has occurred, little post BBN deuterium processing is thought to have taken place, and thus the measured value gives a reasonable handle on the primordial BBN abundance. The best measured system [20] yields a deuterium to hydrogen fraction of

$$(D/H) = (3.3 \pm 0.5) \times 10^{-5} \; (2\sigma) \quad (4)$$

This, in turn, leads to a contraint on the baryon fraction of the Universe, via standard BBN,

$$\Omega_B h^2 = .0190 \pm .0018 \; (2\sigma) \quad (5)$$

where the quoted uncertainty is dominated by the observational uncertainty in the D/H ratio, and where $H_0 = 100h$. Thus, taken at face value, we now know the baryon density in the universe today to an accuracy of about 10%!

When first quoted, this result sent shock waves through some of the BBN community, because this value of Ω_B is only consistent if the primordial helium fraction (by mass) is greater than about 24.5%. However, a number of previous studies had claimed an upper limit well below this value. However, recent studies, for example, place an upper limit on the primordial helium fraction closer to 25%.

In any case, even if somehow the deuterium estimate is wrong, one can combine all the other light element constraints to produce a range for $\Omega_b h^2$ consistent with observation:

$$\Omega_B h^2 = .016 - 0.025 \quad (6)$$

ii. CMB constraints: Beyond the great excitement over the observation of a peak in the CMB power spectrum at an angular scale corresponding to that expected for a flat universe lay some excitement/concern over the small apparent size of the next peak in the spectrum, at higher multipole moment (smaller angular size). The height of the first peak in the CMB spectrum is related to a number of cosmological parameters and thus cannot alone be used to constrain any one of them. However, the relative height of the first and second peaks is strongly dependent on the baryon fraction of the universe, since the peaks themselves arise from compton scattering of photons off of electrons in the process of becoming bound to baryons. Analyses of the two first small-scale CMB results originall produced a constraint which was in disagreement with the BBN estimate. However, more recent data indicates $\Omega_B h^2 = 0.021$, precisely where one would expect it to be based on BBN predictions.

Most recently reported measurements of ^3He in the Milky Way Galaxy give the constraint, $^3He/H = (1.1 \pm 0.2) \times 10^{-5}$, which in turn implies $\Omega_B h^2 = 0.02$. Thus, all data is now consistent with the assumption that the Burles and Tytler limit on $\Omega_B h^2$ is correct, adding further confidence in the predictions of BBN. Taking the range for H_0 given earlier, one derives the constraint on Ω_B of

$$\Omega_B = .045 - 0.15 \quad (7)$$

4.2 Ω matter

Perhaps the second greatest change in cosmological prejudice in the past decade relates to the inferred total abundance of matter in the Universe. Because of the great intellectual attraction Inflation as a mechanism to solve the so-called Horizon and Flatness problems in the Universe, it is fair to say that most cosmologists, and essentially all particle theorists had implicitly assumed that the Universe is flat, and thus that the density of dark matter around galaxies and clusters of galaxies was sufficient to yield $\Omega = 1$. Over the past decade it became more and more difficult to defend this viewpoint against an increasing number of observations that suggested this was not, in fact, the case in the Universe in which we live.

The earliest holes in this picture arose from measurements of galaxy clustering on large scales. The transition from a radiation to matter dominated universe at early times is dependent, of course, on the total abundance of matter. This transition produces a characteristic signature in the spectrum of remnant density fluctuations observed on large scales. Making the assumption that dark matter dominates on large scales, and moreover that the dark matter is cold (i.e. became non-relativistic when the temperature of the Universe was less than about a keV), fits to the two point correlation function of galaxies on large scales yielded [21,22]:

$$\Omega_M h = .2 - .3 \tag{8}$$

Unless h was absurdly small, this would imply that Ω_M is substantially less than 1.

New data from the Sloan and 2DF surveys refine this limit further, with reported values of [23,24]

$$\Omega_M = 0.23 \pm 0.09 \, (2DF) \tag{9}$$

$$\Omega_M h \approx 0.14^{+.11}_{-.06} \, (2\sigma) \, (Sloan) \tag{10}$$

The second nail in the coffin arose when observations of the evolution of large scale structure as a function of redshift began to be made. Bahcall and collaborators [25] argued strongly that evidence for any large clusters at high redshift would argue strongly against a flat cold dark matter dominated universe, because in such a universe structure continues to evolve with redshift up to the present time on large scales, so that in order to be consistent with the observed structures at low redshift, far less structure should be observed at high redshift. Claims were made that an upper limit $\Omega_B \le 0.5$ could be obtained by such analyses.

A number of authors have questioned the systematics inherent in the early claims, but it is certainly clear that there appears to be more structure at high redshift than one would naively expect in a flat matter dominated universe. Future studies of X-ray clusters, and use of the Sunyaev-Zeldovich effect to measure cluster properties should be able to yield measurements which will allow a fine-scale distinction not just between models with different overall dark matter densities, but also models with the same overall value of Ω and different equations of state for the dominant energy [26].

