Four readings on cosmic microwave background radiation and dark matter:

1. The first five pages of a "The Cosmic Microwave Background: The history of its experimental investigation and its significance for cosmology" by Dr. Ruth Durrer in Jun 2015. The first few pages of references are provided. The complete document can be found at https://arxiv.org/pdf/1506.01907.

2. Announcement of 2006 Nobel Prize in Physics for the first measurements of the ripples in the CMB, awarded to Drs. John Mathur and George Smoot.

3. A Nature magazine op-ed written by Dr. Wayne Hu, University of Chicago, when the first Boomerang experiment measurements came out in 2000. If you want to explore more, check out his website (a bit old) at http://background.uchicago.edu/~whu/intermediate/intermediate.html

4. Another Nature Article written on the first results from the Planck Satellite mission, where the CMB has been measured to extraordinary precision (see https://www.nature.com/news/planck-snaps-infant-universe-1.12671)

REVIEW ARTICLE

The Cosmic Microwave Background: The history of its experimental investigation and its significance for cosmology

Ruth Durrer

Université de Genève, Département de Physique Théorique, 1211 Genève, Switzerland

E-mail: `ruth.durrer@unige.ch`

Abstract. This review describes the discovery of the cosmic microwave background radiation in 1965 and its impact on cosmology in the 50 years that followed. This discovery has established the Big Bang model of the Universe and the analysis of its fluctuations has confirmed the idea of inflation and led to the present era of precision cosmology. I discuss the evolution of cosmological perturbations and their imprint on the CMB as temperature fluctuations and polarization. I also show how a phase of inflationary expansion generates fluctuations in the spacetime curvature and primordial gravitational waves. In addition I present findings of CMB experiments, from the earliest to the most recent ones. The accuracy of these experiments has helped us to estimate the parameters of the cosmological model with unprecedented precision so that in the future we shall be able to test not only cosmological models but General Relativity itself on cosmological scales.

Submitted to: *Class. Quantum Grav.*

1. Historical Introduction

The discovery of the Cosmic Microwave Background (CMB) by Penzias and Wilson, reported in Refs. [1, 2], has been a 'game changer' in cosmology. Before this discovery, despite the observation of the expansion of the Universe, see [3], the steady state model of cosmology still had a respectable group of followers. However, if the 'excess antenna temperature' measured by Penzias and Wilson isotropically in all directions [1] was correctly interpreted by the preceding paper in the same issue of the Astrophysical Journal [2], the Universe was clearly adiabatically expanding and cooling as postulated by Lemaître [4]‡ using a solution of Einstein's field equation found previously by Friedman [6]. In 1978, Penzias and Wilson were rewarded with the Physics Nobel Prize for their discovery.

In the Big Bang model, the Universe starts out from a hot, dense initial state and subsequently expands and cools. It had been noted already some time ago by Gamow and collaborators [7–9], that the Big Bang model predicts a background of cosmic radiation, a relic from the hot early phase. Its temperature had been estimated to be of the order of a few degrees Kelvin (in the above papers values from 5K to 50K can be found). The discovery by Penzias and Wilson indicated a CMB temperature of 3K.

After the discovery of the CMB, the Big Bang model of cosmology was established. Together with the observation and explanation of the cosmic abundance of light elements, especially ^{4}He [10, 11], it strongly indicates that the Universe was much hotter and denser in the past. The Hubble expansion law, see [3] for details, predicts that also the wavelength of photons expands so that they are redshifted. The redshift z denotes the relative difference of the wavelength at the observer, λ_o, to the wavelength of the emitter, λ_e, i.e., $z = (\lambda_o - \lambda_e)/\lambda_e$. The energy density of the Universe was actually dominated by the contribution from CMB photons at $z \gtrsim 4000$, i.e. $T \gtrsim 10^4 K \simeq 0.93$eV.

The history of Arno Penzias and Robert Wilson is quite amusing (see acount by A. Penzias and by R. Wilson in [12]). These two young radio astronomers employed by Bell Laboratories at Holmdel, New Jersey, were observing the sky with a radio telescope which had been built to investigate radio transmission from communication satellites. They had the most advanced radio receiver of the time, a so called horn antenna, see Fig 1, with a 'cold load' cooled with liquid Helium to suppress interference with the detector heat. But despite this they found a persistent, isotropic receiver noise which was significantly larger than what they had expected. Also after checking their equipment thoroughly and removing a "white dielectric" (pigeon droppings), this mysterious background noise which corresponded to an antenna temperature of about 3.5K at 7.35 cm would not disappear.

‡ This original reference is in French. One can also read [5], the English translation by Eddington, which, however, omits the important estimate of the Hubble constant and the discussion of the age problem.

After a discussion at the phone, a friend, (the radio astronomer B.F. Burke from MIT) sent Penzias a preprint by Jim Peebles from Princeton University predicting a cosmic background radiation. Penzias then called Robert Dicke in Princeton and told him that he had measured 'an excess antenna temperature' of about 3K. Dicke, together with Peter Roll and David Wilkinson visited Bell Labs to see the data and the details of the experiment. When Dicke was convinced they had a result, Penzias suggested to him that they write a paper together, but Dicke declined (A.A. Penzias in [12]).

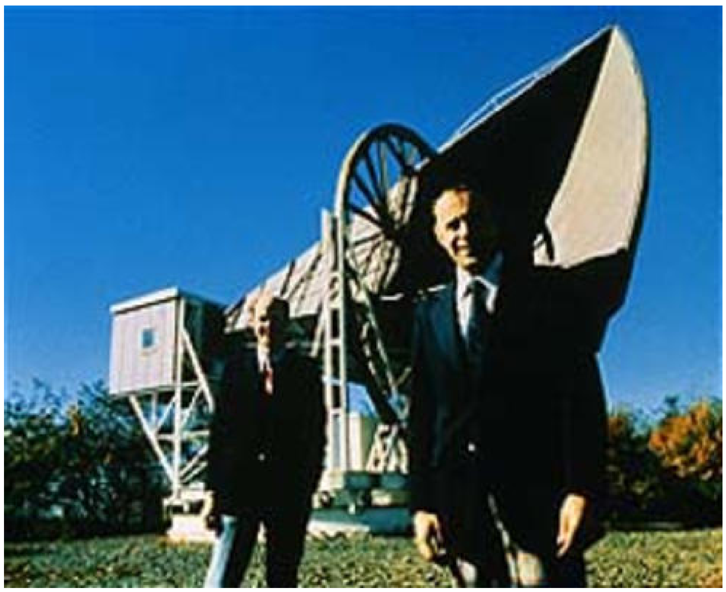


Figure 1. Arno Penzias and Robert Wilson in front of their radio telescope. the most sensitive and modern radio telescope in 1965.

