

BOOMERANG DATA SUGGEST A PURELY BARYONIC UNIVERSE

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ABSTRACT

The amplitudes of peaks in the angular power spectrum of anisotropies in the microwave background radiation depend on the mass content of the universe. The second peak should be prominent when cold dark matter is dominant but is depressed when baryons dominate. Recent microwave background data are consistent with a purely baryonic universe with $\Omega_m = \Omega_b$ and $\Omega_\Lambda \approx 1$.

Subject headings: cosmic microwave background — cosmology: theory — early universe

1. INTRODUCTION

At present, the standard cosmological paradigm is a universe in which ordinary matter is a minor constituent, with $\sim 90\%$ of the mass being in some nonbaryonic form. This is usually presumed to be some new fundamental particle (e.g., weakly interacting, massive particles or axions), which in the astronomical context is generically referred to as cold dark matter (CDM). “Standard” CDM began as a compelling and straightforward theory with few moving parts (e.g., Blumenthal et al. 1984). It has evolved into a model (Λ CDM) with many fine-tuned parameters (e.g., Ostriker & Steinhardt 1995). This might reflect our growing knowledge of real complexities, or it might be a sign of some fundamental problem.

As yet, we have no direct indication that CDM actually exists. Consequently, the assumption that it makes up the vast majority of mass in the universe remains just that: an assumption. The presumed existence of CDM is a well-motivated inference based principally on two astrophysical observations. One is that the total mass density inferred dynamically greatly exceeds that allowed for normal baryonic matter by big bang nucleosynthesis ($\Omega_m > \Omega_b$). The other is that the cosmic microwave background is very smooth. Structure cannot grow gravitationally to the rich extent seen today unless there is a non-baryonic component that can already be significantly clumped at the time of recombination without leaving incriminatingly large fingerprints on the microwave background.

Nevertheless, CDM faces some severe problems, especially at smaller scales (e.g., Moore 1994; Flores & Primack 1994; McGaugh & de Blok 1998a; Moore et al. 1999; Navarro & Steinmetz 2000; Sellwood 2000). Since the existence of CDM remains an assumption, it seems prudent to consider the case of a purely baryonic universe. In this context, it is not surprising that the second peak is constrained to have a small amplitude in the data reported by recent microwave background experiments (de Bernardis et al. 2000; Hanany et al. 2000). It is expected (McGaugh 1999).

2. PRIOR PREDICTIONS

Models for the angular power spectrum of fluctuations in the microwave background have many free parameters (Seljak & Zaldarriaga 1996). Many of these parameters are degenerate (Efstathiou & Bond 1999), making it possible to fit a wide variety of models to any given data set (e.g., Lange et al. 2000). This makes the role of prior constraints, and a priori predictions, particularly important.

Fortunately, the baryon content is the principal component

that affects the relative amplitude of the even and odd peaks. For the baryon content specified by the abundances of the light elements and big bang nucleosynthesis (e.g., Tytler et al. 2000), both should be present. However, the even-numbered rarefaction peaks should be more prominent when CDM dominates the mass budget. When it does not, baryonic drag suppresses their amplitude (Hu, Sugiyama, & Silk 1997). As Ω_{CDM} declines, the amplitude of the second peak declines with it. In the case where $\Omega_{\text{CDM}} \rightarrow 0$, the second peak is expected to have a much smaller amplitude than in Λ CDM (McGaugh 1999), consistent with the hints of a small secondary peak in the Boomerang (de Bernardis et al. 2000) and Maxima-1 data (Hanany et al. 2000).

The a priori predictions for the standard Λ CDM paradigm and the pure baryon case (McGaugh 1999) are shown together with the Boomerang data¹ in Figure 1. In addition to the illustrative cases I published previously, I have now carefully chosen parameters (Table 1) that satisfy all the constraints that went into building Λ CDM in the first place (Ostriker & Steinhardt 1995; Turner 1999), updated to include the recent estimate of $\Omega_b h^2 = 0.019$ (Tytler et al. 2000). All reasonable variation of the parameters that were considered in Λ CDM prior to the Boomerang results significantly overpredict the amplitude of the second peak. This is difficult to avoid as long as one remains consistent with big bang nucleosynthesis and cluster baryon fractions (Evrard 1997; Bludman 1998).

