Boomerang returns unexpectedly

Martin White
Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, MA 02138

Douglas Scott and Elena Pierpaoli
Department of Physics & Astronomy,
University of British Columbia, Vancouver, BC, V6T 1Z1

ABSTRACT

Experimental study of the anisotropy in the cosmic microwave background (CMB) is gathering momentum. The eagerly awaited Boomerang results have lived up to expectations. They provide convincing evidence in favor of the standard paradigm: the Universe is close to flat and with primordial fluctuations which are redolent of inflation. Further scrutiny reveals something even more exciting however – two hints that there may be some unforeseen physical effects. Firstly the primary acoustic peak appears at slightly larger scales than expected. Although this may be explicable through a combination of mundane effects, we suggest it is also prudent to consider the possibility that the Universe might be marginally closed. The other hint is provided by a second peak which appears less prominent than expected. This may indicate one of a number of possibilities, including increased damping length or tilted initial conditions, but also breaking of coherence or features in the initial power spectrum. Further data should test whether the current concordance model needs only to be tweaked, or to be enhanced in some fundamental way.

Subject headings: cosmology: theory – cosmic microwave background

1. Introduction

The study of the Cosmic Microwave Background (CMB) anisotropy holds the promise of answering many of our fundamental questions about the Universe and the origin of the large-scale structure (see e.g. Bond 1996; Bennett, Turner & White 1997; Lawrence, Scott & White 1999). The development of CMB research can be split into 5 main phases. Firstly, the mere existence of the CMB showed that the early Universe was hot and dense. Secondly, the blackbody nature of the CMB spectrum and its isotropic distribution implied that the Universe is approximately homogeneous on large scales. The third step came with the detection of anisotropies, confirming that structure grew through gravitational instability. Now we are entering the fourth stage. The recently released Boomerang data (de Bernardis et al. 2000) provide support for a model with adiabatic initial conditions and a Universe with approximately flat geometry. The fact that our theories are holding up so well gives us further reason to believe that the CMB can be used as a precision cosmological tool. With the imminent launch of MAP, we are on the verge of the fifth phase, which involves determining the precise values of the fundamental cosmological parameters to figure out exactly what kind of Universe we live in.

1 A paper about a boomerang by an Australian and his mates.
Most of the unmined cosmological information available from the CMB anisotropy is encoded in the acoustic signatures, the series of peaks and troughs in the spectrum at subdegree scales, which we are only now beginning to probe experimentally. Because the properties of the photon-baryon oscillations are determined by the background, while the driving force is described by the model for the perturbations, the acoustic signatures provide a unique opportunity to probe both the background cosmology and the model for structure formation. For example the position of the first peak, or indeed any other feature, provides a measure of the angular diameter distance to last scattering. The relative heights of the peaks provide information about the baryon ‘drag’ on the photons and thus the baryon-to-photon ratio. The relative peak locations provide information on the perturbations as they crossed the horizon and thus indirectly on the mechanism for their production (see e.g. Hu, Sugiyama & Silk 1997).

In the last year or so there have been several new CMB data sets which have begun to reveal the structure contained in the acoustic peaks (see e.g. Lineweaver 1999; Dodelson & Knox 2000; Melchiorri et al. 2000; Pierpaoli, Scott & White 2000; Efstathiou 2000; Tegmark & Zaldarriaga 2000; Lahav et al. 2000; Le Dour et al. 2000 for analyses of these data). Now with the first estimate of the power spectrum from a sub-set of the Antarctic flight of the Boomerang experiment we are entering a whole new regime of precision. There are 3 striking things about this new power spectrum estimate. Firstly, and most importantly, it corroborates the basic picture of cosmological structure formation – the shape is a confirmation of flat models of the sort inspired by inflation, dominated by a cosmological constant, as has become the standard paradigm. However, the position of the first peak appears at slightly larger angular scales than might have been expected. And lastly, another possibility for something unexpected comes through a hint that the second peak may not be as pronounced as most models would predict. We will make some general comments about the existence of the first acoustic peak, and then in the rest of this Letter we focus on these latter two surprising features of the new data (see also Hu 2000).