They finally decided to publish two separate papers back to back. The first by R.H. Dicke, P.J.E. Peebles, P.G. Roll and D.T. Wilkinson [2] with the title "Cosmic Black-Body Radiation" which interprets the findings as the cosmic background radiation, the CMB, a signature of the hot Big Bang, and the second by A.A. Penzias and R.W. Wilson [1] with the modest title "A Measurement Of Excess Antenna Temperature At 4080 Mc/s". Here 'Mc/s' are Mega cycles per second hence MHz. This paper reported a "bare-boned account of our measurement – together with a list of possible sources of interference which had been eliminated" (Arno Penzias in [12]). For this discovery they were awarded the Nobel Prize in 1978.

What was the reason for this delay of 13 years? It was certainly not that the cosmological community had not appreciated the importance of their discovery. On the contrary, the Princeton group under R. Dicke had a running experiment at the same time which soon confirmed the discovery by Penzias and Wilson [13] at 3.2cm and several experiments showing also the isotropy of the radiation [14] followed soon. Nevertheless, already Gamow [7] had predicted that the CMB should be a *thermal*, i.e., a blackbody radiation and this was confirmed once measurements not only in the Rayleigh Jeans part but also in the Wien part of the spectrum, at frequencies $\nu \gtrsim 150$GHz had been made. It took until the 70s to convince the community that the spectrum was a blackbody and therefore a relict from the Big Bang (see contributions by Robert W. Wilson and R. Bruce Partridge in [12]).

Already before the discovery by Penzias and Wilson, excited rotation states of CN (cyanogen) molecules in interstellar space had been observed, first by McKellar (1940), and then by Adams (1941) [15, 16], which corresponded to a sky temperature of about 3K. But they had not been interpreted as due to the CMB. Now we know that they are excited by CMB radiation and in several publications they have later been used to measure the CMB temperature, see e.g. [17].

As mentioned above, immediately after the discovery by Penzias and Wilson, cosmologists started to look for anisotropies in the CMB radiation. This was motivated by the assumption that structure in the Universe, galaxies, clusters, voids and filaments formed from small initial fluctuations by gravitational instability. If this idea is correct, then these initial fluctuations must also be present in the CMB. For a long time the searches for anisotropies just revealed a dipole which was first announced in 1969 [18] (see figure 2 for a representation of modern dipole data). Only upper limits were reported on smaller angular scales. In the late 80s, when the present author was a graduate student in cosmology, we knew that $(\Delta T/T) \lesssim 10^{-4}$ and therefore a purely baryonic Universe could not form the observed structure after decoupling from the CMB radiation. Since baryons can only start clustering once they decouple from the photons and becomes pressureless, there is simply not enough time for so small initial fluctuations to grow to form the observed structures. Dark matter, i.e. particles which do not interact with CMB photons so that their fluctuations can start growing earlier, is needed. Since pressureless matter fluctuations only can start growing once they dominate the energy density of the Universe, a sufficient amount of dark matter is needed. Long before, Fritz Zwicky had postulated the existence of dark matter in galaxy clusters as the only possibility to explain their large virial velocities [19]. Later, in the 1970s, Rubin et al. [20, 21] introduced dark (non-luminous) matter to explain the flat rotation curves of stars and satellites around galaxies.

In November 1989 the NASA satellite COBE was launched. It not only measured the CMB spectrum with amazing precision but it also found fluctuations in the CMB on the level of 10^{-5}. After this, the dam was broken and many experiments were performed on Balloons (e.g Boomerang), from earth, especially from the south pole (e.g. ACBAR) but also from the Atacama desert (e.g. ACT), and from space, the WMAP and Planck satellites. They revealed not only the temperature anisotropies with high precision but also the slight polarization which is generated on the last scattering surface by the direction dependence of Thomson scattering.

In the remainder of this review, I shall discuss the results from these experiments and their relevance for cosmology. I think it is fair to say that the CMB is the most precious dataset for cosmology. This is not only due to the very precise experiments, but also to the fact that the data can be understood by simple linear cosmological perturbation theory with some non-linear terms added which are well under control.

In the next section I report the discovery of the CMB dipole and its significance. In Section 3 the findings from the COBE satellite are discussed which led to the second Nobel prize given for the CMB. To appreciate the importance of these findings I give a brief introduction to cosmological perturbation theory and to the theory of inflation. I shall not derive the results but only describe them and explain their physical origin. Mathematical derivations can be found in the original literature or in my book on the subject [22]. Section 4 is devoted to the more recent experiments, mainly the NASA satellite WMAP and the ESA satellite Planck. I also present a brief introduction to the cosmic history and to cosmological parameters. This is needed to understand why these measurements allow us to determine the cosmological parameters, i.e. the handful of 'arbitrary' numbers which govern the evolution of the Universe, with unprecedented precision. CMB polarization and its significance are discussed in Section 5 and in Section 6 an outlook on the future of CMB physics is attempted. In Section 7 I conclude.

At this point I also want to make a disclaimer. There are so many CMB experiments, all of them contributing their essential part to the puzzle, that there is simply not enough space to describe all of them. Also, I think this would not lead to a very entertaining article. Therefore my citations of experiments, apart from the really crucial ones, is somewhat accidental and I apologize if your favorite experiment is not mentioned.

Notation: In this article the speed of light, Planck's constant and Boltzmann's constant are set to unity, $c = \hbar = k_B = 1$. This means that time and length have the same units which is the inverse of the unit of mass, energy or temperature. The Planck mass is defined by $m_P^2 = 1/\sqrt{G} = \sqrt{\hbar c/G} \simeq 1.22 \times 10^{19}$GeV.

2. The CMB dipole

In 1969 Conklin [18] and soon after that Henry (1971) [23], reported the first finding of a dipole anisotropy in the CMB. Later, Corey and Wilkinson (1976) [24] performed a more precise and detailed experiment with better error control which also detected the dipole. The latest measurements of the dipole have been reported by the satellite experiments COBE [25] and WMAP [26]. The latest value is

$$\left(\frac{\Delta T}{T}\right)_{\rm dipole} = (1.2312 \pm 0.0029) \times 10^{-3} \,. \tag{2.1}$$

Here T is the photon temperature and ΔT is its fluctuation amplitude on a scale of 180^o. We interpret this value as due to our proper motion with respect to the surface of last scattering. Indeed, an observer moving with velocity $\mathbf{v}$ relative to a source in direction $\mathbf{n}$ emitting a photon with proper momentum $\mathbf{p} = -\epsilon\mathbf{n}$ sees this photon red-

Cut off here. What follows are the first of the references.

fluctuations actually emerged from quantum fluctuations during a phase of very rapid expansion, inflation. In other words the fluctuations in the CMB, the largest structures in our Universe, come from quantum fluctuations which have expanded and then have frozen in as classical fluctuations of the spacetime metric.