In contrast, the a priori prediction for a purely baryonic universe is consistent with the data (Fig. 1). The amplitude of the second peak² is predicted to be much lower than in universes dominated by CDM, as observed. The power spectra models in Figure 1b are identical to the models I published previously (McGaugh 1999). The only difference is that I have scaled the geometry to match the precise position of the first peak. This mapping is effectively an adjustment of the angular scale by a factor α so that $l \rightarrow \alpha l$ (Table 1). The Boomerang data prefer a geometry that is marginally closed, which leads to $\alpha < 1$. This is equivalent to a small adjustment in the value of Ω_Λ (Table 1). Once the geometry is fixed, the rest follows. It is

¹ There is a significant zero-point offset between Boomerang and Maxima-1. To rectify this, one must choose an arbitrary scaling factor (Hanany et al. 2000). I have therefore refrained from combining the two data sets. It is the shape of the power spectrum, and not its normalization, that is important here. The two data sets are consistent in this respect.

² In McGaugh (1999) I described the baryonic models as having the second peak completely suppressed, with the third peak appearing to be the second. This is not correct. Such a situation can occur, but only for baryon-to-photon ratios greater than allowed by big bang nucleosynthesis. The second peak discussed there and here is indeed the second (rarefaction) peak. The difference between Λ CDM and purely baryonic models is in the amplitude of this peak.

