OXFORD CAMBRIDGE AND RSA EXAMINATIONS

Advanced GCE

PHYSICS B (ADVANCING PHYSICS) **2865/01**

Advances in Physics

JUNE 2003

ADVANCE NOTICE ARTICLE

May be opened and given to candidates upon receipt.

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it through carefully. Spend some time looking up any technical terms or phrases you do not understand. You are ***not*** required to research further the particular topic described in the article.
- For the examination on 26 June 2003 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the *Advancing Physics* Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section A of Paper 2865, Advances in Physics, will refer to this *Advance Notice* article, and may give additional data related to it.
- Section A will be worth about 60 marks
- Section B will consist of two questions. These will ***not*** be based on the *Advance Notice* article. Section B will be worth about 30 marks.
- Four marks are available for the quality of written communication assessed over the whole paper.

This insert consists of 7 printed pages and 1 blank page.

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Probing the early Universe

New data confirms the Big Bang theory

The current cosmological picture of the Universe is that it started much smaller and much hotter than at present, and then suddenly expanded. Originally suggested by the cosmological redshift of distant galaxies, this model has largely been established from two observations:

- the ratio of the light elements hydrogen and helium in the Universe,
- and the cosmological microwave background radiation.

Until recently, these factors were quite separate, but more recent observations of the cosmological microwave background have been detailed enough to allow astronomers to confirm that the early Universe did in fact contain the ratio of hydrogen to helium that was expected. Furthermore, observations of distant sources in the X-ray, visible and infrared regions of the electromagnetic spectrum have given extra information about the early Universe.

Investigating the Cosmic Microwave Background Radiation (CMBR)

The currently accepted 'Big Bang' theory of cosmology states that when the Universe was very young it was much hotter and denser than the centre of our Sun. At that stage it was an opaque plasma of sub-atomic particles and radiation (photons) colliding with each other. As it expanded, the Universe became less dense and cooler, falling to a temperature of about 3 K at the present time. When the Universe was roughly 300 000 years old, it had cooled to about 3000 K. This is cool enough for the sub-atomic particles to combine into atoms. This made the Universe transparent; the photons could travel through it without being scattered or being absorbed.

Just as the temperature of a gas is related to the average kinetic energy of its molecules, so the temperature of a collection of photons is related to the photon energies, and these energies depend on their frequencies. Perfect emitters of radiation emit a range of different frequencies. For any particular frequency f, the energy ΔE emitted within a narrow frequency range Δf varies in a way that depends on the temperature of the radiator, as shown in Fig. 1.

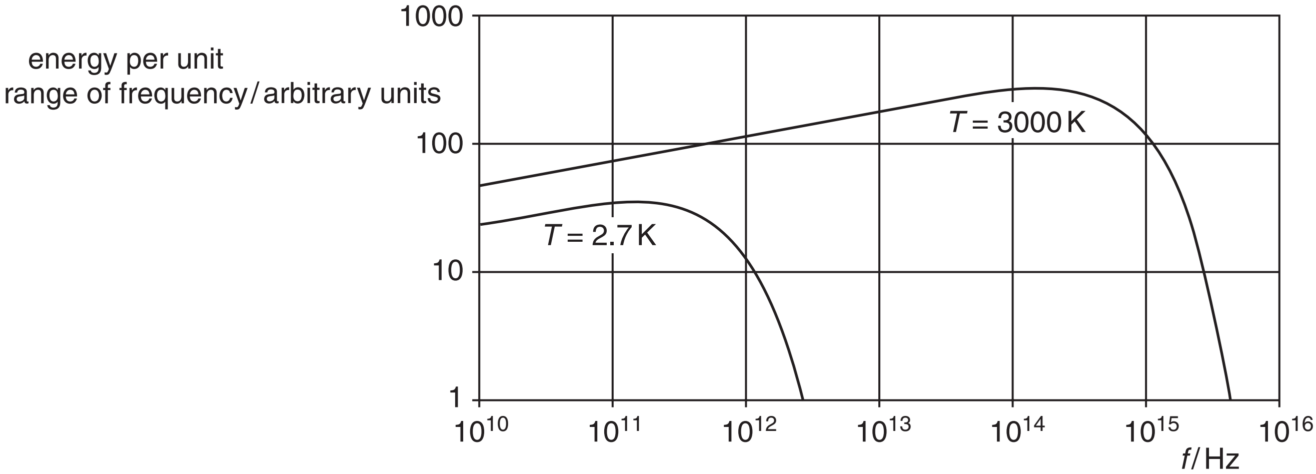

Fig. 1

The relationship shown in Fig. 1 was first devised by Max Planck to describe the variation of the intensity of the radiation emitted by perfect radiators, and was the starting point of quantum physics. The photons which had last interacted with matter when the Universe had a temperature of 3000 K now form the radiation associated with a temperature of 2.7 K, microwaves of wavelength about a millimetre. In the 1980s, the Cosmic Background Explorer (COBE) satellite measured the intensity of the microwave background at different frequencies, and established that it did indeed correspond closely to a temperature of 2.73 K.

