THE COSMOLOGICAL BACKGROUND RADIATION

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge CB2 1RP, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1999

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Times 10/13pt, in 3B2 [KT]

A catalogue record for this book is available from the British Library

Library of Congress cataloging in publication data

Lachièze-Rey, Marc.
The cosmological background radiation/
Marc Lachièze-Rey and Edgard Gunzig.
p. cm.
Includes bibliographical references.
ISBN 0 521 05215 7.—ISBN 0 521 05215 7 (pbk.)
1. Cosmic background radiation. 2. Astrophysics. I. Gunzig, E.,
(Edgard) II. Title.
QB991.C64L33 1999
523.1–dc21 98-39471 CIP

ISBN 0 521 05215 7 hardback
ISBN 0 521 05215 7 paperback

Contents

1
Introduction

In July 1965 the *Astrophysical Journal* (vol. 142, p. 419), an American periodical, announced the discovery of a background electromagnetic radiation. This radiation was isotropic and unpolarized, exhibited no seasonal variation and was of cosmic origin. The authors of the article were two physicists from the Bell Telephone Laboratory, Arno Penzias and Robert Wilson.

In the same issue of the journal (vol. 142, p. 414) four astrophysicists from the Institute for Advanced Study at Princeton, Robert Dicke, Jim Peebles, Peter Roll and David Wilkinson, suggested that this newly discovered radiation had in fact been emitted during a phase of the universe when it was very hot and dense. This was precisely what had been predicted by the so-called big bang model proposed by George Gamow, Ralph Alpher and Robert Herman fifteen years previously and following the work of Georges Lemaître.

The discovery of this radiation, now named the 'cosmic background radiation' was and still is considered a very powerful argument in favour of the big bang model. In recognition of the capital importance of their discovery, Penzias and Wilson were awarded the Nobel Prize for Physics in 1978.

1.1 The discovery of the background radiation

In fact the discovery of the cosmological microwave background radiation was partly due to chance. At the end of the 1950s the laboratories of the Bell Telephone Company had started to work on the problems of satellite communication. NASA was soon to launch the ECHO satellite in 1959. The expected signal from this satellite would be very weak, therefore it was necessary to develop a highly sensitive receiver. Two of the Bell

Company laboratories were well placed to contribute to this programme. At one of these, Murray Hill, work was being carried out on detectors to improve their sensitivity. At the other site at Holmdel in New Jersey, only fifty kilometres from Princeton, people were perfecting a horn antenna. The geometrical form of such an antenna is particularly useful for the detection of weak signals because they are largely able to cut out ‘nuisance’ radiation from behind. This was why such a horn with a 3 m opening was constructed in 1961 for the detection of the weak signals from ECHO.

A few years earlier the two radio astronomers Arno Penzias and Robert Wilson had joined the laboratory. In fact they had a special interest in this antenna. It was sufficiently sensitive, once it had been equipped with an appropriate detector, to observe astronomical sources of small angular diameter. In fact, for sources of the right angular diameter for its beam, it was the most sensitive radio telescope in existence. Because of its compactness and excellent directivity it would be able to measure its gain accurately and identify all possible sources of nuisance noise. It thus presented the possibility of making absolute measurements rather than just the differential measurements to which radio astronomers are usually limited.

In 1963 the antenna lay unused and the two radio astronomers inherited some of it. After being used for the ECHO satellite it had been adapted for the TELSTAR satellite. To this end a MASER receiver operating at 7.3 cm, that is at a frequency of 4.08 GHz, was installed, backed up by an amplification stage. The task of the two radio astronomers was to transform the instrument into a radio telescope and then calibrate it properly. In order to make the most of its capabilities, they intended to use it for observations requiring absolute flux measurements, observe regions of our Galaxy and confirm the spectra of a number of radio sources. In fact they expected above all to show that no radiation came from the halo of our Galaxy at a wavelength of around 7 cm. As a follow up they intended to construct a receiver working at 21 cm and thus, amongst other things, study the hydrogen present in clusters of galaxies.

One of the first tasks of Penzias was to build a liquid helium cryostat to replace the liquid nitrogen cryostat and so ensure the effective cooling of the detector. From their very first observations the two radio astronomers noticed that they were registering a higher flux than they had predicted. Radio astronomers often express measured fluxes as temperatures. Penzias and Wilson had recorded ‘temperatures’ that were too high. So it was necessary to work out the contributions from the sky, the antenna itself, the wave-guide and the various parts of the apparatus. This excess temperature was not understood, but several explanations were still possible. First of all it was possible that emission from the atmosphere at these wavelengths might be stronger than had previously been thought. However, the lack of any variation of the signal with direction appeared to rule out this explanation. It was also possible that man-produced interference affected the readings. In order to look at this possibility more closely, Penzias and Wilson undertook to sweep the horizon with the antenna. The observations excluded both this explanation and a possible origin from our Galaxy, the Milky Way. The only other possibility was that discrete astronomical sources were responsible, but, given the properties of the best known of these, this seemed just as improbable.

