the curved-space or spherical geometry which the German mathematician Bernhard Riemann had devised in 1854 – a non-Euclidean geometry in which straight lines do not exist, and where the shortest distance between two points is a curve called a geodesic. Light and all electromagnetic radiation in curved space-time must therefore travel in geodesics.

The idea of curved space-time where nothing can move in a straight line may seem a little exotic, but one only has to consider navigating on the Earth's surface to see that it is no way peculiar. When navigating across an ocean no mariner can travel in a straight line because the Earth's surface is curved (Fig. 8·6). the shortest route is not a straight line (he would have to dive through water and ocean bottom for that!) – it is a GREAT CIRCLE, the equivalent on a three-dimensional sphere of a geodesic in curved four-dimensional space-time. It is worth noting too, that on Earth a very small area of its surface can be considered flat, just as a very small volume of curved space-time has a flat geometry.

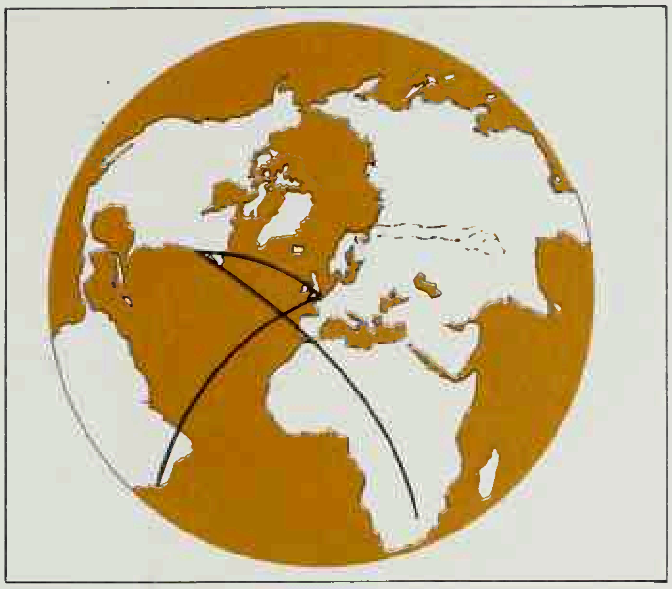

Fig. 8·6
On the 'spherical' surface of the Earth, the shortest paths between places are curved lines: these are in fact 'great circles' of which the equator is the best known example.

Observational proofs of relativity

No theory, however ingenious or attractive, is acceptable unless it can make valid predictions, that is, unless it can forecast some consequences which can be checked by observation. Over astronomical volumes of space there are three clear tests for relativity; one is the motion of the perihelion of Mercury, another the apparent displacement of stars near the Sun, and the third a redshift on the spectrum of a massive radiating body. The movement of the perihelion of Mercury's orbit is due to the perturbations of the other planets, and is observed to be 574 arc sec. per century, but Newton's gravitation theory predicts a motion which is too small by 43 arc sec. per century. Using relativity calculations the error virtually vanishes; Einstein's gravitation theory gives the correct result.

The apparent displacement of starlight passing close to the Sun (Fig. 8·7) is due to the Sun's gravitational field; if we compare photographs of a star field at night and the star field close to the Sun at the time of a total solar eclipse, this displacement can be measured. Newton in the eighteenth century had conjectured that light had mass, and according to his gravitation theory the deflection of starlight by the Sun should amount to 0·87 arc sec. According to relativity the curvature of space-time caused by the Sun should give a deflection twice this amount, 1·75 arc sec., and in 1919 the first measurements to test the theories were made. Observations in Sobral, Brazil by Andrew Crommelin and on the Island of Principe in the Gulf of Guinea by Arthur Eddington, were made at the particularly favourable eclipse of that year when the Sun was close to the Hyades open cluster, and the results obtained were 1·98 and 1·61 arc sec. Later eclipse observations by William Campbell and Robert Trumpler in 1922 gave a value of 1·72 arc sec. Although there was some spread in values of these delicate observations, Newtonian theory was obviously inadequate; the observations clearly confirming relativistic gravitation.

Another consequence of the deviation of light in a gravitational field, predicted earlier but only recently discovered, is the existence of **gravitational lenses**. If a sufficiently massive body occurs between us and another celestial object, not only will the light from the latter be displaced, but double images may be produced. This was first confirmed from radio observations of a distant quasar, and several cases are now known, including purely optical ones. In each case the intervening object is a galaxy, but their detection has sometimes been very difficult due to their great distance and near-invisibility, even though most of them seem to be massive elliptical galaxies.

Another prediction from relativity was that spectral lines emitted from a massive body will be redshifted. Thus, if one compares the spectrum of an element in the laboratory and a similar element on the Sun, the lines from the Sun should suffer a redshift. This test is again difficult to make, the gravitational redshift being only some two parts per 10^6, but it has been found to be present, while spectra from the dense companion of Sirius, where the expected shift is some thirty times greater, also show the predicted shift.

There is no doubt that these three independent confirmations of relativity put the theory in a very sound position, and in studying the cosmos, the universe as a whole, the validity of relativity is accepted.

Fig. 8·7 Space is distorted close to a massive body. Thus a beam of starlight is deflected and, in the case of the Sun, a star close in the line of sight appears in a different position.