2. A distinct acoustic peak

The presence of a narrow, well defined peak in the angular power spectrum (for which earlier evidence existed: Dodelson & Knox 2000; Melchiorri et al. 2000; Pierpaoli, Scott & White 2000) has important consequences. Primarily it shows that the theoretically expected acoustic peaks are in fact present in nature! A well defined narrow peak implies that whatever caused the fluctuations did so at very early times rather than actively driving the photon-baryon fluid at recombination (such as would happen in models based on topological defects, for example). By the time the anisotropies formed at $z \sim 10^3$, the growing mode of the perturbations was dominant. The width of the peak is then essentially a measure of the inertia of the baryon-photon fluid at last scattering.

We show in Fig. 1 the Boomerang data from de Bernardis et al. (2000) along with some theoretical models and a compilation of older data from Pierpaoli et al. (2000). In comparison with the older data, the Boomerang data appear lower around the first peak. Note however that the Pierpaoli et al. (2000) points are somewhat anti-correlated with their nearest neighbors. Thus the disagreement is not quite as large as it appears. The remaining discrepancy is consistent with the $\sim 10\%$ calibration uncertainty between experiments. In other words, on a power spectrum plot, one is allowed to shift the power spectrum estimates from individual data sets by as much as 20% vertically relative to each other. It appears then that the Boomerang data set has a lower overall calibration (as did the data from the Boomerang test flight, Mauskopf et al. 2000) than some of the earlier experiments.
It is a dramatic verification of the simplest cosmological models that the existence of such a peak, made at least as early as 1978 (Doroshkevich, Sunyaev & Zel’dovich 1978), has been confirmed by experiment. This sort of clear test of theoretical ideas is quite uncommon in cosmology!

3. First peak position

The Boomerang data show a peak which lies at lower $\ell$ than the canonical value for a flat universe, which is $\ell \approx 220$. The first explanation for this would be that we live in a closed universe; however it is interesting to ask what other options exist. Firstly, the peak position comes from a quadratic fit to the data between $\ell = 50$ and 300 (de Bernardis et al. 2000). Thus at least some of the constraint pushing the peak to lower $\ell$ is in the rapid decrease in power beyond the peak. We have checked that the peak position is unaffected by the precise functional form used, but it remains true that the low effective $\ell_{\text{peak}}$ may be explained partly by the same physics that makes the second peak lower than expected. Nevertheless, Fig. 1 shows clearly that the $\Lambda$-dominated ‘concordance model’ (Ostriker & Steinhardt 1995) does not give a good fit around the peak.

As shown in Hu & White (1996a; 1996b), using the first peak to measure the angular diameter distance to last scattering can be a subtle business. Fortunately the positions of the peaks are sensitive to few of the many other cosmological parameters that alter the anisotropy spectrum. If the baryon density is constrained to satisfy big-bang nucleosynthesis, then it introduces a negligible uncertainty on the peak positions. Higher order effects do not change the peak positions. Of course, any effect on the power spectrum which reduces small-scale power will also shift the peak a little to the left, but this is essentially negligible for reasonable parameters (e.g. for tilt $0.7 \leq n \leq 1.3$).

The major effect, then, is the angular diameter distance to last scattering and the physical matter density $\propto \Omega_M h^2$. If we hold the distance to the last scattering surface fixed a low matter density universe, which has last scattering closer to the radiation dominated epoch, has a peak broadened and shifted leftwards. This effect is small, however, and is usually overcome by the cosmological dependence of the distance to last scattering. For a flat universe with fixed $\Omega_B h^2$, the distance to the last scattering surface is a function of $\Omega_M$ and $h$, being shorter for high $\Omega_M$ or $h$. Thus the $\ell$ of the first peak decreases slightly with increasing $\Omega_M$ or $h$. We show this in Fig. 2, where we plot the $\ell$ of the first peak as a function of $\Omega_M$ for flat models. For reasonable cosmological parameters the first peak can be as low as 210 even in a flat universe. For $\ell_{\text{peak}} < 210$, one starts violating other cosmological constraints.

