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The Book of Universes

John D. Barrow

About the Author

John D. Barrow is Professor of Mathematical Sciences and Director of the Millennium Mathematics Project at Cambridge University, Fellow of Clare Hall, Cambridge, a Fellow of the Royal Society, and the current Gresham Professor of Geometry at Gresham College, London. His principal area of scientific research is cosmology, and he is the author of many highly acclaimed books about the nature and significance of modern developments in physics, astronomy, and mathematics, including The Origin of the Universe; The Universe that Discovered Itself; The Book of Nothing; The Constants of Nature; The Infinite Book: a Short Guide to the Boundless, Timeless and Endless, The Artful Universe Expanded, and New Theories of Everything, and Cosmic Imagery. This is a book about universes. It tells a story that revolves around a single extraordinary fact: that Albert Einstein's famous theory of relativity describes a series of entire universes. Not many solutions to Einstein's tantalising universe equations have ever been found, but those that have are all remarkable. Some describe universes that expand in size, while others contract. Some rotate like a top, while others are chaotically unpredictable. Some are perfectly smooth, while others are lumpy. Some permit time travel into the past. Only a few allow life to evolve within them; the rest, if they exist, remain unknown and unknowable to conscious minds.

Our story will encounter universes where the laws of physics can change from time to time and from one region to another, universes that have extra hidden dimensions of space and time, universes that are eternal, universes that live inside black holes, universes that end without warning, colliding universes, inflationary universes, and universes that come into being from something else – or from nothing at all.

Gradually, we are introduced to the latest and the best descriptions of the Universe as we understand it today, together with the concept of the 'Multiverse' – the universe of all possible universes – that modern theories of physics lead us to contemplate. Here, in The Book of Universes we are confronted with the most fantastic and far-reaching speculations within the entire realm of science.

BY THE SAME AUTHOR

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(with Joseph Silk)

L'Homme et le Cosmos
(with Frank J. Tipler)

The Anthropic Cosmological Principle
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Pi in the Sky

Perché il mondo è matematico?

Impossibility

The Origin of the Universe

Between Inner Space and Outer Space

The Universe that Discovered Itself

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THE BOOK OF UNIVERSES

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THE BODLEY HEAD
LONDON

Epub ISBN: 9781409028802
Version 1.0
www.randomhouse.co.uk

Published by The Bodley Head 2011
2 4 6 8 10 9 7 5 3 1

First published in Great Britain in 2011 by
The Bodley Head
Random House, 20 Vauxhall Bridge Road,
London SW1V 2SA

www.bodleyhead.co.uk
www.rbooks.co.uk

Addresses for companies within The Random House Group Limited can be found at:
www.randomhouse.co.uk/offices.htm

The Random House Group Limited Reg. No. 954009

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

ISBN 9781847920980

To Tilly

For whom there are many universes to come

Contents

Something unknown is doing we don’t know what.

Arthur S. Eddington

Preface

Universes are big at the moment. And this is a book about universes. It is a story that revolves around a single unusual and unappreciated fact: that Albert Einstein showed us how to describe possible universes – entire universes. Previously, there had been discussion about the structure of our universe for thousands of years. All manner of exotic pictures had been created to describe or explain it. The results were often driven by religious, nationalistic, artistic or personal prejudices. They were stories. In the early twentieth century, things suddenly changed: Einstein showed us how to find all the possible universes that were consistent with the laws of physics and the character of gravity, how to reconstruct their pasts and predict their futures. But actually finding them was no easy task. Ever since, astronomers, mathematicians and physicists have struggled to solve Einstein's intricate equations and find these universes. This book is about that struggle and the possibilities it gradually uncovered.

What a gallery of possible universes there are. Many bear the names of some of the most famous scientists of the twentieth century. Some expand in size, others contract, some rotate like a top while others are totally chaotic. Some are perfectly smooth, while others are lumpy, or shaken in different directions by cosmic tides; some oscillate forever, some become lifeless and cold, while others head towards a runaway future of ever-increasing expansion. Some permit time travel into the past, while others threaten to allow infinitely many things to happen in a finite amount of time. Only a few allow life to evolve within them; the rest must remain unexperienced by conscious minds. Some end with a bang, some with a whimper. Some don’t end at all.

Our story will encounter universes where the laws of physics can change from time to time and from one region to another, universes that have extra hidden dimensions of space and time, universes that are eternal, universes that live inside black holes, universes that end without warning, colliding universes, inflationary universes, and universes that come into being from something else – or even from nothing at all.