The Universe acts as a giant magnifying glass. It enlarges tiny quantum fluctuations from a very high energy phase into the largest observable structures.

While this text was finalised, the new 2015 Planck data came out, see especially [144]. However, since these data are still preliminary, and since they mainly differ from the 2013 release by somewhat smaller error bars, I have not included them in this review.

Acknowledgments

I thank Martin Kunz and Malcolm MacCallum for useful discussions and Francesco Montanari for help with a figure. This work is supported by the Swiss National Science Foundation.

References

[1] Penzias A A and Wilson R W 1965 *Astrophys.J.* **142** 419–421

[2] Dicke R, Peebles P, Roll P and Wilkinson D 1965 *Astrophys.J.* **142** 414–419

[3] MacCallum M 2015 *Class. Quant. Gravity* **32** 124002

[4] Lemaitre G 1927 *Annales Soc.Sci.Brux.Ser.I Sci.Math.Astron.Phys.* **A47** 49–59

[5] Lemaitre G 1931 *Mon.Not.Roy.Astron.Soc.* **91** 483–490

[6] Friedman A 1922 *Z.Phys.* **10** 377–386

[7] Gamow G 1948 *Nature* **162** 680–682

[8] Alpher R and Hermann R 1948 *Nature* **162** 774–775

[9] Alpher R and Hermann R 1948 *Phys. Rev.* **75** 1089–1095

[10] Gamow G 1946 *Phys.Rev.* **70** 572–573

[11] Alpher R, Bethe H and Gamow G 1948 *Phys.Rev.* **73** 803–804

[12] Peebles P, Page L and Partridge R 2009 *Finding the Big Bang* (Cambridge University Press)

[13] Roll P G and Wilkinson D T 1967 *Physical Review Letters* **16** 405–409

[14] Partridge R B and Wilkinson D T 1967 *Physical Review Letters* **18** 557–559

[15] Adams W S 1941 *Pub. Ast. Soc. Pac.* **53** 209

[16] McKellar A 1940 *Pub. Ast. Soc. Pac.* **52** 187

[17] Roth K C, Meyer D M and Hawkins I 1993 *Astrophys. J. Lett.* **413** L67–L71

[18] Conklin E 1969 *Nature* **222** 971–979

[19] Zwicky F 1937 *Astrophys. J.* **86** 217

The Nobel Prize in Physics 2006

*The Nobel Prize in Physics for 2006 is awarded to **John C. Mather** and **George F. Smoot** for their discovery of the basic form of the cosmic microwave background radiation as well as its small variations in different directions. The very detailed observations that the Laureates have carried out from the COBE satellite have played a major role in the development of modern cosmology into a precise science.*

From unexpected noise to precision science

The cosmic microwave background radiation was registered for the first time in 1964. Arno Penzias and Robert Wilson (who were awarded the 1978 Nobel Prize in Physics for this discovery) first mistook the radiation for irrelevant noise in their radio receivers (in fact, the cosmic microwave background is part of that "blizzard"-like noise we all receive on our television sets whenever normal transmission is interrupted). However, a theory predicting microwave background had already been developed in the 1940s (by Alpher, Gamow and Herman) and the discovery therefore made an important contribution to the ongoing discussion about the origins of the Universe.

Two competing cosmological theories in particular were on the agenda at this time: either the Universe had been created in an initial Big Bang and then continued to expand, or it had always existed in a Steady State. The Big Bang-scenario actually predicts the existence of microwave background radiation, so the discovery by Penzias and Wilson naturally gave additional credibility to that theory.

The blackbody origin of the Universe

According to the Big Bang-scenario, our Universe developed from a state of intense heat. There are as yet no well-established theories about this primordial condition of the Universe, but immediately afterwards it appears to have been filled with an incredibly intensive radiation. Radiation emitted by such a glowing "body" is distributed between different wavelengths (light colours) in a specific manner, where the shape of the spectrum depends only on the temperature. Without knowing anything about the radiation apart from its temperature it is possible to predict exactly what the spectrum is going to look like. The somewhat contradictory term used to describe this kind of radiation is blackbody radiation. Spectra like these can also be created in a lab, and the German Max Planck – who received the Nobel Prize in Physics for 1918 – was the first to describe their particular shape. Our own sun is in fact a "blackbody", even though its spectrum is less perfect than that of the cosmic microwave background radiation.

According to the Big Bang scenario, the background radiation gradually cools down as the Universe expands. The original black body shape of the spectrum has however been conserved. At the time when the radiation was emitted, the chaotic mass which was then our Universe was still very hot, around 3000 degrees. The background radiation we measure today has however cooled down significantly, now corresponding to radiation emitted by a body with a temperature of only 2.7 degrees above absolute zero. This means the wavelengths of the radiation have increased (a rule of thumb for blackbody radiation is that the lower the temperature, the longer the wavelength). That is why the background radiation is now found in the microwave area (visible light has much shorter wavelengths).

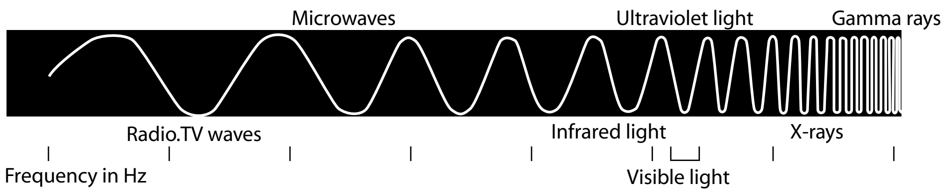


Figure 1

Leaving earth

The first measurements of the cosmic microwave background were made from high mountain summits, rocket probes and balloons. The Earth's atmosphere absorbs much of the radiation, hence the measurements need to be carried out at great altitude. But even at these high altitudes only a small part of the spectrum belonging to the background radiation can actually be measured. A large proportion of the wavelengths included in the spectrum are so efficiently absorbed by air that it is necessary to conduct the measurements outside the Earth's atmosphere. Therefore the first, earthbound measurements (including those made by Penzias and Wilson) never managed to show the blackbody quality of the radiation. This made it difficult to know if the background radiation was really of the type predicted by the Big Bang scenario. In addition, earthbound instruments cannot easily investigate all directions of the Universe, which made it difficult to prove that the radiation was indeed a true background, similar in all directions. Measuring from a satellite solves both these problems – the instruments can be lifted above the atmosphere and measurements can easily be made in all directions.

In 1974 the US Space Administration, NASA, issued an invitation to astronomers and cosmologists to submit proposals for new space-based experiments. This led to the initiation of the COBE-project, the COsmic Background Explorer. **John Mather** was the true driving force behind this gigantic collaboration in which over 1000 individuals (scientists, engineers and others) were involved.