One of the best overall constraint on the total density of clustered matter in the universe comes from the combination of X-Ray measurements of clusters with large hydrodynamic simulations. The idea is straightforward. A measurement of both the temperature and luminosity of the X-Rays coming from hot gas which dominates the total baryon fraction in clusters can be inverted, under the assumption of hydrostatic equilibrium of the gas in clusters, to obtain the underlying gravitational potential of these systems. In particular the ratio of baryon to total mass of these systems can be derived. Employing the constraint on the total baryon density of the Universe coming from BBN, and assuming that galaxy clusters provide a good mean estimate of the total clustered mass in the Universe, one can then arrive at an allowed range for the total mass density in the Universe [27,28,29]. Many of the initial systematic uncertainties in this analysis having to do with cluster modelling have now been dealt with by better observations, and better simulations (i.e. see [30]), so that now a combination of BBN and cluster measurements yields:

$$\Omega_M = 0.35 \pm 0.1 \quad (2\sigma) \tag{11}$$

Combining these results, one derives the constraint:

$$\Omega_M \approx 0.3 \pm 0.05 \quad (2\sigma) \tag{12}$$

4.3 Equation of State of Dominant Energy:

The above estimate for Ω_M brings the discussion of cosmological parameters full circle, with consistency obtained for a flat 13 billion year old universe, but not one dominated by matter. As noted previously, a cosmological constant dominated universe with $\Omega_M = 0.3$ has an age which nicely fits in the best-fit range. However, based on the data discussed thus far, there was no direct evidence that the dark energy necessary to result in a flat universe actually has the equation of state appropriate for a vacuum energy. Direct motivation for the possibility that the dominant energy driving the expansion of the Universe violates the Strong Energy Condition actually came somewhat earlier, in 1998, from two different sets of observations of distant Type 1a Supernovae. In measuring the distance-redshift relation [31,32] these groups both came to the same, surprising conclusion: the expansion of the Universe seems to be accelerating! This is only possible if the dominant energy is "cosmological-constant-like", namely if "$\omega < -0.5$ (recall that $\omega = -1$ for a cosmological constant).

In order to try and determine if the dominant dark energy does in fact differ significantly from a static vacuum energy—as for example may occur if some background field that is dynamically evolving is dominating the expansion energy at the moment—one can hope to search for deviations from the distance-redshift relation for a cosmological-constant-dominated universe. To date, none have been observed. In fact, existing measurements already put a (model dependent) limit of approximately $-1.7 \le \omega \le -0.7$ [33]. Recent work [34] suggests that the best one might be able to do from the ground using SN measurements would be to improve this limit to $\omega \le -0.7$. Either other measurements, such as galaxy cluster evolution observations, or space-based SN observations would be required to further tighten the constraint.

5 Conclusions: A Cosmic Uncertainty Principle

I list the overall constraints on cosmological parameters discussed in this review in the table below. It is worth stressing how completely remarkable the present situation is. After 20 years, we now have the first direct evidence that the Universe might be flat, but we also have definitive evidence that there is not enough matter, including dark matter, to make it so. We seem to be forced to accept the possibility that some weird form of dark energy is the dominant stuff in the Universe. It is fair to say that this situation is more mysterious, and thus more exciting, than anyone had a right to expect it to be.

Table 2. Cosmological Parameters 2001

Parameter	Allowed range	Formal Conf. Level (where approp.)
H_0	70 ± 5	2σ
t_0	$13^{+7}_{-1.8}$	2σ
$\Omega_B h^2$	$.02 \pm .004$	2σ
Ω_B	0.045 ± 0.015	2σ
Ω_M	0.3 ± 0.1	2σ
Ω_{TOT}	1.03 ± 0.1	2σ
Ω_X	0.7 ± 0.1	2σ
ω	≤ -0.7	2σ

The new situation changes everything about the way we think about cosmology. In the first place, it demonstrates that Geometry and Destiny are no longer linked. Previously, the holy grail of cosmology involved determining the density parameter Ω, because this was tantamount to determining the ultimate future of our universe. Now, once we accept the possibility of a non-zero cosmological constant, we must also accept the fact that any universe, open, closed, or flat, can either expand forever, or reverse the present expansion and end in a big crunch [35]. But wait, it gets worse, as my colleague Michael Turner and I have also demonstrated, there is no set of cosmological measurements, no matter how precise, that will allow us to determine the ultimate future of the Universe. In order to do so, we would require a theory of everything.

On the other hand, if our universe is in fact dominated by a cosmological constant, the future for life is rather bleak [36]. Distant galaxies will soon blink out of sight, and the Universe will become cold and dark, and uninhabitable....

This bleak picture may seem depressing, but the flip side of all the above is that we live in exciting times now, when mysteries abound. We should enjoy our brief moment in the Sun.

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