Gradually, we will find ourselves meeting the latest and the best descriptions of the universe we see around us today, together with the concept of the ‘Multiverse’ – the Universe of all possible universes – that modern theories of physics lead us to contemplate. These are the most fantastic and far-reaching speculations in the whole of science. They challenge us to ask whether the exhibits in our gallery of possible universes actually exist or whether there is only one that achieves this special status.

Other cosmology and astronomy books have focused on particular topics – dark matter, dark energy, the beginning of the universe, inflation, life-supporting coincidences, or the end of the universe – but this book introduces the reader to whole universes and the histories of their discovery, along with the personalities of the scientists who found them, in a coherent and unified way.

I would especially like to thank Katherine Ailes, Allen Attard, Donato Bini, Arthur Chernin, Hyong Choi, Pamela Contractor, Cecile De Witt, Charles Dyer, Ken Ford, Carl Freytag, Gary Gibbons, Owen Gingerich, Jörg Hensgen, Bob Jantzen, Andre Linde, Kay Peddle, Arno Penzias, Remo Ruffini, Doug Shaw, Will Sulkin, Kip Thorne and Don York for their help with editing, gathering pictures and providing other important historical details. I would also like to thank Elizabeth for her careful support and our now not-so-young children for their questions and the granddaughter to whom this book is dedicated.

John D. Barrow
Cambridge

1 Being in the Right Place at the Right Time

I know it’s all in our minds, but a mind is a powerful thing.
Colin Cotterill[1]

TWO MEN WALKING

I am always surprised when a young man tells me he wants to work at cosmology; I think of cosmology as something that happens to one, not something one can choose.
William H. McCrea[2]

The old gentleman walking down the street looked the same as ever – distinguished but slightly dishevelled, in a Bohemian style, a slow-walking European on an American main street, sad-faced, purposeful but not quite watching where he was going, always catching the attention of the locals as he made his way politely through the shoppers and the contra-flow of students late for lectures. Everyone seemed to know who he was but he avoided everyone’s gaze. Today, he had a new companion, very tall and stockily built, a little the worse for wear, untidy but in a different way to his companion. They were both deep in conversation as they made their way, walking and talking, oblivious of the shop windows beside them. The older man listened thoughtfully, sometimes frowning gently; his younger companion enthusiastically pressing his point, occasionally gesticulating wildly, talking incessantly. Neither spoke native

English but their accents were quite different, revealing resonances with many places. Intent on crossing the street, they stopped, lingering at the kerbside as the traffic passed. The traffic lights changed and they continued quietly across the street, both momentarily concentrating on light, sound and relative motion. Suddenly, something happened. The taller man started to say something again, making a dart of his hand. The traffic was moving again now but the old man had stopped, dead in his tracks, oblivious to the cars and the hurrying pedestrians. His companion's words had consumed his thoughts entirely. The cars roared past on both sides leaving the two of them marooned in their midst like a human traffic island. The old man was deep in thought, the younger one reiterating his point. Eventually, resuming contact with the moving world around them, but forgetful of where they had been going, the older man led them silently towards the pavement – the one they had stepped off a minute ago – and they walked and talked their way from whence they had come, lost in this new thought.

The two men had been talking about universes.[3] The place was Princeton, New Jersey, and the time was during the Second World War. The younger man was George Gamow, or 'Gee-Gee' to his friends, a Russian émigré to the United States. The older man was Albert Einstein. Einstein had spent the previous thirty years showing how we could understand the behaviour of whole universes with simple maths. Gamow saw that those universes must have had a past that was unimaginably different to the present. What had stopped them both in their tracks was Gamow's suggestion that the laws of physics could describe something being created out of nothing. It could be a single star; but it might be an entire universe!

FUNNY THINGS, UNIVERSES

> History is the sum total of the things that could have been avoided.
> Konrad Adenauer

What is the universe? Where did it come from? Where is it heading? These questions sound simple but they are amongst the most far-reaching that have ever been posed. Depending upon how much you know, there are many answers to the question of what we mean by 'universe'.[4] Is it just everything you can see out in space – perhaps with the space in-between thrown in for good measure? Or is it everything that physically exists? When you draw up the list of all those things to include in 'everything' you start to wonder about those 'things' that the physicists call the 'laws of Nature' and other intangibles like space and time. Although you can't touch or see them, you can feel their effects, they seem pretty important and they seem to exist – a bit like the rules of football – and we had better throw them in as well. And what about the future and the past? Just focusing on what exists *now* seems a bit exclusive. And if we include everything that has *ever* existed as part of the universe, why not include the future as well? This seems to leave us with the definition that the universe is everything that has existed, does exist and will ever exist.