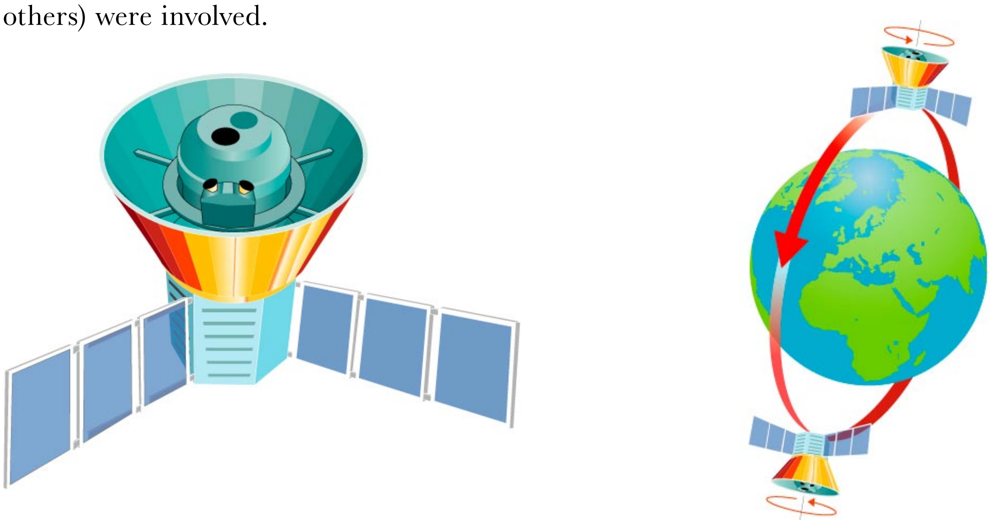


Figure 2. The COBE satellite enabled measurement of the cosmic microwave background in all directions.

John Mather was also in charge of one of the instruments on board, which was used to investigate the blackbody spectrum of the background radiation. **George Smoot** was in charge of the other determinative instrument, which was to look for small variations of the background radiation in different directions.

NASA's original idea was for COBE to be launched into space by one of the space shuttles. However, after the tragic accident in 1986 when the shuttle Challenger exploded with its crew on board, shuttle operations were discontinued for several years. This meant that the future of COBE was in jeopardy. Skilful negotiations finally enabled John Mather and his collaborators to obtain a rocket of their own for COBE, and the satellite was finally launched on November 18, 1989.

The first results arrived after only nine minutes of observations: COBE had registered a perfect blackbody spectrum! When the curve was later shown at a conference in January 1990, it was greeted with standing ovations. The COBE-curve turned out to be one of the most perfect blackbody spectra ever to be measured. (See Fig. 3)

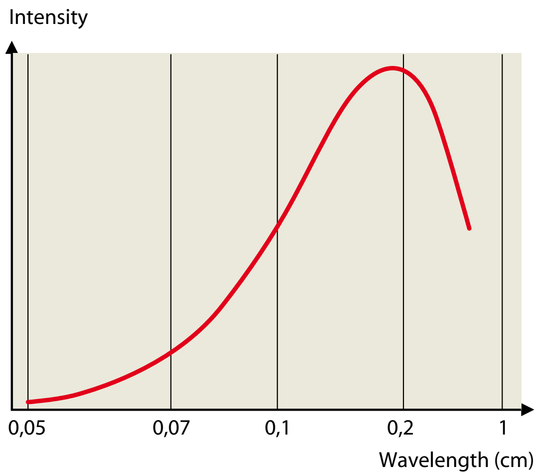


Figure 3. The wavelength distribution of the cosmic microwave background radiation, measured by COBE, corresponds to a perfect blackbody spectrum. The shape of such a spectrum depends only on the temperature of the emitting body. The wavelengths of the microwave background are found in the millimetre range, and this particular spectrum corresponds to a temperature of 2.7 degrees above absolute zero.

The birth of galaxies

But this was only a part of COBE's results. The experiment for which George Smoot was responsible was designed to look for small variations of the microwave background in different directions. Minuscule variations in the temperature of the microwave background in different parts of the universe could provide new clues about how galaxies and stars once appeared; why matter in this way had been concentrated to specific localities in the Universe rather than spreading out as a uniform sludge. Tiny variations in temperature could show where matter had started aggregating. Once this process had started, gravitation would take care of the rest: Matter attracts matter, which leads to stars and galaxies forming. Without a starting mechanism however, neither the Milky Way nor the Sun or the Earth would exist.

The theory that tries to explain how the aggregation of matter is initiated deals with quantum mechanical fluctuations in the Universe during the very first moments of expansion. The same type of quantum mechanical fluctuations result in the constant creation and annihilation of particles of matter and antimatter in what we normally think of as empty space. This however is one of those aspects of physics that cannot readily be understood without using mathematics. Let us therefore simply assert that the variations in temperature measured in today's Universe are thought to be the result of such quantum fluctuations and that according to the Big Bang theory it is also thanks to these that stars, planets, and finally life could develop. Without them, the matter of which we consist would be found instead in a totally different form, spread out uniformly over the Universe.

Visible and dark matter

When the COBE-experiments were planned, it was first thought that the variation in temperature of the microwave background necessary to explain the appearance of galaxies would be about one thousandth of a degree Centigrade. That is small indeed, but things were to prove even worse: While COBE was still being constructed, other researchers reported that the influence of dark matter (a large proportion of the matter in the universe that we cannot see) meant that the variations in temperature to be sought for would rather be in the range of a hundred-thousandth of a degree. The dark matter in itself is in fact an important agent for the aggregation of matter, which means that the variations in temperature necessary to explain the initiation of this process are even smaller than previously believed.

To find such extremely small temperature variations was a great challenge. Even though the instrument was redesigned, the results from COBE became much more uncertain and difficult to interpret than expected. The variations were so small that they were difficult to distinguish from irrelevant noise – so how could one know that they were indeed real? When the results were finally published, in 1992, it turned out however that they could be correlated to ground-based measurements, albeit even more uncertain in themselves than the COBE-measurements. The directions in space in which COBE had registered temperature variations turned out to be exactly the same as those where variations seemed to have been detected from Earth and using balloons.

On April 29, 1992 the English physicist Stephen Hawking said in an interview in The Times that the COBE results were "the greatest discovery of the century, if not of all times".

Speculation becomes precision

On the COBE-satellite the cosmic background radiation was collected in six big funnels, or horns, which constantly swept space in all directions. By using several funnels at once, it was possible to measure in several directions and wavelengths simultaneously, thereby correcting for any temporary disturbances. Each funnel collected radiation from a section of seven degrees of the sky. The temperature of the radiation within this section was then compared to the temperature in the other funnel of a pair, and with the average temperature for the whole sky. In this manner a map of the temperature variations in Space was created (See fig. 4).