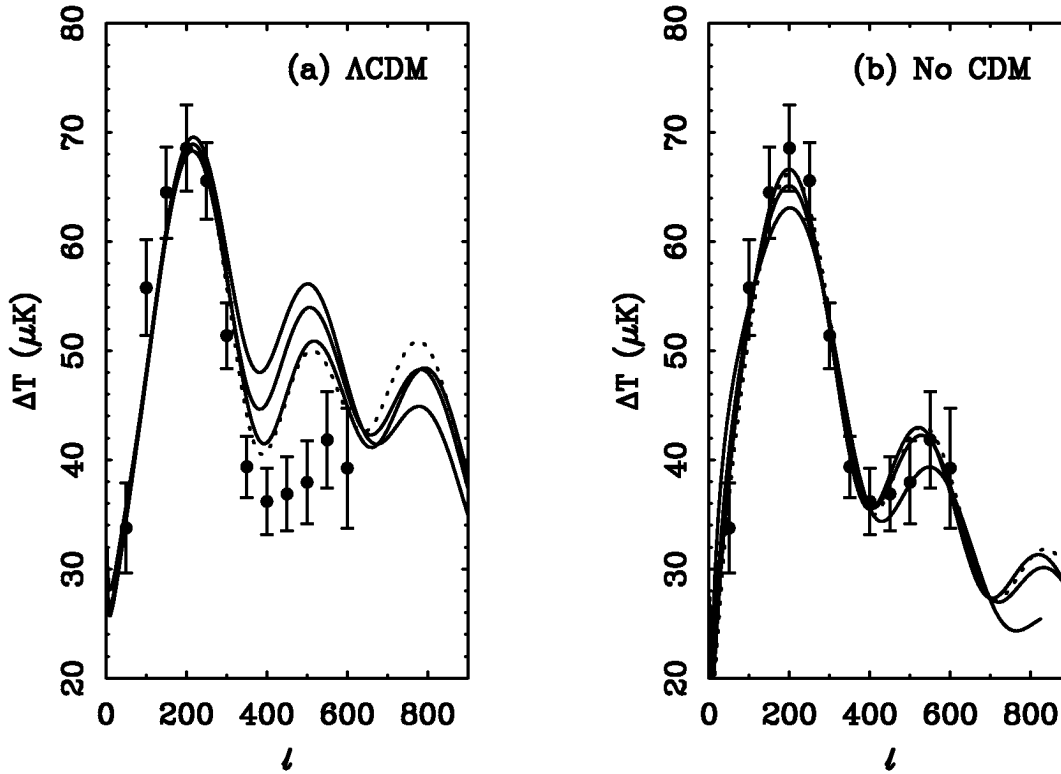


FIG. 1.—A priori predictions of (a) Λ CDM and (b) purely baryonic models plotted against the Boomerang data. The amplitudes of the models are arbitrary and are scaled to match the amplitude of the first peak. Solid lines in (a) are the Λ CDM models of McGaugh (1999) with baryon fractions $f_b = 0.05, 0.10,$ and 0.15 (Λ CDM models 1, 2, and 3 of Table 1) in order of decreasing amplitude of the second peak. These are illustrative of reasonable Λ CDM models. The dotted line shows a reproduction of all the parameters of “standard” Λ CDM (e.g., Turner 1999). The low amplitude of the second peak was unexpected; all reasonable variations of the parameters of the Λ CDM model that were considered before the Boomerang results predicted a second peak considerably larger in amplitude than allowed by the data. In contrast, the data are consistent with the a priori predictions for a purely baryonic universe containing no CDM. The solid lines are identical to the previously published $\Omega_b = 0.01, 0.02,$ and 0.03 models of McGaugh (1999) with geometry scaled to match the position of the first peak (Table 1). Also shown is a model (dotted line) with the baryon density given recently by Tytler et al. (2000). The data are consistent with a purely baryonic universe devoid of CDM.

the shape of the power spectrum, and not the geometry, in which there is a test of the presence or absence of CDM. I have not adjusted the shape *at all* from what I predicted in McGaugh (1999); this is as close to a “no-hands” model as one can come. The pure baryon models provide a good description of the data.

In addition to the models of McGaugh (1999), I illustrate in Figure 1b a model that adheres to the most recent estimate of $\Omega_b h^2$ (Tytler et al. 2000). In this case I have adjusted Ω_Λ to match the position of the first peak so that $\alpha = 1$ (Table 1). The shape of the power spectrum measured by the Boomerang

experiment is well predicted by taking strong priors for $\Omega_b, H_0,$ and so on, with the most important being the pure baryon prior $\Omega_{\text{CDM}} = 0$. Simply scaling the preexisting models with two fit parameters, the amplitude ΔT and the geometry, provides a good fit: $\chi_r^2 < 1$ (Table 1). The data are consistent with a cosmology in which³ $\Omega_m = \Omega_b$ and $\Omega_\Lambda \approx 1$.

3. QUANTITATIVE MEASURES

In order to make a fit-independent, quantitative prediction of the differences expected between the Λ CDM and pure baryon cases, I proposed (McGaugh 1999) several geometry-independent measures. These are the ratio of positions of observed peaks l_{n+1}/l_n , the absolute amplitude ratio of the peaks $(C_{l,n}/C_{l,n+1})_{\text{abs}}$, and the peak-to-trough amplitude ratio $(C_{l,n}/C_{l,n+1})_{\text{rel}}$.

Of these measures, the first is the least sensitive and the last is the most sensitive. The ratio of the positions of the first two peaks is expected to differ by only a small amount. Until this quantity is accurately measured, it does not provide a strong test. Should a second peak appear in future data, it does not necessarily favor Λ CDM—a second peak is expected in either case, in roughly the same position. What does provide a clear distinction is the last measure, the peak-to-trough amplitude ratio of the first two peaks. This distinguishes between a second

TABLE 1
MODEL PARAMETERS AND LIKELIHOODS

| Model | Ω_b | Ω_{CDM} | Ω_Λ | α^a | χ_r^2 | $P(\chi_r^2)$ |
|--------------------------------------|------------|-----------------------|------------------|-------------------|------------|---------------|
| Prior Λ CDM 1 | 0.010 | 0.200 ^b | 0.790 | 1.00 ^c | 13.34 | $\ll 10^{-3}$ |
| Prior Λ CDM 2 | 0.020 | 0.200 ^b | 0.780 | 1.00 ^c | 8.30 | $\ll 10^{-3}$ |
| Prior Λ CDM 3 | 0.030 | 0.200 ^b | 0.770 | 1.00 ^c | 4.60 | $\ll 10^{-3}$ |
| D/H ^d Λ CDM | 0.039 | 0.317 | 0.644 | 1.00 ^c | 3.72 | $\ll 10^{-3}$ |
| Prior Baryon 1 | 0.010 | 0.000 | 0.990 | 0.55 | 1.90 | 0.05 |
| Prior Baryon 2 | 0.020 | 0.000 | 0.980 | 0.62 | 0.89 | 0.55 |
| Prior Baryon 3 | 0.030 | 0.000 | 0.970 | 0.66 | 0.58 | 0.81 |
| D/H ^d Baryon | 0.034 | 0.000 | 1.010 | 1.00 | 0.55 | 0.83 |

^a Geometric scaling factor $l \rightarrow \alpha l$.