If we were feeling really pedantic we might take an even grander view of the universe, which includes not only everything that can exist but also everything that could exist – and finally, even that which cannot exist. Some medieval philosophers[5] were drawn to this sort of completeness, adding everything that has existed, does exist and will not exist to the catalogue of what was, is and will be. This approach seems bent upon creating new problems in an area where there are enough already. Yet recently it has re-emerged in modern studies of the universe, albeit in a slightly different guise. Modern cosmologists are not only interested in the structure and history of our universe but also in the other types of universe that might have been. Our universe has many special and (to us at least) surprising properties that we want to evaluate in order to see if they could have been otherwise. This means that we have to be able to produce examples of 'other' universes so as to carry out comparisons.

This is what modern cosmology is all about. It is not just an exercise in describing our universe as completely and as accurately as possible. It seeks to place that description in a wider context of possibilities than the actual. It asks 'why' our universe has some properties and not others. Of course, we might ultimately discover that there is no other possible universe (whose structure, contents, laws, age and so forth are different in a way we can conceive of) apart from the one we see. For a long time, cosmologists were rather expecting – even hoping – that would turn out to be the case. But recently the tide has been flowing in the opposite direction and we seem to be faced with many different possible universes, all consistent with Nature's laws. And, to cap it all, these other universes may not be only possibilities: they may be existing in every sense that we attribute to ordinary things like you and me, here and now.

THE IMPORTANCE OF PLACE

> And [Jacob] dreamed, and behold a ladder set up on the earth, and the top of it reached to heaven: and behold the angels of God ascending and descending on it.
>
> Book of Genesis[6]

People have been talking about the universe for thousands of years. It was *their* universe, of course, not to be confused with ours. For many it would have been just the land as far as they could journey. Or maybe it was the night sky of planets and stars that could be seen with the naked eye. Most ancient cultures tried to create a picture or a story about what they saw around them, whether it be in the sky, on the ground or under the sea.[7] This drawing of a bigger picture was not originally driven by an interest in cosmology, but was simply important to convince themselves, and others, that things had a meaning and *they* were part of that meaning. To admit that there were parts of reality about which they had no conception or control would have created a dangerous uncertainty. This is why ancient myths about the nature of the universe always seem so complete: everything has a place and there is a place for everything. There are no ‘maybes’, no caveats, no uncertainties and no possibilities awaiting further investigation. They really were ‘theories of everything’, but they are not to be confused with science.

Your time and place on Earth influenced the sense you would make of the universe around you. If you lived near the Equator then the apparent motions of the stars each night were clear and simple. They rose, passed up and over your head throughout the night and then descended to set on the opposite horizon. Every night was the same and it felt as though you were at the centre of these celestial movements. But if you lived far from the Tropics the heavens looked very different. Some stars rose above the horizon and set later that night, they came straight up and over your head before falling back to the horizon. Others never rose or set and were always above the horizon. They seemed to trace out circles around a great centre in the sky, like they were pinned to a wheel turning on its axis. It must have made you wonder what was special about that place around which the stars turned. Many myths and legends about the great millstone in the sky were framed by the inhabitants of northern latitudes to make some sense of that great nightly swirl of stars.

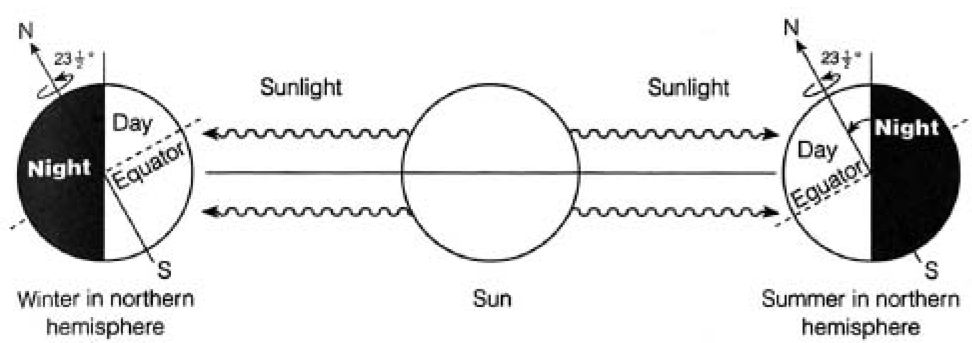

Figure 1.1 The Earth’s rotation axis, running through the North and South Poles, is tilted at about 23.5 degrees with respect to the vertical perpendicular to the Earth’s orbital plane.