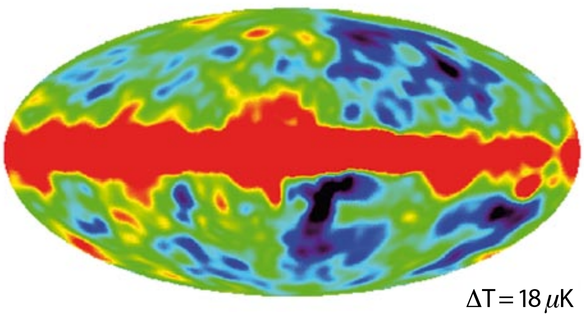


Figure 4. A sky-map of the temperature variations-measured by COBE. Red corresponds to higher temperature and blue to lower. The variations are minuscule – in the range of a hundred-thousandth of a degree.

Funnels with smaller angles (which offer better resolution) have been used in later measurements like those conducted by the WMAP, Wilkinson Microwave Anisotropy Probe (named after David Wilkinson, who passed away in 2002 and who for a very long time was an important driving force behind the measurements of background radiation and an inspiration also to the COBE-team).

By comparing the variation in the temperature measured within different angles it is also possible to calculate the relationship between the density of visible matter, dark matter, and (in combination with other measurements) the dark energy of the Universe. The word "dark" in this context means that we cannot see and measure this type of matter or energy. That is why measurements of the variations in temperature become particularly important – they offer an opportunity to indirectly determine the density of this type of matter and energy. Because of this, the COBE-project can also be regarded as the starting point for cosmology as a precision science: For the first time cosmological calculations (like those concerning the relationship between dark matter and ordinary, visible matter) could be compared with data from real measurements. This makes modern cosmology a true science (rather than a kind of philosophical speculation, like earlier cosmology).

In this way, the measurements of COBE and WMAP have also provided the basis for calculations concerning the fundamental shape of the Universe. The conclusion seems to be that the Universe is Euclidian – that is, our everyday geometry which tells us that two parallel lines will never cross each other seems to hold even on the cosmological scale. This is an important result since other geometries can be imagined, although they defy our everyday experience.

An interesting idea – that the Universe inflated very rapidly in its early stages – could explain this finding as well as several others made using the new precision measurements.

The COBE-experiment has also initiated several new areas of investigation within both cosmology and particle physics.

New cosmological measurements aim at an even better understanding of what happened the moments before the background radiation was emitted. Studying the microwave background in even more detail is expected to provide new answers.

In particle physics the goal is to understand what constitutes dark matter. This is one of the tasks of the new LHC (Large Hadron Collider) accelerator, which will soon be in use at CERN, the European centre for nuclear research.

LINKS AND FURTHER READING

The Academy's website, www.kva.se, and http://nobelprize.org have more information on this year's Prizes, including a web-TV broadcast of the press conference and advanced information mainly intended for the research community.

Scientific articles:

J. Mather et al. 1990 Astrophys. J (Letter) 354, 37
G. Smoot et al. 1992 Astrophys. J (Letter) 396,1
R.W. Wilson, 1978 The Cosmic Microwave Background Radiation, Les Prix Nobel, p. 113

Books:

Mather, J.C. and Boslough, J. 1996: the very first light (BasicBooks 1996)
Smoot, G. and Davidson, K. 1993: Wrinkles in Time (Little, Brown and Company, London 1993)
Weinberg, S. 1993: The First Three Minutes, 2nd edition (BasicBooks 1988&1993)

Link:

Presentation of COBE project at the NASA web site:
http://lambda.gsfc.nasa.gov/product/cobe/

THE LAUREATES

John C. Mather

Astrophysics Science Division
NASA Goddard Space Flight Center
Code 665, Observational Cosmology
Greenbelt, MD 20771,
USA

http://universe.gsfc.nasa.gov/staff/CVs/John.Mather/

US citizen. Born 1946 (60). PhD in physics in 1974 from the University of California at Berkeley, CA, USA. Senior Astrophysicist at NASA's Goddard Space Flight Center, Greenbelt, MD, USA.

George F. Smoot

Lawrence Berkeley National Laboratory,
1 Cyclotron Road,
Berkeley, CA 94720
USA

http://aether.lbl.gov/

US citizen. Born 1945 (61) in Yukon, FL, USA. PhD in Physics in 1970 from MIT, Cambridge, MA, USA. Professor of Physics at the University of California, Berkeley, CA, USA.

Ringing in the new cosmology

Wayne Hu

Balloon experiments over Antarctica have produced a long-awaited temperature map of the microwave sky. The map reveals sound waves that can be used to probe the early Universe.

According to the theory of the Big Bang, the Universe started hot and dense and then expanded and cooled. In the hot, dense conditions of the early Universe, photons were tightly glued to matter. When the Universe was about 300,000 years old the temperature dropped below 3,000 K, allowing atomic hydrogen to form and releasing the photons. These photons, which travelled freely through the Universe as it expanded and cooled, make up the cosmic microwave background (CMB) we see today. Ten to twenty billion years after the Big Bang, the CMB is a cold sea of photons with an average temperature of 2.7 K (−270 °C). These photons are all around us, causing about 1% of the noise on our television sets.

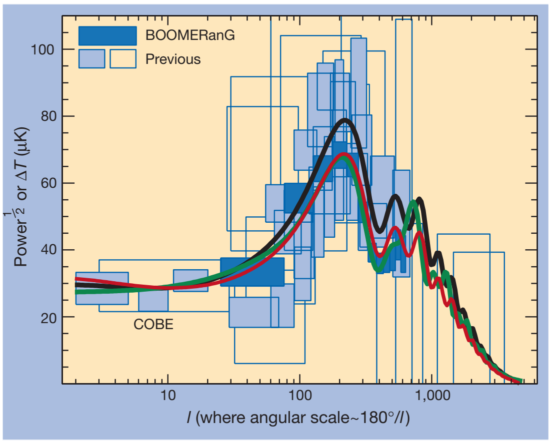
When it was discovered in the 1960s, the CMB was found to be remarkably uniform across the sky. It was not until 1992 that the Cosmic Background Explorer (COBE) satellite[1] discovered temperature variations (or ripples) at the level of 1 part in 100,000. Temperature maps of the CMB form a snapshot image of the Universe when it was extremely young. So these ripples reflect tiny density fluctuations in the primordial soup of particles. These same density fluctuations are thought to grow by gravitational attraction into the familiar structures we see today (stars, galaxies and clusters of galaxies). This is the gravitational instability model of structure formation.