^b Models with $\Omega_{\text{CDM}} = 0.3$ and 0.4 with the same baryon fraction and $\Omega_b h^2$ give the same result.

^c $\alpha \approx 0.93$ gives the best match to the position of the first peak.

^d Adheres to $\Omega_b h^2 = 0.019$ (Tytler et al. 2000).

³ A small neutrino mass $m_\nu \lesssim 1$ eV is also admissible.

peak that stands well above the first trough, as expected with CDM, and one that does not, as expected without it.

These measures are readily extracted from the Boomerang data. They are reported in Table 2, together with the a priori predictions of the Λ CDM and pure baryon cases. The data clearly fall in the regime favored by the pure baryon case.

The result remains in the regime favored by the pure baryon case even if we adjust strategically chosen pairs of data points in the direction favorable to CDM. For example, increasing the amplitude of the point at $l = 500$ where the second peak should occur in Λ CDM by 1σ and decreasing by 1σ the amplitude of the point at $l = 400$ where the trough should occur does not suffice to move the result away from the range favored by the pure baryon case. This is more than a 2σ operation, as it is a coordinated move that would also impact surrounding data points. The Boomerang data clearly favor the case of zero CDM.

4. OTHER SOLUTIONS

Shortly after the Boomerang results were announced, various papers appeared that attempted to explain the observed lack of a second peak. These take advantage of the many free parameters that are available in models of the microwave background. One solution is to increase the baryon content rather than reduce the CDM content. In order to retain CDM one significantly violates either big bang nucleosynthesis constraints (Tegmark & Zaldarriaga 2000) or cluster baryon fractions, or both. These were critical pieces of evidence that led to Λ CDM; it is not a trivial matter to dispose of them in order to force the new data into compliance with the model du jour.

Another solution is to somehow erase the peaks subsequent to the first. This can happen if the microwave background photons encounter a significant optical depth, which requires substantial reionization at quite early times (Miller 2000; Peebles, Seager, & Hu 2000). How this could come about is unclear. There may also be decoherence of the ideal signal (White, Scott, & Pierpaol 2000), in which case the microwave background will retain little information of interest beyond the position of the first peak.

These effects were not expected, and it is not necessary to invoke any of them if CDM does not exist. The small observed amplitude of the second peak is natural and expected. Nevertheless, any of these effects could occur. The physics is the same in either case—the only difference is the presence or absence of CDM. It is much easier to explain the low observed amplitude of the second peak without CDM. That does not mean optical depth or decoherence or some other mundane effect need not matter in the purely baryonic case.

At present, a simple universe devoid of CDM suffices to explain the Boomerang data. *If* the universe remains simple, the pure baryon case continues to make clear predictions. As data accumulate, the second peak should become clear. It is only marginally suggested by the data so far, but it should resolve into the shape predicted by the models in Figure 1b. The amplitude of this second peak will be smaller than the a priori expectations of Λ CDM models. Beyond this, the power spectrum should continue to roll off to smaller angular scales so that the third peak has a lower absolute amplitude than the second.

5. JUST BARYONS

The angular power spectrum of the recent microwave background data favor a purely baryonic universe over one dom-

TABLE 2
QUANTITATIVE MEASURES

| Parameter | l_2/l_1 | $(C_{l_1}/C_{l_2})_{\text{abs}}$ | $(C_{l_1}/C_{l_2})_{\text{rel}}$ |
|---|------------|----------------------------------|----------------------------------|
| Λ CDM ^a | ≤ 2.4 | < 1.9 | < 3.6 |
| Pure Baryon ^a | ≥ 2.6 | > 2.1 | > 5.0 |
| Measured ^b | 2.75 | 2.68 | 7.7 |
| 2σ variation ^c | 2.63 | 2.40 | 5.6 |

^a Values expected a priori.

^b Values as measured by Boomerang at each apparent peak ($l_1 = 200$ and $l_2 = 550$).