All that remained was to check the radiation due to the antenna itself. After a very detailed and accurate calculation they concluded that this could not provide an explanation. In spring a couple of pigeons had nested in the shelter provided by the antenna. Was it possible that this might have caused some bizarre electromagnetic effect? They got rid of the pigeons and carefully cleaned the antenna, but the problem remained. Faced with these repeated failures, they were almost prepared to give up all hope of obtaining absolute measurements of the halo of our Galaxy. Nevertheless, one day they happened to speak with an astrophysicist colleague (B. Burke) who had heard others mention a background radiation. Jim Peebles, an astrophysicist at Princeton, had in fact performed calculations that implied such predictions from big bang models. Burke advised them to contact the Princeton group under Dicke. A meeting was organised. The Princeton group confirmed, somewhat disappointedly, that they had arrived, albeit a bit late, at this conclusion and understood the nature of the discovery. Two articles were sent jointly to the *Astrophysical Journal*.

In fact Penzias and Wilson initially were not really interested in cosmology. The Princeton group, on the other hand, had expected such observations to be made. Robert Dicke, its director, and Jim Peebles had carried out calculations showing that, because of its expansion, the universe should be filled with such radiation[1]. Two of their colleagues, Peter Roll and David Wilkinson, had begun to design a radiometer capable of measuring it. Already for several months the group had been dedicating itself to building what was later to be called 'Dicke's Radiometer' in order to measure the

[1] In fact these calculations had been performed in the framework of an oscillating universe, in which cycles of collapse, rebounding and renewed expansion took place.

cosmological (microwave) background radiation. (Henceforth we shall use the abbreviation CMBR for the cosmological microwave background radiation.) Although the Princeton group was not aware of it at that time, the existence of this radiation had been predicted long before. Alpher and Herman, the collaborators of George Gamow, had in 1949 predicted its existence at a temperature of a few degrees Kelvin. The USSR astrophysicists Doroshkevich and Novikov had also independently predicted its existence in 1964.

After the confirmation of the discovery the Princeton group began an observational study of this background radiation. In 1965 Roll and Wilkinson carried out measurements at wavelength $\lambda = 3$ cm. This measurement gave some idea of the spectrum of the radiation. Its thermal nature which had been predicted by the big bang model seemed to confirm the model. The temperature was estimated to be 3.0 ± 0.5 K. Subsequently other measurements confirmed its thermal nature and by the middle of 1966 the spectrum from 2.6 mm to 21 cm had been established.

Moreover the radiation had been detected much earlier, around 1940, by two American astronomers, Adams and Dunham, at the Mount Wilson Observatory, although they had not recognised it as such. They had discovered weak interstellar emission lines which were later identified with CH, CH^+ and CN molecules. The radiation was produced by excited molecules and the temperature had been estimated by 1941 to be around 2.3 K ($\lambda = 2.64$ mm; see section 7.5). Shortly after the 1965 observations several authors realised that these molecules were in fact excited by photons from the CMBR. These results not only confirmed the existence of the radiation but also provided a measurement at another wavelength. They thus further confirmed that the radiation's spectrum followed a black-body curve.

1.2 The origin of the background radiation

There are two very important characteristics of this radiation filling the entire universe: on the one hand its perfect isotropy (it has the same properties, most importantly its intensity, in every direction in the sky); and on the other hand its distribution in terms of wavelength, or in other words its spectrum, obeys extremely accurately what physicists call the black-body law. As far as we know at present, only thermal processes, that is processes produced by a system in thermal equilibrium, are capable of producing such radiation. On the other hand the isotropy strongly indicates that the processes involve the universe as a whole. The only way to understand the origin of such a phenomenon is to suppose that the entire universe went through a phase in which matter and electromagnetic radiation were in thermal equilibrium. This is precisely what Gamow and his collaborators had predicted around 1940. The Princeton group had made a similar prediction just before 1965. For both it was of prime importance to explain the relative abundances of the chemical elements in the universe as a whole within the framework of the newly formulated big bang model.

By big bang we shall mean a scenario in which the universe passed through an extremely hot and dense primordial phase. This does not necessarily imply an initial singularity[2], 'birth' or 'creation' of the universe[3].

The originality of these models stems from the idea that the primordial universe was sufficiently dense and hot for almost its entire contents to be in thermodynamic equilibrium (in a sufficiently distant past). In this case the laws of thermodynamics or, more precisely, the laws of quantum statistics allow one to calculate the characteristics of the various populations of particles and quanta present. Thus electromagnetic radiation behaved as black-body radiation since at this time the universe itself behaved as a black body.

It is a long time since the universe was in thermal equilibrium. One of the main occurrences marking the end of this coupling between matter and radiation goes by the name *recombination*. It took place about 15 thousand million years ago, about half a million years after the beginning of our phase of expansion, which is somewhat incorrectly called the 'birth of the universe'. (The exact times depend on the particular cosmological model adopted.)

Before recombination matter was ionised and the electrons were free and very numerous. The photon density was very high. Frequent collisions between photons and electrons ensured complete equilibrium of matter and radiation. Because of this the universe was opaque and any information carried by a photon was rapidly lost during the continual scatterings with the free electrons. As a result, this optical and radio astronomy can reveal nothing whatsoever about this period. The CMBR dates from the epoch of recombination, that is from the time when the universe became transparent.

[2] The possible avoidance of an initial singularity was extensively discussed in 'Self-consistent cosmology, the inflationary universe, and all that . . .' (Gunzig E. & Nardone P., *Fundamentals of Cosmic Physics*, 1987, vol. 11, pp. 311–443).

[3] For the possible avoidance of an initial singularity see, for example, *Cosmology, A First Course*, by Marc Lachièze-Rey, Cambridge University Press.

Because of this fact it provides us with the earliest information that we can hope to receive about the universe, at least in the form of electromagnetic radiation. It can reveal to us the state of the universe in its earliest stages, stages described by the big bang model.