Opposite page; Fig. 8·3 and below: Astronauts under zero gravity conditions. The photograph shows Ed White during the Gemini IV mission in June 1965

300 000·13 km per s. Clearly there is something special about the way the universe is constructed for this to happen.

Special relativity

In considering a theory in which all motion is relative, in which Newton's concept of absolute motion did not exist, Einstein took into account the results of the Michelson-Morley experiment, paying special attention to the interpretation of the Dutch and Irish physicists, Hendrik Lorentz and George Fitzgerald. They had claimed that the nil result could be squared with the physics of the time – 'classical physics' – if one considered that length, mass and time changed in a moving body compared with a stationary one. Mathematically, Lorentz showed that the length of a moving body should be diminished by an amount which depended on the square root of the quantity $(1 - v^2/c^2)$, where v represents the velocity of the moving body and c the velocity of light. Then if a body moved with the speed of light, v would equal c, and v^2/c^2 would be equal to 1; but if this were so $(1 - v^2/c^2)$ would become zero, and the body would have no length at all – clearly, a nonsensical answer. Lorentz also derived relationships for the mass of a body (which increased with velocity) and for time (which also increased); these also contained the square root of $(1 - v^2/c^2)$, and gave nonsensical answers for travel at the speed of light.

Einstein saw the deep implications of these results and realized that they demanded a full scale revision of the laws of physics. The increase of mass with velocity, for instance, involved the whole question of kinetic energy (the energy of motion) and made him realize that there was an equivalence between mass m, and energy E, leading to the famous equation:

$$E = mc^2.$$

It was also clear to him that the velocity of light was not only an invariant, but was also a limiting velocity, so that it became one of the tenets of relativity that nothing can travel faster than light. Again, there could be no absolute motion because there was no fixed frame of reference in the universe. Also, since time was involved and was relative in bodies moving relative to one another, Einstein realized that the simultaneity of events was also relative – that is, because one observer might see two events happening at the same instant, this apparent simultaneity would not be seen by other observers moving relative to the first observer. For instance, suppose someone on our Galaxy observes two events – the explosions of two widely separated supernovae, say – in another galaxy, and sees these happen together. We cannot tell whether these explosions were truly simultaneous without knowing their distances. But consider another observer on another galaxy moving relative to our Galaxy. The other observer's values for length and time will be different to those made in our Galaxy (how different will be proportional to their relative velocity v), so they will not see the explosions simultaneously. Whether or not one observes simultaneity depends, then, on one's frame of reference. In other words, if there is no absolute reference standard of motion in the universe, there is no absolute reference standard of simultaneity either.

Since time as well as place are relative according to the theory, it would lead to errors to consider questions of space and time separately. Therefore, relativity is concerned with 'events', which incorporate the three 'dimensions' of space (length, breadth, height) and the 'dimension' time – a **space-time universe**. Although time intervals will differ from one frame of reference to another, and space intervals will vary too, by placing them in a space-time combination, relativity does give an unchanging or **invariant** interval between events. Of course if we are dealing only with events measured in a single frame of reference, then time and space differences are the same for all observers; this is what we are accustomed to in our everyday experience for, of course, our measurements are all made on our own frame of reference, the Earth.

To make it as simple as possible, in special relativity Einstein considered only frames of reference in uniform (that is, non-accelerated) relative motion. Appreciation of this explains the so-called twin paradox, which is sometimes claimed to show that the principle of relativity – the absence of any absolute frame of reference in the universe – is untrue. As usually stated the paradox is about twins, one of whom stays on Earth while the other goes off in a space vehicle and then returns. According to the Lorentz equation, time for the space traveller has gone more slowly than that for the observer on Earth; therefore, when he returns he will be younger than his stationary twin. In this way we can tell which frame of reference is the standard or absolute one. Yet the paradox is not real. The age difference does not invalidate relativity, and the paradox is false because we do not have two uniformly moving frames of reference; there is only one. Any second frame associated with the space traveller would have to move in uniform not accelerated motion: however, the space traveller undergoes acceleration as he leaves the Earth, slows down prior to his return, and so on.

General relativity

In considering the motion of bodies, Newton devised the concept of universal gravitation to explain why a body falls to Earth, or to the centre of any massive body, with accelerated motion. On Earth this acceleration is 9·81 m per s^2. Naturally, Newton thought of gravitation as acting instantaneously, but Einstein's relativity theory did not accept instantaneous action: no interactions can take place at a speed greater than that of light. Gravity may, therefore, be transmitted with the velocity of light, but no faster. To take this into account, Einstein had to develop general relativity so that it could incorporate not only the non-accelerated frames of reference of special relativity – **inertial** frames as they are called – but also frames of reference in relative accelerated motion. The incorporation of gravity raised many difficult problems, not least due to the relative nature of mass and length. In Newtonian gravity theory, the force of gravitational attraction is proportional to the masses