Unravelling the Big Bang with the Planck Satellite

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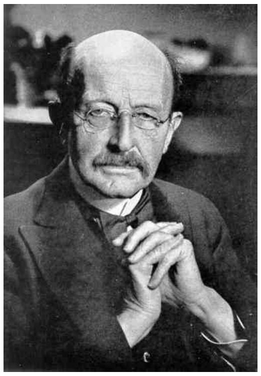
The Planck satellite (pictured to the right) was launched succesfully by an Ariane 5 rocket at lunchtime on the 14th May. The first proposals for the Planck satellite were submitted to the European Space Agency (ESA) in 1993. It has taken sixteen years of hard work by many engineers and scientists to go from those initial proposals to atested satellite ready for launch. I could write a book about the ups and downs (and there have been many of them) during the last sixteen years. But in this article, I want to focus on the main science goals of Planck. Why have so many people dedicated so much time to Planck, and why have so many countries in Europe, Canada and the USA provided the cash to build the satellite?



The Planck satellite is named after the German physicist Max Planck (1858-1947, pictured to the left). In attempting to explain the spectrum of 'black body' radiation (the radiation emitted from a perfect absorber) Planck introduced the concept of energy quanta. This was the first step towards quantum mechanics (which underpins so much of the fantastic technology that we take for granted every day). The satellite was named after Planck in 1996 by the then ESA Director of Science Roger Bonnet. (Previously the satellite went under the clumsy acronym COBRAS/SAMBA). Bonnet chose the name because the satellite is designed to study the black body radiation left over from the hot Big Bang. This is quite a good reason, but I think an even better argument for naming our satellite after Planck comes from his perceptive discovery of so-called 'natural' units. Here is what Planck says about these natural units:

> *'These necessarily retain their meaning for all times and for all civilisations, even extraterrestials and non-human ones.'*

Fundamental physics involves three constants of nature:

$$\boxed{\hbar, \quad c, \quad G.}$$

The first is Planck's constant which tells us the scale of the quantum world. The second is the speed of light, encoding the Einstein's relativity principle. The third is Newton's constant, which quantifies the strength of the force of gravity. For a theoretical physicist each of these constants can be taken to be unity. Their values expressed in familiar units, metres, seconds and so on, are of no fundamental significance. Our standardised units are human constructions, chosen for our convenience. (This is why Planck refers to 'extraterrestrials' in the quotation cited above.) So, a metre is roughly the length of a long step, a second is about the time interval between heartbeats, and a kilogram is about the maximum amount of pasta that you can eat. Let's see the values of Planck's 'natural' units in terms of our more familiar units:

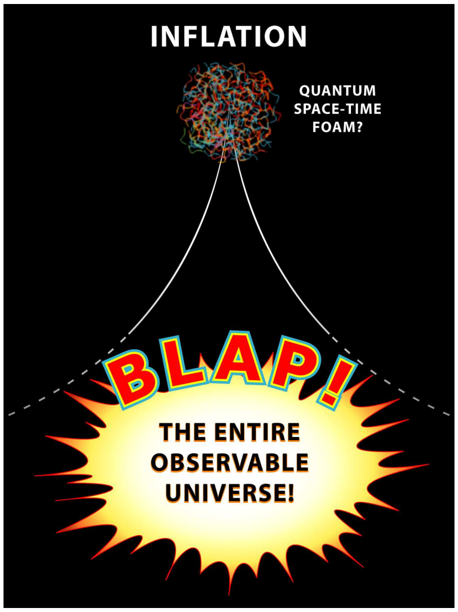
The Planck length: $\left(\frac{\hbar G}{c^3}\right)^{1/2} = 1.6 \times 10^{-35}$ metres,
The Planck mass: $\left(\frac{\hbar c}{G}\right)^{1/2} = 2.1 \times 10^{-8}$ kilograms,
The Planck time: $\left(\frac{\hbar G}{c^5}\right)^{1/2} = 5.4 \times 10^{-44}$ seconds,
The Planck energy: $\left(\frac{\hbar c^5}{G}\right)^{1/2} = 1.2 \times 10^{19}$ GeV.

The 'holy grail' of theoretical physics is to explain the complexity of our physical world in its entirety by combining quantum mechanics, gravity and relativity. One can immediately see from this table that this is potentially problematic. The natural length scale of physics, the Planck length, is tiny in comparison to the size of the observable Universe (which is around 50 billion light years). The natural mass scale is much smaller than the total mass in the observable Universe (and also many orders of magnitude greater than the masses of elementary particles). The Planck time is much smaller than the age of the Universe (around 14 billion years) and the natural energy scale is immense (fifteen orders of magnitude higher than the energies achievable in the Large Hadron Collider at CERN). The discordance between these numbers and what we know about our Universe lies at the heart of some 'big' cosmological questions:

- Why is the Universe so big?
- Why is the Universe so old?
- Why is the entropy in our observable Universe so big?
- Why is the entropy in our observable Universe so small?
- Why is the Universe so uniform and isotropic?
- Where did the structure – stars, galaxies, clusters of galaxies...., come from?
- What happened at the Big Bang?
- Was there anything before the Big Bang?
- What is the fate of our Universe?

