Gravity waves goodbye

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Abstract

The detection of a stochastic background of long-wavelength gravitational waves (tensors) in the cosmic microwave background (CMB) anisotropy would be an invaluable probe of the high energy physics of the early universe. Unfortunately a combination of factors now makes such a detection seem unlikely: the vast majority of the CMB signal appears to come from density perturbations (scalars) - detailed fits to current observations indicate a tensor-to-scalar quadrupole ratio of $T/S < 0.5$ for the simplest models; and on the theoretical side the best-motivated inflationary models seem to require very small $T/S$. Unfortunately CMB temperature anisotropies can only probe a gravity wave signal down to $T/S \sim 10\%$ and optimistic assumptions about polarization of the CMB only lower this another order of magnitude.

Inflation is the only known mechanism for producing an almost scale-invariant spectrum of adiabatic scalar (density) fluctuations, a prediction which is steadily gaining observational support. The simplest models of inflation also predict an almost scale-invariant spectrum of gravity waves. A definitive detection of these waves would constitute a window onto physics at higher energies than have ever been probed before. Indeed, it has been realized for some time that, for monomial inflation models within the slow-roll approximation, measurement of this spectrum could allow a reconstruction of the inflaton potential itself [1]. Unfortunately, a combination of factors now makes this seem unlikely: the vast majority of the CMB signal probably comes from scalar perturbations, for reasons we shall now describe.

Theoretically one could imagine that whatever mechanism produces the initial fluctuations which seeded structure formation would produce all three types of perturbations (scalar, vector and tensor) roughly equally. If this happens early enough, the vector modes – representing fluid vorticity – would decay with the expansion of the universe leaving only scalar and tensor perturbations today. Unfortunately we live in a “special” universe in which
the perturbations appear to be both adiabatic and close to scale-invariant (equal contribution to the metric perturbation per logarithmic interval in wavelength). Our best paradigm for producing such fluctuations is amplification of quantum fluctuations by a period of accelerated expansion, i.e. inflation. Within this paradigm we shall see that $T/S$ is expected to be considerably smaller than the naive $1 : 1$ ratio.

While some simple models of inflation predict $T/S \simeq 1$, we would hope that inflation would one day find a home in modern particle physics theories. From this perspective, there is currently a “considerable theoretical prejudice against the likelihood” \[3\] of an observable gravity wave signal in the CMB anisotropy. While our knowledge of physics above the electroweak scale is extremely uncertain, a large $T/S$ requires two unlikely events. First the scale of variation of the inflaton field during inflation would need to be $\mathcal{O}(m_{Pl})$ or greater, which is inconsistent with an ordinary extension of the standard model \[2\]. Secondly, the size of the inflaton potential would necessarily be $V^{1/4} \sim 10^{-2}m_{Pl}$, orders of magnitude larger than generically expected from particle theory \[2\]. Thus inflation, in a particle physics context, predicts that the scalar perturbations will be dramatically enhanced over the tensor perturbations. A separate line of argument, involving a description of inflation motivated by quantum gravity, leads to a prediction of $T/S \simeq 1.7 \times 10^{-3} \[3\].

What is the situation on the observational side? The measurement of the large-angle CMB anisotropies by the COBE satellite has been followed by ground- and balloon-based observations of the smaller scale regions of the CMB power spectrum. Measurements on a range of scales are needed to constrain gravity waves, since tensors are expected to contribute only to angular scales greater than about $1\textdegree$. Thus large-scale power greater than that expected from the extrapolation of small-scale scalar power can be attributed to tensors. This small-scale power can be measured from the CMB itself or additionally from matter fluctuations in more recent epochs, allowing a large lever arm in scale.

We have recently placed upper limits on $T/S$ using a variety of observations \[4\]. We used CMB anisotropy data as well as information about the matter fluctuations from galaxy correlation, cluster abundance, and Lyman $\alpha$ forest measurements. Our limits include a variety of additional constraints (such as the age of the universe, cluster baryon density, and recent supernova measurements), in all cases marginalizing over the relevant but as yet imprecisely determined cosmological parameters. We placed constraints on exponential and polynomial inflaton potential models; these “large-field” models predict substantial $T/S$ and are therefore of interest here. We found $T/S < 0.5$ at 95% confidence, with the small-angle CMB data providing the bulk of the constraint (see Fig. 1).

In the next several years a pair of satellite missions should dramatically improve our picture of the CMB. MAP and especially the Planck Surveyor will map the CMB at unprecedented precision. What can we expect from these missions regarding gravity wave constraints? With a cosmic variance limited experiment capable of determining only the anisotropy in the CMB, but with all other parameters known, one can measure $T/S$ only if it is larger than about 10% \[3\]. To additionally measure the tensor spectral index and check the inflationary consistency relation \[1\] requires $T/S$ to be a factor of several larger. This is in conflict with current theoretical prejudice, and realistically also in conflict with the experimental limits.

One can potentially improve sensitivity to $T/S$ by measuring the polarization of the CMB. With more observables the error bars on parameters are tightened. In addition,
polarization breaks the degeneracy between reionization and a tensor component, both of which affect the relative amplitude of large and small angular scales, allowing extraction of smaller levels of signal [6]. Model dependent constraints on a tensor perturbation mode as low as 1% appear to be possible with the Planck satellite [7], though numerical inaccuracies plagued earlier work [8] making these numbers somewhat soft.

Scalar modes have no “handedness” and hence they generate only parity even, or $E$-mode polarization [6,9]. A detection of $B$-mode polarization would thus indicate the presence of other modes, with tensors being more likely since vector modes decay cosmologically. Unfortunately the detection of a $B$-mode polarization will be a formidable experimental challenge. The level of the signal is expected to be very small: only a few tens of nK. One can regain some signal-to-noise ratio by concentrating on the sign of the correlation of polarization with temperature anisotropies on large-angular scales (scalar polarization is tangential around hot spots, while tensor polarization is radial). Unfortunately only a small fraction of the signal is correlated, so again the signal is extremely small (less than $1\mu$K), and the correlation is swamped by the scalar signal unless $T/S$ is significant.

The ground-based laser interferometers LIGO and VIRGO, the proposed space-based interferometer LISA, and millisecond pulsar timing offer another conceivable route to primordial gravity wave detection. However, the long lever arm from the horizon scale to the scales probed by these experiments makes direct detection infeasible [10–12].

All of these arguments combine to considerably reduce the optimism for the detailed reconstruction of the inflaton potential through cosmological gravity wave measurement. However, since inflation appears to predict low $T/S$, it is good news that observations support a small tensor contribution. The apparent demise of the significance of tensors for the CMB has one important consequence: detection of even a modest contribution of gravity waves would profoundly affect our view of early universe particle physics.
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