The reason for this variation in the appearance of the night sky around the world is a tilt of the axis around which the Earth rotates each day (Figure 1.1). As the Earth orbits the Sun, the line through the Earth's North and South Poles[8] around which it rotates each day is not perpendicular to the line its orbit traces. It is tilted away from the vertical at about 23.5 degrees. This has many remarkable consequences: it is the reason for the seasons. If there were no tilt then there would be no seasonal changes in climate; if the tilt were much larger then the seasonal variations would be far more dramatic. However, if you know nothing about the motion of the Earth around the Sun, or the tilt of its axis, and merely look at the stars in the sky each night, the tilt ensures that there will be a very different sky on view at different latitudes on Earth.

If we extend the line from the South to the North Pole out into space it points in a direction that we call the North Celestial Pole and away from the South Celestial Pole. As the Earth rotates, at night we will see the fixed stars apparently rotating past in the opposite direction across the sky. If they remain visible they will be completing a great circle on the sky each time the Earth completes a daily revolution. However, not all of these circular paths across the sky will be completely visible to us because part of the path will lie below our horizon. In Figure 1.2 we show what a sky watcher living at a latitude of L degrees in the northern hemisphere will see on a clear night.[9]

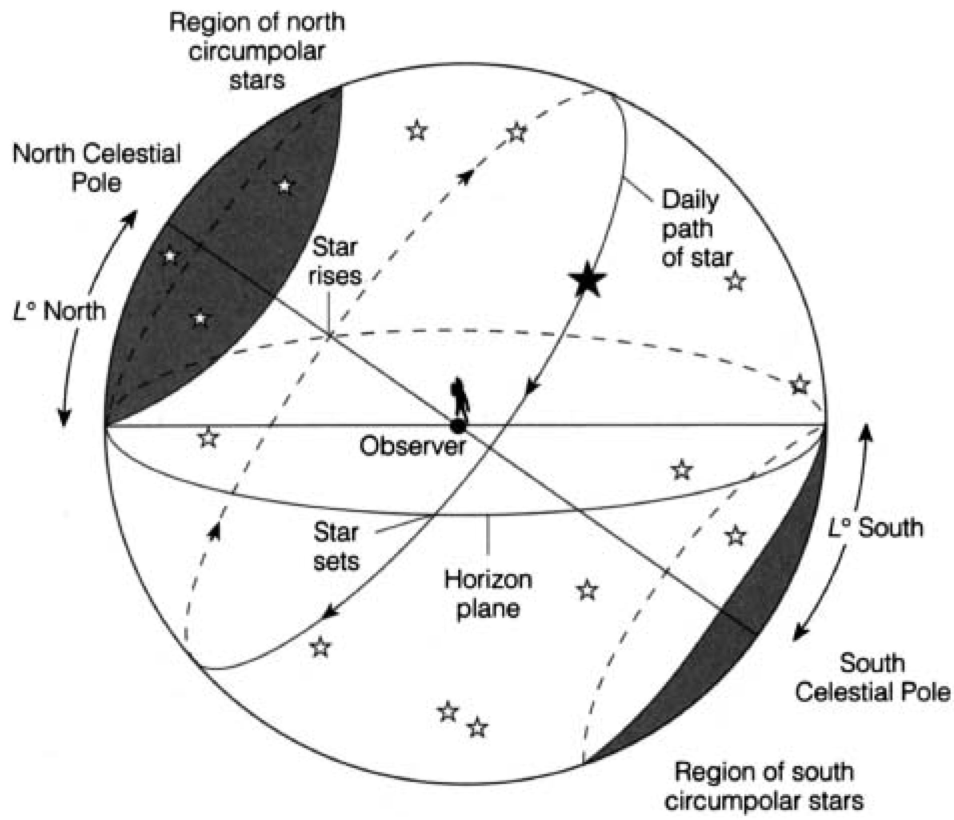

Figure 1.2 The celestial sky seen by astronomers who are located at a latitude of *L* degrees north. Only half of the sky is visible to them at any moment. Some stars, the north circumpolar stars, are so close to the North Celestial Pole that they never set below the horizon. A second group, around the South Celestial Pole, called the south circumpolar stars, are never seen by the same astronomers because they do not rise above the horizon.