^c Values measured by making 1σ changes to each of two strategically chosen data points in the direction favoring CDM.

inated by CDM. Yet, a conventional baryonic universe with $\Omega_m = \Omega_b$ faces the same problems mentioned in the introduction that led to the invention of CDM. For one, $\Omega_m > \Omega_b$; dynamical measures give a total mass density an order of magnitude in excess of the nucleosynthesis constraint on the baryon density. The other is that the gravitational growth of structure is slow: $\delta \sim t^{2/3}$. This makes it impossible to grow large-scale structure from the smooth initial state indicated by the microwave background within the age of the universe.

These arguments are compelling, but are themselves based on the assumption that gravity behaves in a purely Newtonian fashion on all scales. A modification to the conventional force law might also suffice. One possibility that is empirically motivated is the modified Newtonian dynamics (MOND) hypothesized by Milgrom (1983). MOND supposes that for accelerations $a \ll a_0 \approx 1.2 \times 10^{-10} \text{ m s}^{-2}$, the effective acceleration becomes $a \rightarrow (g_N a_0)^{1/2}$, where g_N is the usual Newtonian acceleration that applies when $a \gg a_0$. There is no dark matter in this hypothesis, so the observed motions must relate directly to the distribution of baryonic mass through the modified force law.

MOND has had considerable success in predicting the dynamics of a remarkably wide variety of objects. These include spiral galaxies (Begeman, Broeils, & Sanders 1991; Sanders 1996; Sanders & Verheijen 1998), low surface brightness galaxies (McGaugh & de Blok 1998b; de Blok & McGaugh 1998; McGaugh et al. 2000), dwarf spheroidal galaxies (Milgrom 1995; Mateo 1998), giant elliptical galaxies (Sanders 2000), groups (Milgrom 1998) and clusters of galaxies (Sanders 1994, 1999), and large scale filaments (Milgrom 1997). The empirical evidence that supports MOND is rather stronger than is widely appreciated.

Moreover, MOND does a good job of explaining the two observations that motivated CDM. The dynamical mass is overestimated when purely Newtonian dynamics is employed in the MOND regime, so rather than $\Omega_m > \Omega_b$ one infers $\Omega_m \approx \Omega_b$ (Sanders 1998; McGaugh & de Blok 1998b). The early universe is dense, so accelerations are high and MOND effects⁴ do not appear until after recombination. When they do, structure grows more rapidly than with conventional gravity (Sanders 1998), so the problem in going from a smooth microwave background to a rich amount of large-scale structure is also alleviated. Since everything is normal in the high-acceleration regime, all the usual early universe results are retained.

In order to get the position of the first peak right, we must invoke the cosmological constant in either the conventional or MOND case. In the former case, it was once hoped that there would be enough CDM that $\Omega_m = 1$. In the latter case, Λ may

⁴ Assuming a_0 is constant.

have its usual meaning, or it may simply be a place holder for whatever the geometry really is. One possible physical basis for MOND may be the origin of inertial mass in the interaction of particles with vacuum fields. A nonzero cosmological constant modifies the vacuum and hence may modify inertia (Milgrom 1999). In this context, it is interesting to note that for the parameters indicated by the data, $\Omega_m = \Omega_b$ and $\Omega_\Lambda \approx 1$, the transition from matter domination to Λ -domination is roughly coincident with the transition to MOND domination.

The value of Ω_Λ indicated by this scenario is in marginal conflict with estimates from high-redshift supernovae (Riess et al. 1998; Perlmutter et al. 1999). Modest systematic effects might be present in Type Ia supernovae data which could reconcile these results. It is difficult to tell at this early stage how significant the difference between $\Omega_\Lambda \approx 0.7$ and $\Omega_\Lambda \approx 1$ really is. Even if this difference is real, it may simply indicate the extent to which MOND affects the geometry. This is analogous to the variable- Λ scenarios called quintessence that have recently been considered (e.g., Caldwell, Dave, & Steinhardt 1998).

6. CONCLUSIONS

Prior to the publication of the data from recent microwave background experiments, I had investigated the power spectrum

of anisotropies that would be expected for a purely baryonic universe devoid of CDM (McGaugh 1999). Such a cosmology predicts a small amplitude for the second peak. This prediction is consistent with the subsequently published data (de Bernardis et al. 2000; Hanany et al. 2000).