COBE told us what the large-scale fluctuations in the background look like, but cosmologists today are more interested in the small-scale fluctuations. Astronomers divide up the sky into angular degrees, so that 90° is the distance from the horizon to a point directly overhead. COBE measured temperature ripples from the 10° to 90° scale. This scale is so large that there has not been enough time for structures to evolve. At the degree scale, on the other hand, the process of structure formation imprints information in the ripples about conditions in the early Universe.

Since the COBE discovery, many ground and balloon-based experiments have shown that the ripples peak at the degree scale[2,3]. On page 955 of this issue, de Bernadis *et al.*[4] report the first high-resolution maps of the CMB over a significant part of the sky. The results are part of the BOOMERanG experiment, in which a microwave telescope was carried at high altitudes during a long balloon flight over Antarctica. The authors take a power spectrum from their detailed maps of the CMB, much as you would if you wanted to analyse background noise. They find that the peak in the power spectrum of the CMB has exactly the right form to be the ringing or acoustic phenomena long awaited by cosmologists (Box 1). Such acoustic phenomena probe the conditions of the early Universe as a kind of cosmic ultrasound (Fig. 1, overleaf).

The properties of the observed peak have important implications for cosmology[5]. They depend mainly on the spectrum of initial fluctuations and fundamental cosmological parameters. The location and width of the peak strongly imply that the initial fluctuations that created the sound waves were in place on the largest scales at the earliest times. The only known mechanism for setting these perturbations in place is a

Box 1 The second peak in the spectrum



Before the BOOMERanG data[4] discussed here, all the evidence pointed towards a model of the Universe that is flat and lightweight (low dark-matter density), with an initial spectrum of density fluctuations whose power is constant across all length scales[6]. This standard model (black curve) is strongly inconsistent with the observed lack of a prominent second peak in the power spectrum of the cosmic microwave background.

There are at least three possible explanations for the 'missing' peak. First, the initial density fluctuations could actually increase with length scale, thereby suppressing small-scale fluctuations. This is known as a 'tilted' model (red curve, 10% tilt). This solution would have important implications for the particle physics of inflation and observations of gravitational waves.

The second possibility is that the density of baryons (ordinary matter) is as much as 50% higher than the value implied by the abundance of light elements in the Universe and the theory of their synthesis in the first few minutes after the Big Bang (nucleosynthesis)[6]. Any extra baryons cannot be in the stars we see today. If this were the solution, the question of where most of the baryons are today becomes even more puzzling[7]. At the very least, the BOOMERanG data place a lower limit on the baryon density that is comparable to the nucleosynthesis estimate.

A value for the dark-matter density higher than the standard one-third of the critical density also helps fits the power spectrum better (green curve; three times as much dark matter and 50% more baryons), at the expense of agreement with other cosmological data[6]. The standard value can also be made to work by lowering the predicted height of the peaks relative to the COBE measurements at the 10° scale by any one of several effects.

A testable consequence of either high-baryon-density solution is that the third peak should be higher in amplitude than the second.

The final and perhaps most speculative solution is if the formation of atomic hydrogen were to be delayed until the Universe was nearly 30% older, either through an unknown source of energy or through a change in our understanding of atomic physics at early times. This would increase the time available for the acoustic oscillations to dissipate and hence suppress the smaller peaks. A combination of some or all of these solutions may also provide the answer and perhaps avoid any extreme departures from the standard model. **W.H.**

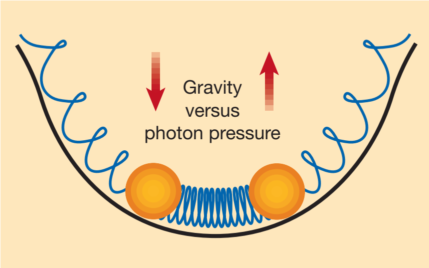


Figure 1 **What astronomers see in the fine structure of the cosmic microwave background is actually sound waves. Acoustic phenomena have long been a general prediction of gravitational instability models of structure formation[8]. Gravitational force compresses the primordial plasma until resistance from photon pressure reverses the motion, leading to acoustic oscillations. Because compression raises the temperature, this results in hot and cold spots that are visible in the microwave sky today.**

period of rapid (faster than light) expansion in the early Universe called inflation. In inflationary models, quantum fluctuations are carried from the microscopic to cosmic scale by the rapid expansion. If this interpretation is correct, then there should be a second peak that is smaller than the first, and a third peak that is comparable to or larger than the second.

In the inflationary context, the structure of the peaks is governed mainly by three fundamental parameters. These are the curvature of the Universe, the density of ordinary matter (or baryons), and the density of dark matter. The location of the first peak in the power spectrum provides the best measure of the curvature of the Universe, and hence the total amount of matter in the Universe. Einstein told us that matter curves space: the familiar force of gravity is no more than the curvature of space–time. To see this fact, consider the surface of the Earth. Two people travelling due north from the Equator on different lines of longitude will nonetheless meet at the North Pole. Ignorant of the curvature of the Earth, they might attribute this fact to a strange attractive force.

The same thing happens to CMB photons on their way to the observer if the Universe is spatially curved. The intervening matter and energy acts as a giant (de)magnifying glass that bends the photon trajectories. The BOOMERanG result supports a flat Universe, which means that the total mass and energy density of the Universe is equal to the so-called critical density. A perfectly flat Universe will remain at the critical density and keep on expanding forever, because there is not enough matter to make it recollapse in a 'big crunch'.

Perhaps the most intriguing aspect of the BOOMERanG results is the lack of a prominent second peak at half the angular scale of the first. If the second peak predicted by inflation exists, it is of much smaller amplitude than the first. Indeed it must be significantly smaller than expected from the simplest models (Box 1). The key to resolving the mystery of the second peak will be measurements of higher precision and resolution, perhaps from the forthcoming full analysis of the BOOMERanG data — but, if not, certainly from the MAP satellite to be launched in November. Regardless of the outcome, these data show that we have clearly entered a new era of precision cosmology, in which we can begin to talk with certainty about the origin of structure and the content of matter in the Universe. ■

Wayne Hu is at the Institute for Advanced Study, School of Natural Sciences, Olden Lane, Princeton, New Jersey 08540, USA.
e-mail: whu@sns.ias.edu

1. Smoot, G. *et al. Astrophys. J. Lett.* **396,** L1–L4 (1992).
2. Miller, A. D. *et al. Astrophys. J. Lett.* **524,** L1–L4 (1999).
3. Mauskopf, P. D. *et al. Astrophys. J. Lett.* (in the press).
4. de Bernadis, P. *et al. Nature* **404,** 955–959 (2000).
5. Hu, W., Sugiyama, N. & Silk, J. *Nature* **386,** 37–43 (1997).
6. Bahcall, N. *et al. Science* **284,** 1481–1488 (1999).
7. Fukugita, M., Hogan, C. J. & Peebles, P. J. E. *Astrophys. J.* **503,** 518–530 (1998).
8. Peebles, P. J. E. & Yu, J. T. *Astrophys. J.* **162,** 815–836 (1970).