Our sky watcher's horizon divides the sky in half. Only the part of it above the horizon can be seen at any moment. Observing from a latitude of *L* degrees north means that the North Celestial Pole lies *L* degrees above the horizon and the South Celestial Pole lies *L* degrees below it. The Earth's rotation makes the sky appear to rotate in a westerly direction around the North Celestial Pole. Stars are seen to rise on the easterly horizon and then move up the sky before reaching their highest point, or ‘zenith’, after which they descend and set on the westerly horizon.[10]

There are two groups of stars that are not seen to follow this nightly rise and fall in the sky. Stars inside a circle that extends *L* degrees from the North Celestial Pole complete their apparent circles in the sky without ever disappearing below the horizon. If the sky is clear and dark they can always be seen.[11] For European sky watchers today, they include the stars in the Plough and Cassiopeia groups. Conversely, there is a collection of southern stars within a circular region of the same extent around the South Celestial Pole which are never seen by the southern-hemisphere sky watcher in our picture. They never rise above his horizon.[12] This is why the constellation of the Southern Cross can never be seen from northern Europe. Crucially, we can see that the size of these regions of the sky that are always visible or invisible varies with the latitude of the sky watcher. As your latitude increases and you move away from the Equator, so the sizes of these regions increase as well. In Figure 1.3 we show how the sky would appear to sky watchers at three very different terrestrial latitudes.

At the Equator, the latitude is zero and there are no regions of ever-visible or never-visible stars. An equatorial sky watcher can glimpse every bright star, although the two Celestial Poles are lost in the haze down on the far horizons in practice. The stars rise and ascend to their highest points in the sky. As each star rises, its direction remains relatively constant and is an excellent navigational beacon for wayfaring on land or sea throughout the night. There is almost no sideways motion in the darkness and the sky seems to be very symmetrical and simple. Our sky watchers gain the impression that they are at the centre of things, beneath a celestial canopy of overarching and predictable motions that seem to be there for their convenience. The universe looks as if they are central to it.

At the extreme case of the North Pole, the latitude is 90 degrees and the visible stars neither rise nor set. They move in circles around the sky. The Celestial North Pole is directly overhead and all the stars circle around it. It looks like the focal point of the universe and we are directly beneath it.

At more temperate northerly latitudes, like that of ancient Stonehenge in Britain at 51 degrees, there is an in-between situation. Stars lying within 51 degrees of the Celestial Pole will be seen to complete concentric circles on the sky with the Pole as their centre. Other stars will rise above the horizon, ascend to their zeniths, then descend and set. The sky appears extremely lopsided. Different stars follow different paths between their rising and setting. Most striking of all, though, is the great swirl of stars in the direction of the Celestial Pole, all circling it as if it is the hub of a great cosmic wheel (Figure 1.4). For those sky watchers who know nothing of astronomy, or the motion of the Earth, there seems to be a special place in the sky.