In 1991 COBE also measured tiny fluctuations in the intensity in different directions, showing that the early Universe was not quite uniform. These intensity variations are extremely weak, but strong enough to indicate that the temperatures of those regions were not all identical. The more intense regions correspond to hotter spots in the CMBR and the less intense regions correspond to cooler spots in the CMBR. Matter condensed sooner in the cooler regions. For this reason, the fluctuations seen in the CMBR correspond to fluctuations in the density of the early Universe.

Gravitational attraction within the denser regions made the matter within them collapse into smaller, denser structures. By the time that the Universe was about 1 billion years old, these dense regions had collapsed into the large structures, such as galaxies and clusters of galaxies, that we see today. Thus the CMBR is a link between the hot, smooth early Universe and the cool, lumpy Universe of today. As the Universe is now very far from uniform, consisting of galaxies in clusters with vast tracts of empty space between them, this measurement was an important confirmation of the Big Bang Theory.

Ground-based investigation of the CMBR

The non-uniformity of the microwave background has been investigated recently in greater detail without the need for satellite telescopes. Instead of using expensive rockets to lift the telescopes above the obscuring atmosphere, they are raised aloft by the oldest method used by man — balloons. If the total weight of the telescope and the helium balloon to which it is attached is less than the weight of the air they displace, they float upwards to a point where the weight and upthrust forces balance. The first measurements were made by the BOOMERANG project (*Balloon Observations Of Millimetric Radiation And Geophysics*) above Antarctica. The South Pole was chosen, because the continuous sunlight and stable air currents over Antarctica during the summer in the southern hemisphere enable stratospheric balloon flights lasting between 10 and 20 days. A balloon carried the BOOMERANG telescope on a 10 day trip around the Antarctic continent between 29 December, 1998 and 9 January, 1999, as shown in Fig. 2. In order to make its extremely sensitive measurements, BOOMERANG was lifted above 99% of the atmosphere to an altitude of 35 km. At this height, the balloon had expanded to a volume of 1 000 000 m^3.

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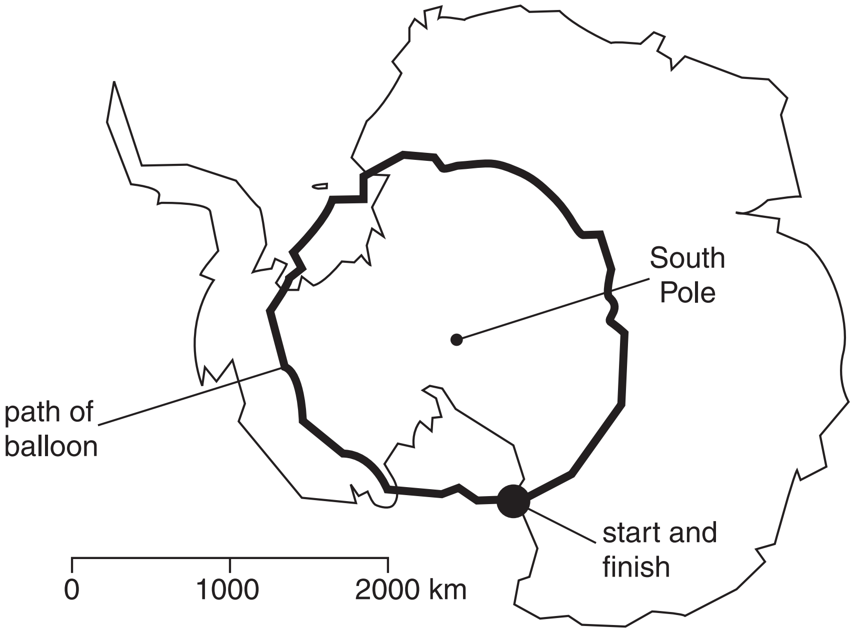

Fig. 2

The observations made confirmed the COBE findings, but also revealed more detail of the early Universe. This was because the resolution of BOOMERANG is greater than COBE; an angle of about 1° compared with COBE's 7° to 10° of angle. Using these more accurate observations and similar data provided by another balloon-borne telescope, the tiny fluctuations in the CMBR were investigated with increased precision and resolution.

The inflationary model of cosmology suggests that the early dense Universe underwent a period of exponential expansion for a very tiny fraction of a second. An analysis of the BOOMERANG data that was published in April 2001 confirmed some aspects of this model, but tantalisingly lacked the resolution to confirm other aspects, which would be revealed in fluctuations occurring over angles of 1° or less.