The Boomerang data are well described by a model in which all cosmological parameters except the geometry are fixed to values measured by independent means. Once the position of the first peak is fixed, no tuning of any of the many other parameters is required to explain the low observed amplitude of the second peak. This is not surprising; it is simply what is expected in a purely baryonic universe.

Consideration of a purely baryonic universe is motivated by the recent successes (e.g., McGaugh & de Blok 1998b) of the hypothesized alternative to dark matter known as MOND (Milgrom 1983). Such a modification to conventional dynamics does appear to be viable. Taken in sum, the data suggest a universe in which $\Omega_m = \Omega_b$ and $\Omega_\Lambda \approx 1$.

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REFERENCES

- Begeman, K. G., Broeils, A. H., & Sanders, R. H. 1991, *MNRAS*, 249, 523
 Bludman, S. A. 1998, *ApJ*, 508, 535
 Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, *Nature*, 311, 517
 Caldwell, R. R., Davé, R., & Steinhardt, P. J. 1998, *Ap&SS*, 261, 303
 de Bernardis, P., et al. 2000, *Nature*, 404, 955
 de Blok, W. J. G., & McGaugh, S. S. 1998, *ApJ*, 508, 132
 Efstathiou, G., & Bond, J. R. 1999, *MNRAS*, 304, 75
 Evrard, A. E. 1997, *MNRAS*, 292, 289
 Flores, R. A., & Primack, J. R. 1994, *ApJ*, 427, L1
 Hanany, S., et al. 2000, preprint (astro-ph/0005123)
 Hu, W., Sugiyama, N., & Silk, J. 1997, *Nature*, 386, 37
 Lange, A. E., et al. 2000, preprint (astro-ph/0005004)
 Mateo, M. L. 1998, *ARA&A*, 36, 435
 McGaugh, S. S. 1999, *ApJ*, 523, L99
 McGaugh, S. S., & de Blok, W. J. G. 1998a, *ApJ*, 499, 41
 ———. 1998b, *ApJ*, 499, 66
 McGaugh, S. S., Schombert, J. M., Bothun, G. D., & de Blok, W. J. G. 2000, *ApJ*, 533, L99
 Milgrom, M. 1983, *ApJ*, 270, 371
 ———. 1995, *ApJ*, 455, 439
 ———. 1997, *ApJ*, 478, 7
 ———. 1998, *ApJ*, 496, L89
 Milgrom, M. 1999, *Phys. Lett. A*, 253, 273
 Miller, M. C. 2000, preprint (astro-ph/0003176)
 Moore, B. 1994, *Nature*, 370, 629
 Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G. 1999, *MNRAS*, 310, 1147
 Navarro, J. F., & Steinmetz, M. 2000, *ApJ*, 528, 607
 Ostriker, J. P., & Steinhardt, P. J. 1995, *Nature*, 377, 600
 Peebles, P. J. E., Seager, S., & Hu, W. 2000, *ApJ*, 539, L1
 Perlmutter, S., et al. 1999, *ApJ*, 517, 565
 Riess, A. G., et al. 1998, *AJ*, 116, 1009
 Sanders, R. H. 1994, *A&A*, 284, L31
 ———. 1996, *ApJ*, 473, 117
 ———. 1998, *MNRAS*, 296, 1009
 ———. 1999, *ApJ*, 512, L23
 ———. 2000, *MNRAS*, 313, 767
 Sanders, R. H., & Verheijen, M. A. W. 1998, *ApJ*, 503, 97
 Seljak, U., & Zaldarriaga, M. 1996, *ApJ*, 469, 437
 Sellwood, J. A. 2000, *ApJ*, in press (astro-ph/0004352)
 Tegmark, M., & Zaldarriaga, M. 2000, preprint (astro-ph/0004393)
 Turner, M. S. 1999, *PASP*, 111, 264
 Tytler, D., O'Meara, J. M., Suzuki, N., & Lubin, D. 2000, *Phys. Scr.*, 85, 12
 White, M., Scott, D., & Pierpaol, E. 2000, preprint (astro-ph/0004385)