Thus we have suggestive evidence that the Universe may be spatially closed. Inflationary models certainly exist (e.g. Linde 1995), in which a closed universe is created ‘from nothing’ (Zel’dovich & Grishchuk 1984). Historically there has been much interest in closed universes (see Björnsson & Gudmundsson 1995, White & Scott 1996, and references therein), since the spatial surfaces are compact (Wheeler 1968; Hawking 1984) and the total energy, charge and angular momentum are zero (Landau & Lifshitz 1975). This has appealing properties of finiteness and flux conservation for formal studies, and hence has been preferred by various authors on grounds that are essentially philosophical, or at least mathematical (for an interesting historical discussion see Misner, Thorne & Wheeler 1973, §21.12 and §27.1). In other words, faced with the choice of $\Omega_{\text{tot}} = 1 + \epsilon$ or $1 - \epsilon$, there may be reasons to choose the former.
4. Second peak height

The new Boomerang power spectrum indicates at first sight a rather weak second peak. The important thing to say here is that there is still a great deal of power at scales $\ell = 400-600$. In other words, the power spectrum has certainly not damped to zero, and there most certainly is a second peak. The question is: how high is it? At face value, the data would appear to indicate that the peak is rather flat. However, we would caution that the data are probably more uncertain at these small scales, since a number of corrections need to be applied. Uncertainties in beam size, beam asymmetry, pixelization, the effects of bolometer time constant etc., can all lead to systematic effects on these scales. Nevertheless, the Boomerang team has modeled these effects and it seems that the basic prediction of the standard $\Lambda$-dominated model (solid line in Fig. 1), for example, would give a higher peak than the data seem to indicate. It is therefore worth investigating how one obtains a lower second peak, in relation to the first.

A wealth of information is stored in the peak heights, but their signature is more model dependent than the locations. To obtain a large ratio of power between the first and second peaks, we would naturally like to have a large first peak, which points indirectly to a low matter density universe. The argument goes as follows (Hu & White 1996b). Two primary effects govern the peak heights: baryon drag and the driving force of photon self-gravity. As a perturbation enters the horizon, the fluid is compressed by its self-gravity. Photon pressure resists the compression, causing the photon-baryon contribution to the potential to decay. The fluid is then released into the acoustic phase in this highly compressed state. The photons are intrinsically 'hot' and do not need to battle against a large gravitational potential when streaming to the observer, leading to a large temperature anisotropy on the sound horizon scale. This 'driving effect' does not occur if the potentials are dominated by an external source, such as cold dark matter. Thus the first peak is boosted relative to the low-$\ell$ plateau in universes with low matter density. The baryons additionally provide inertia to the photon-baryon fluid, enhancing the compressions and retarding the rarefactions. Since the first peak in adiabatic models is a compression, a high baryon content enhances the first peak.

In addition to lowering the matter density, one could obtain decaying potentials at last scattering by increasing the radiation content of the Universe, for example through decaying neutrino models (Bardeen, Bond & Efstathiou 1987; Dodelson, Gyuk & Turner 1994) or volatile neutrino models (Pierpaoli & Bonometto 1999). These models also have an enhanced first peak (White, Gelmini & Silk 1995). For a wide range of neutrino mass and lifetime, the neutrino decay happens while the modes relevant to CMB anisotropies are outside the horizon, and thus decaying neutrino models mimic models with a very large ‘equivalent number of neutrinos’ $N_e$. As an example, let us consider a model with $\Omega_M = 1$ and $h = 0.65$.