These are some of the problems that the Planck satellite has been designed to solve. The first two problems are closely related to Planck's natural units. Somehow, the immense scale and age of our Universe must emerge from physics at the Planck scale. Entropy measures information content. The 'natural' value from fundamental physics is one quantum bit of information. In fact, our observable Universe contains 10^{80} quantum bits of information. Why this enormous discrepancy? The third and fourth questions on the list are, at first sight, contradictory. However, in contrast to a quantum physicist, a specialist in gravity theory might imagine putting all of the matter in our observable Universe into a gigantic black hole. This would have 10^{120} quantum bits of information, 40 orders of magnitude higher than what we see. To a gravity theorist, the entropy of our Universe seems unnaturally small. This is because the Universe is very nearly homogeneous and isotropic. But why was it created in such a special state, when it could have been much more complicated? To add to the mystery, the Universe is not *perfectly* uniform. It contained small fluctuations that grew to make the structure – the stars, planets and galaxies – that we see today. Where did these irregularities come from? Why did the 'Creator' go to all the bother of making a big, uniform and isotropic Universe and then mar his creation by adding fluctuations of a thousandth of a percent?

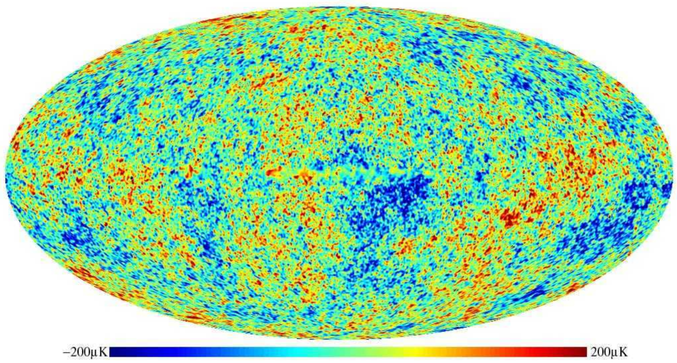
To explain these questions, we need to understand the physics of the Big Bang. The Big Bang is sometimes described as a 'singularity' in space-time. This can't be true. There was something there at the Big Bang – some structure or object – that we, as a human species, need to probe and understand. This is a formidable challenge, but one that we should rise to.



At present, our ideas are very sketchy. The 'best bet' at explaining some of the 'big' cosmological problems raised above, is the theory of inflation. According to the inflationary model, at some time shortly after the Big Bang the Universe developed a negative pressure that caused the Universe to expand faster than the speed of light. A small 'patch' of the Universe, maybe no bigger than a Planck length, (see the sketch to the right) can be expanded exponentially in scale to end up much bigger than our observable Universe (perhaps by several hundred orders of magnitude or more). The huge size, age and entropy of our Universe is explained by this exponential expansion. Furthermore, irregularities in the intial geometry can be smoothed out during inflation explaining the large-scale uniformity and isotropy of the Universe. (Though as the distinguished mathematical physicist, Roger Penrose, points out this 'smoothing' aspect is less well understood.) But in my view, the most spectacular consequence of inflation is that it provides a mechanism for expanding quantum irregularities from the microscopic scale to produce classical fluctuations on cosmological scales. According to inflation, the tiny fluctuations that grew to make all of the strucure in our Universe, from planets to superclusters of galaxies, have a quantum origin.

Inflation, as a concept, is beautiful and incredibly powerful. The principal drawback is that we have not yet found a compelling mechanism for inflation from fundamental physics. The fundamental physics at the time of inflation (of order 10^{-35} seconds or less after the Big Bang) is so poorly understood that it is not possible to produce a rigorous theory of inflation. Instead, cosmologists develop so called 'phenomenological' models – if the physics looks something like this, then the Universe inflates like this. Thankfully, many of the observable consequences of inflation are not very sensitive to the speculations on the physics. Phenomenological models of inflation have been very useful and we have learned a lot about different classes of inflationary models. But the details of inflation certainly are sensitive to the physics, and the details matter. The corollary is that sensitive measurements of things like the amplitude and scale-dependence of cosmological fluctuations or the detection of gravitational waves from inflation can provide hard facts about the fundamental physics operating at these early times. Our ambitious goal for the Planck satellite is to establish real facts, facts that will transform inflation into a proper theory soundly based on fundamental physics.