Molecular biology

Introns gain ground

Thomas H. Eickbush

Protein-encoding genes of eukaryotes are often disrupted by introns that must be removed from the primary RNA transcript before the transcript is translated into protein. The origin of these apparently useless gene segments, known as spliceosomal introns because of the machinery used to excise them from RNA, has been debated for nearly 25 years. They were initially thought to be remnants of the original formation of genes. But there is mounting evidence that they represent the insertion of mobile elements from elsewhere, the most likely suspects being the mobile group II introns found in bacteria, mitochondria and chloroplast genomes. On page 1018 of this issue[1], Cousineau and co-workers provide further support for this possibility by revealing a means by which group II introns can spread throughout a genome.

A link between group II introns and spliceosomal introns was initially suggested by the remarkable similarity of the two RNA-splicing reactions[2]. Both intron types splice through a two-step transesterification mechanism. The first step is the formation of an intron 'lariat' in which the nucleotide at the 5′ end of the intron is covalently linked to an adenine near its 3′ end. This is followed by joining of the protein-coding exons, coupled to cleavage at the 3′ splice site and release of the intron lariat. In addition to this similarity in chemistry, the sequences at the 5′ and 3′ junctions of the two types of introns are quite similar.

The main difference between the splicing reactions is that the group II introns are self-splicing — they contain highly conserved internal structures that catalyse their own splicing reactions. Removal of nuclear spliceosomal introns, on the other hand, is catalysed by the spliceosome, an elaborate external assembly of small nuclear RNAs and associated proteins. A second feature associated only with group II introns is that some are mobile. So if an intronless copy of a gene is introduced into a cell with one of these mobile introns, a copy of the intron will insert into the equivalent intronless site, a process called homing[3].

The first clue to the mechanism of this movement came with the discovery that the mobile introns encode a reverse transcriptase — an enzyme that can make a double-stranded DNA copy from a single-stranded RNA template. The detailed mechanism of group II intron 'retrohoming' was determined in an elegant combination of studies of introns from yeast mitochondria[4] and of the LtrB intron of the bacterium *Lactococcus lactis*[5,6]. As shown in Fig. 1a, the spliced intron lariat reverse splices into the DNA sense strand at the target site in the intronless gene. The antisense strand is cleaved by an intron-encoded protein with DNA endonuclease activity. Primary recognition of the DNA target site is by base pairing of two regions of the intron RNA and the exon sequences upstream of the insertion site. Synthesis of complementary DNA by the intron-encoded reverse transcriptase, and synthesis of the second DNA strand, complete the reaction.

As well as extensive pairing between the intron RNA and upstream exon sequences, efficient group II retrohoming requires endonuclease recognition of specific bases in the target DNA[7]. This would seemingly preclude group II introns as an origin of spliceosomal introns because a proliferation phase would be required to spread the introns to countless unrelated sites throughout the eukaryotic genome. However, Cousineau *et al.*[1] now show for the first time the ease with which group II introns can expand from their original homes and invade chromosomal sites elsewhere.

The LtrB group II intron of *L. lactis* used in these studies was marked in two ways — with an antibiotic-resistance gene to enable

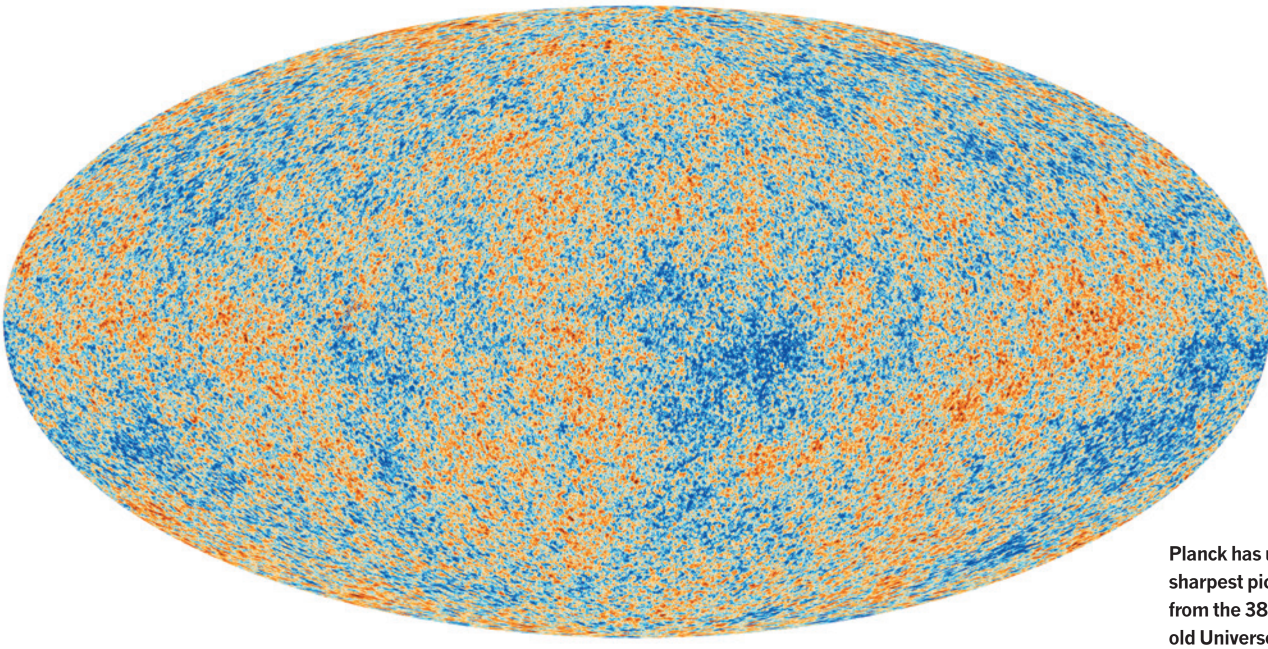
NEWS IN FOCUS

ITALY Minister gives green lights to controversial stem-cell treatments **p.418**

CYBERCRIME Journal impostors snare authors in costly scam **p.421**

PHYSICS How to cook up a Higgs without a massive collider **p.422**

SPECIAL ISSUE *Nature* explores the new landscape of publishing **p.425**



Planck has unveiled the sharpest picture of light from the 380,000-year-old Universe.

PLANCK COLLABORATION/ESA

COSMOLOGY

Planck snaps infant Universe

Space telescope culls exotic creation theories with ultra-precise microwave map.