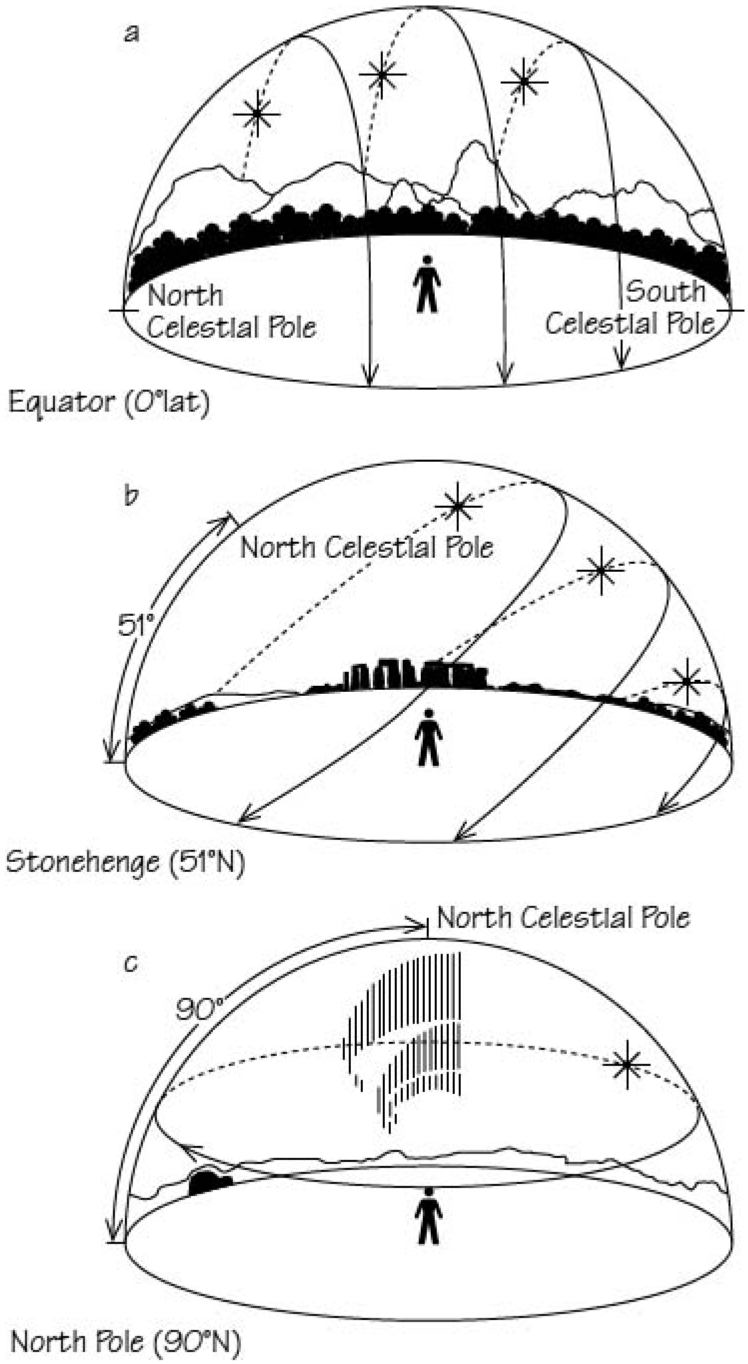

Figure 1.3 The appearance of the night sky seen from three different latitudes on Earth. It differs because of the change in position of the Celestial Pole around which the stars appear to rotate: (a) at the Equator; (b) at the latitude of Stonehenge in England; (c) at the North Pole.

This is one reason why there is a geographical dimension in the myths about the sky and the nature of the universe around us. Far from the Equator, in Scandinavia and Siberia, we find legends of the great circle in the sky: the millstone at whose centre the gods reside. The nearest star to the centre of the celestial swirl was given a special importance, hosting the throne of the sovereign of the universe around whom all the stars were arrayed.[13]

We will not be interested in tracing these myths any further here. We simply want to highlight how difficult it was to come up with a picture of the universe from an earthbound vantage point. There are significant biases that you will be unaware of when you know nothing about the stars and the rotation and orientation of the Earth.

Even when sophisticated early civilisations started making astronomical observations they still encountered the influence of our particular vantage point. We are confined to a small planet which, along with many other planets, orbits a star. Today we know about this solar system of planets and the hundreds of distant stars which have been found to have other planets around them (more than 500 at present). This familiarity makes it easy for us to forget how difficult it was to get away from an Earth-centred view and understand the motions of the other planets. As a very simple example of the difficulty, let's think about our view from Earth of the motion of a planet like Mars. We will assume that both the Earth and Mars orbit around the Sun in circular orbits, and that the radius of the orbit of Mars is about one and a half times larger than that of the Earth's orbit (Figure 1.5a). Earth takes one year to complete its orbit and we shall assume that Mars takes twice as long to complete its orbit. Now work out the difference between the two orbits as time passes. This tells us the apparent motion of Mars as seen from Earth. A graph of this is shown in Figure 1.5b.

Figure 1.4 A long-time exposure in the direction of the North Celestial Pole records the circular star trails around the Pole, which is located just above the top of the tree in the centre.

This curious heart-shaped loop with a cross-over (called a 'limaçon') is interesting. As we go from the top right towards the left, we see that Mars is moving away from the Earth. When it drops down to cut the horizontal axis at the point -5 the two planets are on opposite sides of the Sun and as far away from each other as possible. Then as Mars starts to return towards the Earth something very strange happens. Mars approaches the Earth and looks as if it is going to collide with it. But then it reverses its direction and moves away again, to resume its long period of motion away from