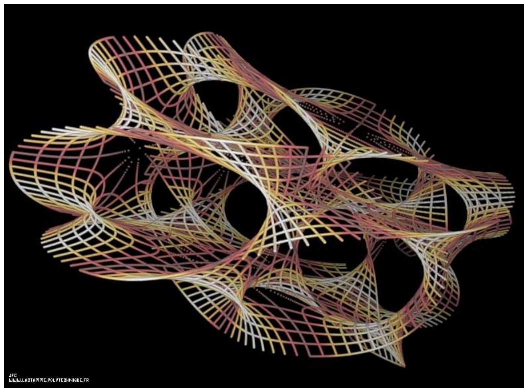
How can this be done? The cosmic microwave background (CMB) radiation was discovered in 1965 by Arno Penzias and Robert Wilson. The CMB is the remnant radiation from the hot Big Bang, that has cooled as the Universe has expanded and now has a temperature of 2.725 degrees above absolute zero. As soon as the CMB was discovered, experimentalists began a search for temperature variations in the CMB (often called 'CMB anisotropies'). These temperature anisotropies had been predicted by theorists as a consequence of small irregularities – the 'seeds' of present day structure – generated in the early Universe. The predicted anisotropies were finally discovered in 1992 by Nasa's COBE satellite. Since then, a large number of experiments have been done to measure the anisotropies with ever finer resolution and sensitivity.



Nasa's WMAP (Wilkinson Microwave Anisotropy Probe, named after David Wilkinson a pioneer in CMB experimental research) satellite is probably the best known and has, without doubt, had the highest impact for cosmology. (See the picture to the left, that shows an all sky map of the CMB temperature variations measured by WMAP. The colour scale of this picture ranges from -200μK to $+200\mu$K.) From WMAP, and other cosmological observations such as distant supernovae and galaxy surveys (and also other CMB experiments), we have learned a lot about the composition of the Universe (most of the matter in the Universe is invisible; about 74% is in the form of mysterious 'dark energy', 22% is in some type of dark matter that clusters under the action of gravity, and only 4% is in ordinary 'baryonic' material that makes up you and me). In addition we have established that simple models of inflation are consistent with observations. But the observations are not yet precise enough to probe the physics of inflation in any detail.

This is where Planck comes in. By flying more sensitive detectors, with higher angular resolution we hope to make more accurate maps of the temperature anisotropies and also to measure their polarization. The extra sensitivity of Planck comes at a price. Planck is flying bolometer detectors that measure the heat induced by CMB photons. These are much more sensitive than the radio frequency detectors used in WMAP, but bolometers can only work if they are cooled to very low temperatures – 0.1 degrees above absolute zero – otherwise they are swamped by thermal noise. Planck is therefore flying a complicated refrigeration system – actually three refrigerators, one to cool from 50 K to 20 K, a second to go from 20 K to

4 K and a third to cool the detectors to 0.1 K. It's compicated and difficult to do. If it all works, Planck deserves to be called the 'coolest' spacecraft that has ever been flown.



What would be the significance of a better understanding of inflation? At present, string theory offers the most promising prospect for a fundamental 'theory of everything'. At first sight, string theory looks far from promising because, for mathematical consistency, it requires 9 or 10 spatial dimensions compared to the three spatial dimensions that we are all familiar with. The extra dimensions must be hidden in some way – compactified into complex topological configurations as shown on the right. There are many possible geometrical arrangements of these hidden dimensions. In addition, string theory contains 'fluxes' – analogues of magnetic fields, that can be wrapped in many different ways within the hidden dimensions. This myriad of possibilities might seem problematic if we are trying to find a unique physical theory. But the existence of large numbers of metastable configurations in string theory (termed the 'landscape' by the Stanford physicist Lenny Susskind) opens up another intruiging line of reasoning. The extra-dimensions provide a kind of DNA – arrange them one way, and the low energy Universe will look like this, arrange them another way and the low energy Universe will be different. This offers the possibility of explaining the complexity of our low energy Universe in terms of simple physical principles – quantum mechanics, relativity and gravity. The extra dimensions of string theory, far from being a problem, become an asset – they provide an explanation for the complexity of the physical world. All configurations exist physically and some of these can produce inflation. We live in the comfortable little corner of a 'multiverse' that has inflated to produce a big and old Universe (necessary for stars to form) and that has just the right low energy characteristics to allow life to form. This idea is still just a sketch, but in the last few years there has been remarkable progress on understanding how inflation might arise in string theory. My bet is that strong observational constraints on inflation will ultimately shed light on the geometry of hidden dimensions.

Why should we care? In these difficult economic times, why should we spend money to study the early Universe? (In the UK, the Research Councils are putting increasing, and in my view overly aggressive, emphasis on research that has direct 'economic impact'). We humans are a bit like goldfish, circling round in our little goldfish bowl. We breed, eat and pollute our environment. Some of us lead happy lives, some of us less so. It would be a tragedy if none of us ever attempted to peer outside our bowl unless there was a direct economic benefit to our fellow fish to do so. We live in a fascinating Universe, but we know very little about it, where it came from or why it exists. It is our moral duty, as a species, to spend some small fraction of our wealth to peer outside our bowl. We don't know what we will find. We know so little about the early Universe that there is tremendous potential for discoveries of completely unanticipated phenomena – phenomena that might revolutionise our understanding of physics. The sweet taste of discovery would more than compensate for the last 16 years of hard work. That is the real reason that I am so enthusiastic about Planck.