BY MARK PEPLOW

For astronomers, it is the ultimate treasure map. On 21 March, the Planck space telescope team released the highest-precision map yet of the cosmic microwave background (CMB), the faint but ubiquitous afterglow of the Big Bang. Crowning nearly 50 years of CMB study, the map records the precise contours of the nascent Universe — and in doing so pins down key parameters of the Universe today.

The tiny fluctuations embedded in the CMB map reveal a Universe that is expanding slightly more slowly than had been thought. That dials back the amount of gravity-countering 'dark energy' to 68.3% of the Universe, and adds a little more unseen dark matter to the mix. It also means that the Universe is a little older: 13.82 billion years old, adding a few tens of millions of years to the previously calculated value. The map even shows that the number of neutrino 'flavours' permeating the cosmos will probably remain at three — had there been a fourth, the Universe would have expanded more quickly during its first moments.

These results represent refinements of numbers obtained by previous missions such as the Wilkinson Microwave Anisotropy Probe (WMAP). Where the Planck spacecraft, watching the sky from a vantage point 1.5 million kilometres away, breaks the most new ground is in its support for the reigning theory that describes the instant after the Big Bang. The theory, known as inflation, holds that during an unimaginably rapid expansion lasting just 10^{-32} seconds or so, the Universe grew from a subatomic point to something the size of a grapefruit that then continued to expand at a more stately pace. This growth spurt would help to explain why the Universe we see today is homogeneous on the largest scales, yet riddled with clumps, filaments and sheets of galaxies.

➲ **NATURE.COM**
For more on the Planck mission:
go.nature.com/ylwzmu

"Planck could have found that there was something majorly wrong with inflation," says astrophysicist Jo Dunkley at the University of Oxford, UK, who has worked on data from Planck and the WMAP. "Instead, we've got new evidence that this expansion did happen."

In the minutes that followed the burst of inflation, particles such as protons and electrons formed from the cauldron of protomatter, and photons began to bounce around like pinballs. It was only 380,000 years later, when the charged plasma cooled into neutral atoms, that those photons could fly freely. Today they make up the CMB, and carry with them an imprint of the quantum fluctuations that roiled the inflationary Universe.

Seen in the map as tiny variations around an average temperature of 2.7 kelvins, the fluctuations caused alterations in the density of matter, which ultimately snowballed into the galaxies seen today. "All the structures we see in the Universe are coming from these little perturbations," says Paul Shellard, a Planck cosmologist at the University of Cambridge, UK. ▸

Inflation, proposed in 1980 by Alan Guth, a physicist now at the Massachusetts Institute of Technology in Cambridge, predicts that the range of temperature variations should follow a bell curve — a smooth Gaussian distribution. Cosmologists had found hints in previous missions that the distribution was not so smooth, suggesting that some other process was involved in inflating the Universe (see *Nature* http://doi.org/bgjd86; 2008). But so far, Planck's temperature data look almost perfectly Gaussian, and standard theories for inflation are looking ever more secure.

"A lot of baroque inflationary models are gone," says Paul Steinhardt, a theoretical physicist at Princeton University in New Jersey, who has tried to poke holes in inflation by proposing theories such as ekpyrosis, which invokes a cyclical Universe that dies and is reborn in a series of Big Bounces.

But the cosmological case is not quite closed. There are a few details in Planck's map that seem out of place: an odd 'cold patch', for example, and a greater proportion of hotspots on one side of the sky. Moreover, Planck's value for the Hubble constant, which describes the rate of expansion of the Universe, is surprisingly low compared with estimates made with other astronomical techniques — perhaps a hint of new physics in play.

Full confirmation of inflation — and clues about what drove it — will depend on the detailed properties of the CMB's photons. The wrenching moment of inflation should have shaken the very fabric of space-time, resulting in gravitational waves. They in turn may have left a pattern in the polarization of the photons. The Planck team expects to release its polarization data early next year. "If we found gravitational waves, we'd get a Nobel prize — it's a big deal," says George Efstathiou, director of the Kavli Institute for Cosmology in Cambridge, UK, and one of Planck's lead researchers.

The exceedingly faint polarization signal may lie beyond the reach of Planck's detectors. Ground-based microwave telescopes, such as the Keck Array in Antarctica, are also in on the hunt, although they are limited to looking at one hemisphere of the sky, and in certain microwave frequencies, because oxygen in Earth's atmosphere can block some of the CMB photons. Charles Lawrence of NASA's Jet Propulsion Laboratory in Pasadena, California, the lead Planck scientist in the United States, says that it may take another space telescope to finish the job, or perhaps even a mission, decades away, to detect the gravitational waves directly.

But in terms of temperature variations, Lawrence says, astronomers will have to be content with Planck, which "squeezes pretty much all the juice out of the CMB". He finds that juice very sweet, even if it leaves a few questions beyond reach. "We have a pretty good idea of what the Universe is, but we don't have the faintest idea why it is," says Lawrence, adding with impish glee: "It's rather fun, isn't it?" ■

BENVEGNÙ/GUAITOLI/CIMAGLIA/JPEG FOTOSERVIZI

A naked woman joined protesters in Rome calling for stem-cell therapy for all incurably ill patients.

REGENERATIVE MEDICINE

Stem-cell ruling riles researchers

Italian health minister's support for a controversial treatment appals the country's scientists.

BY ALISON ABBOTT

Clinics that offer unproven stem-cell treatments often end up playing cat and mouse with health regulators, no matter which country they operate in. In Italy, however, one such treatment now has official sanction. The country's health minister, Renato Balduzzi, has decreed that a controversial stem-cell treatment can continue in 32 terminally ill patients, mostly children — even though the stem cells involved are not manufactured according to Italy's legal safety standards.

The unexpected decision on 21 March has horrified scientists, who consider the treatment to be dangerous because it has never been rigorously tested. In the opinion of stem-cell researcher Elena Cattaneo of the University of Milan: "It is alchemy".

The decision followed weeks of media pressure to authorize compassionate use of the therapy, which was developed by the Brescia-based Stamina Foundation and has been repeatedly banned in the past six years. Now, patient groups are pushing for the treatment to be available to anyone with an incurable illness. Hundreds protested in Rome on 23 March, including a naked woman with pro-Stamina slogans painted on her skin.

Stamina Foundation president Davide Vannoni, a psychologist at the University of Udine, says that the publicity around the treatment has won him 9,000 new patients. He hopes that further modifications to the law will allow him to expand the therapy.

A month ago, an investigatory television programme, *The Hyena*, reported that children with incurable diseases such as spinal muscular atrophy were being denied supposedly important treatment, and Italian show-business personalities joined the call to relax rules on stem-cell treatment.

In Italy, the compassionate use of as-yet-unapproved therapies is allowed on an emergency basis for dying individuals who have no other options, and the national health service must provide them for free. The law requires that health authorities approve the quality of such therapies, but some of its terms