Overcoming the diffraction limit in telescopes

All telescopes are restricted in their resolution by **diffraction**. Waves passing through a circular aperture, such as the opening of the telescope, spread out or diffract through an angle θ that depends on the diameter d of the aperture and the wavelength λ of the waves according to the equation $\sin\theta = 1.22\frac{\lambda}{d}$. A telescope with a larger diameter d will give a smaller diffraction angle θ and therefore better resolution. A single telescope is not able to resolve details in the sky that subtend an angle smaller than θ, as the waves from those two sources will overlap, as shown in Fig. 3.

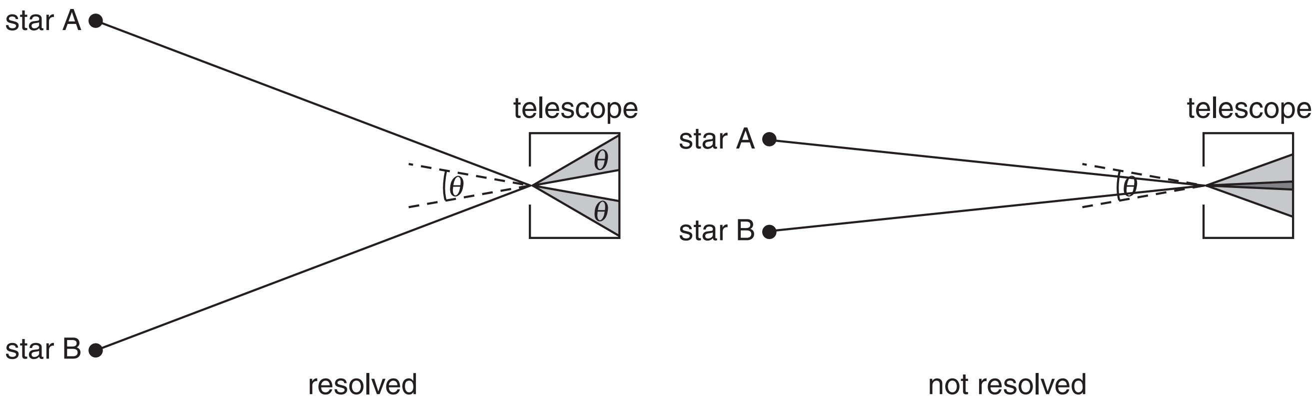

Fig. 3

More precise measurements of the CMBR have been made by two ground-based telescopes in Chile and Antarctica respectively. Unlike BOOMERANG, these are radio-interferometers. Radio-interferometers have long been used in astronomy at wavelengths of tens of centimetres, but the technique has only recently become sufficiently refined for use with the much smaller wavelengths of the CMBR. These instruments analyse the phase differences in signals received at different telescopes to produce a much more accurate ‘map’ of the distribution of signals than would be possible with a single telescope.

A radio-interferometer consists of two or more telescopes separated by a distance corresponding to a very large number of wavelengths. The signals received at two separate telescopes can be combined electronically to give information about the phase difference between them. This is roughly equivalent to having a larger telescope whose diameter is the same as the distance between the two separate telescopes, and that can be hundreds of kilometres. The general principle is outlined in Fig. 4.

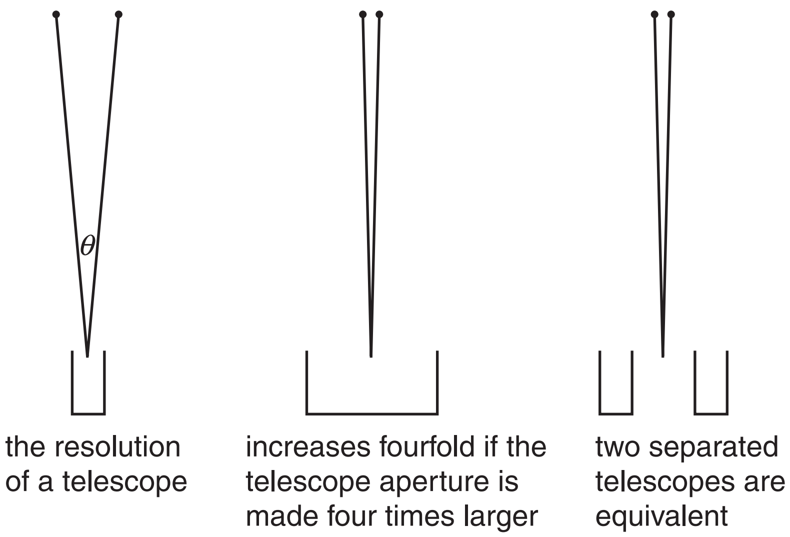

Fig. 4

Using interferometery can greatly increase the resolving power of radio-telescopes, but it is essential to know the precise times at which the signals arrive if the phase differences are to be calculated. Using this method, the small-wavelength radio-interferometers have imaged the CMBR around three times more accurately than BOOMERANG and found the fine fluctuations that BOOMERANG did not observe, at the exact angular spread predicted by inflation theory.