<table>
<thead>
<tr>
<th>$\Omega_M$</th>
<th>$\Omega_B$</th>
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<tbody>
<tr>
<td>0.2</td>
<td>1.81 2.02 2.32 2.62</td>
</tr>
<tr>
<td>0.3</td>
<td>1.70 1.97 2.27 2.62</td>
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<tr>
<td>0.5</td>
<td>1.61 1.90 2.26 2.67</td>
</tr>
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Table 1: The ratio of the height of the first peak to the second peak, for a model with $h = 0.7$ and $n = 1$. This ratio is fixed by the physics at recombination and the initial perturbation spectrum, thus it depends on $\Omega_M h^2$, $\Omega_B h^2$, and $n$. 
To fit large-scale structure we want to increase the horizon at equality by a factor $\sim 2.6$, requiring $N_e \sim 44$. This can be achieved with $(m_\nu/\text{keV})^2 (\tau/\text{yr}) \sim 500$. We show the effect of this in Fig. 1. Note that raising the radiation density has moved the peaks slightly rightwards – a change in the spatial curvature would be necessary to move them left again (e.g. adding $\Omega_\Lambda = 0.5$, long-dashed line in Fig. 1, fits the data).

Other ways of increasing the effective number of relativistic degrees of freedom can achieve the same effect of increasing the height of the first peak compared with the second, for example by adding extra sterile neutrino species or using large lepton asymmetry (Kinney & Riotto 1999). Note that the addition of massive neutrinos (hot dark matter) will generally increase the second peak height relative to the first – which does not help – although it will move the peaks slightly to the left.

The ratio of the heights of the first and second peaks is set by the physics at recombination and the primordial power spectrum. Thus it depends on $\Omega_M h^2$, $\Omega_B h^2$, $n$ and the radiation energy density (parameterized by $N_v$). The effect of tilt is to change the ratios by $(f_2/f_1)^{n-1}$, we show the effect of changing $\Omega_M h^2$ and $\Omega_B h^2$ in Table 1. The Boomerang data give this ratio as approximately 3, so one can see that rather extreme values of the parameters may be required.

A high baryon fraction, coupled with a low matter density or a high radiation density, in a model with less small scale power than scale-invariance predicts, would naturally produce a diminishing series of peaks, including a small second peak. Models with less small-scale power than scale-invariance can arise naturally in inflation ranging from models with power law spectra slightly tilted away from scale-invariance to models with broken power laws or even rapid drops in power at some scale (see Lyth & Riotto 1999 for a recent review). The most natural such models are the tilted models with ‘red’ spectra. The low matter density and high baryon density help to boost the first peak enough to overcome some of the effects of the tilt, making the ratio of the first to second peaks larger. And, finally, a high baryon density reduces the rarefraction peaks, of which the second peak is the first example. We should also point out that low $\Omega_M$ models with some tilt and high $\Omega_B$ have their first peak shifted a little to the left compared with more standard models, though this is a small effect. Models with red spectra sometimes predict tensor anisotropies, which serve to lower the whole peak structure relative to the COBE normalization. This generally makes it more difficult to obtain the necessary power at the first peak.

If we tilt the spectrum to remove small scale power we are limited in how much other small-scale power reducing effects can operate. Thus a high first peak in a tilted model limits the epoch of reionization. Currently limits on the reionization optical depth are $\tau \lesssim 0.3$ (Griffiths, Barbosa & Liddle 1999), although this is somewhat model dependent. A strong constraint on $\tau$ requires combining the CMB data with information from large-scale structure.

More speculatively, the small second peak could be telling us that the peaks are more ‘washed out’ than the inflationary predictions. In other words, there may be some decaying mode left in the fluctuations, or the perturbations may not be entirely synchronized at horizon crossing, so that there may be some loss of coherence of the oscillations. Note that the first peak is well defined, so we would want a source which turned off before those modes entered the horizon, i.e. was acting only at early times, perhaps before equality. Such a source would not be ‘scaling’ and a mechanism would be required to pick out a preferred scale in the Universe, e.g. matter-radiation equality. It would be intriguing if the structure of the peaks told us something fundamental about the origin of the seed perturbations themselves!