"These results are a tremendous confirmation of the inflationary model and also agree extremely well with measurements by other astronomers using completely different methods. It looks like we now have a 'Standard Model of Cosmology,'" said Phil Mauskopf from Cardiff University, a member of the BOOMERANG collaboration.

Investigating Active Galactic Nuclei

Although the CMBR had been detected from the ground, it was not until satellites bearing X-ray detectors were launched that it was discovered that the sky is also awash with X-rays. To investigate this further, X-ray telescopes were developed. X-ray sources called Active Galactic Nuclei are now believed by astronomers to be the main contributors to this X-ray background.

The Chandra X-ray Telescope and the Very Large Telescope

The X-ray observations that identified the Active Galactic Nuclei were made by the **Chandra X-ray Telescope**, launched by the Space Shuttle.

Making a telescope to detect X-rays is not easy, because they are so difficult to focus: the type of glass lens or mirror used in optical telescopes, would be no good! Instead of refraction or ordinary reflection, X-ray telescopes use total internal reflection to focus the X-rays, as shown in Fig. 5.

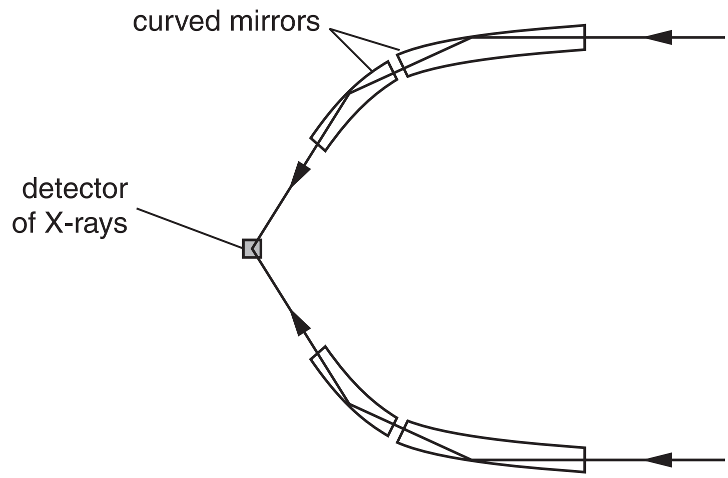

Fig. 5

The method used in X-ray telescopes is to have the path of the X-rays deflected by two carefully shaped curved mirrors at grazing incidence, one after the other. The X-rays undergo total internal reflection in each mirror, but do so at much larger critical angles than visible light – the deflection of the X-rays in Fig. 5 is greatly exaggerated to fit the diagram on the page. This is because the speed of X-rays in glass is only slightly smaller than their speed in a vacuum, so they undergo total internal reflection only at very large critical angles.

The combination of the curved mirrors brings a parallel beam of X-rays to a single point. Chandra has four sets of mirrors of this sort, nested one inside the other.

With a resolution of 0.5 seconds of arc (1.4×10^{-4} degrees, or 2.4×10^{-6} radians), eight times better than any previous instrument, Chandra was able to pinpoint over 300 separate X-ray sources in an exceptionally clear patch of the southern sky known as the Chandra Deep Field South.

The same area of the sky was then also investigated at infrared and visible wavelengths by the **Very Large Telescope** operated by the European Southern Observatory in Chile. This instrument consists of four telescopes, each eight metres in diameter, which can work independently or in combined mode. Astronomers used the Very Large Telescope to obtain infrared and visible spectra of over 100 of the sources identified by Chandra. By analysis of the spectra, it was possible to show that these sources were distant galaxies enveloped in clouds of gas and dust, and the tremendous energies radiated by them suggest that they have giant black holes at their centres.

Giant black holes – objects hundreds of times the mass of our Sun, but compressed into much smaller volumes – have intense gravitational fields. The closest point to a black hole from which any information can be obtained is called the **event horizon** – the intense gravitational field any closer to the centre than this will prevent even photons from escaping. Large quantities of matter falling into such massive black holes from nearby stars would radiate great quantities of high energy photons. This could account for the X-rays emitted by Active Galactic Nuclei.

At about eight billion light years away, we see these Active Galactic Nuclei as they were when the Universe was about half its present age. It is thought that these galaxies are what nearby ones, like our own Milky Way or the great galaxy in Andromeda, were like at much earlier times in their existence. The Chandra data suggest that giant black holes were much more active in the past than at present.

These recent developments in observational astronomy provide a good example of what has been known in astronomy from the earliest observations that Galileo made with his telescope: while technical advances in instrumentation mean that you may observe phenomena which confirm some of your theories, you are certain to discover new things which will force you to reconsider your ideas.

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