A host of other possibilities become even less likely. A source of energy injection at $z \sim 10^3$ could delay recombination and change the damping of the anisotropies, though one would need to take care to not distort the spectrum. Other changes in the physics of recombination could also increase damping, although it is
hard to believe there is much missing in our understanding of the physics of hydrogen and helium atoms (Seager, Sasselov & Scott 2000). The damping scale is an integral over the visibility function (e.g. Hu & White 1997) so to move this to lower $\ell$ we wish to delay recombination. We show the kind of effect that would be required in Fig. 3 where we reduce the Rydberg energy by 10% and 20%, this delays recombination until lower redshift, mimicking the effect of energy injection at $z \sim 1000$. Increasing the coupling of the photons to the baryons at higher $z$, for example by increasing $n_{\text{He}}/n_{\text{H}}$, has effects that are at the per cent level. Variation in fundamental physics, such as a changing fine structure constant (e.g. Kaplinghat, Scherrer & Turner 1999) is a more speculative way to achieve this same goal. Magnetic fields are often invoked to explain unexpected phenomena, but here the simplest ideas tend to increase the small-scale anisotropies.

5. Conclusions

The Boomerang data provide a stunning confirmation of the reality of acoustic oscillations in the photon-baryon fluid at last scattering. The fact that the peak is at $\ell \sim 200$ argues that the Universe is close to spatially flat. The fact that the second peak appears to be smaller than naively expected, while explicable within standard models, could be a clue to something novel in our model of structure formation.

We have argued that the high first peak relative to the second is suggestive of tilt in the primordial power spectrum, a late epoch of M-R equality and a low redshift of reionization. The leftwards nature of the first peak argues for a short distance to last scattering, and in combination with the former this argues that the Universe be (marginally) spatially closed.

The key to making further progress will be the detection of a third peak. Models with a high baryon content will have a high third peak, tilted models will have a lower third peak. Lack of coherence in the oscillations would be more exciting still, since this would be harder to explain. The detection of a second feature in the power spectrum would pin down the fundamental mode of the baryon-photon fluid at last scattering and put us well on our way towards reconstructing the model of structure formation.

Further measurement of the second peak should come with analysis of the full Boomerang 98 data-set, the data from DASI\(^2\) or CBI\(^3\). In addition long-duration CMB balloon flights this coming winter, as well as the imminent launch of MAP\(^4\), should produce much more precise measurements of the relevant $\ell$ range.

The new Boomerang results have shown a remarkable confirmation of the conventional picture for structure formation. On top of that, it is exciting that the data show some hints of a couple of surprises. To make it easier to fit the first peak position, it may be worth bearing in mind the possibility that the Universe may be spatially closed. And, for consistency with the structure of the subsidiary peaks, it is worth keeping an open mind to the possibility that there may yet be some important physical effects which are not contained within the simplest versions of the current standard paradigm.

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\(^2\)http://astro.uchicago.edu/dasi/
\(^3\)http://astro.caltech.edu/~tjp/CBI/
\(^4\)http://map.gsfc.nasa.gov/
Astrophysics.

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Fig. 1.— A comparison of the Boomerang data (solid squares) with an earlier compilation (Pierpaoli et al. 2000; open circles) and some theoretical models. The solid line is the ‘standard’ $\Lambda$CDM model of Ostriker & Steinhardt (1995). The dashed line is an example of a model that has been tweaked to provide a better fit to the Boomerang data: a slightly closed, high baryon, tilted $\Lambda$CDM model with $\Omega_M = 0.4$, $\Omega_\Lambda = 0.7$, $h = 0.6$, $\Omega_B h^2 = 0.025$ and $n = 0.9$. The dotted line is a critical density model with a high baryon fraction $\Omega_B = 0.1$ while the long-dashed line is the decaying neutrino model discussed in the text.
Fig. 2.— The position of the first acoustic peak, $\ell_{\text{peak}}$, as a function of $\Omega_M$ in a flat universe. In all cases we have held $\Omega_B h^2 = 0.02$. We show 4 values of the Hubble constant $H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$: $h = 0.6$, 0.65, 0.70 and 0.75. The region allowed by the Boomerang data is shown hatched.
Fig. 3.— The effect of modifying recombination. Here we have scaled the energy levels in hydrogen by respectively 10% (dotted) and 20% (dashed) to affect the time of recombination, as a simple way of showing the effect of bringing the damping tail to lower $\ell$. 