1.2: Experimental Tests of the Nature of Time

The Hafele-Keating Experiment

In 1971, J.C. Hafele and R.E. Keating of the U.S. Naval Observatory brought atomic clocks aboard commercial airliners and went around the world, once from east to west and once from west to east.[1] (The clocks had their own tickets, and occupied their own seats.) As in the parable of Alice and Betty, Hafele and Keating observed that there was a discrepancy between the times measured by the traveling clocks and the times measured by similar clocks that stayed at the lab in Washington. The result was that the east-going clock lost an amount of time $\Delta t_E = -59 \pm 10\ ns$, while the west going one gained $\Delta t_W = +273 \pm 7\ ns$. This establishes that time is not universal and absolute.

Note

Hafele and Keating, Science, 177 (1972), 168

Figure 1.2.1 - The clock took up two seats, and two tickets were bought for it under the name of "Mr. Clock."

Nevertheless, causality was preserved. The nanosecond-scale effects observed were small compared to the three-day lengths of the plane trips. There was no opportunity for paradoxical situations such as, for example, a scenario in which the east-going experimenter arrived back in Washington before he left and then proceeded to convince himself not to take the trip.

Hafele and Keating were testing specific quantitative predictions of relativity, and they verified them to within their experiment's error bars. At this point in the book, we aren't in possession of enough relativity to be able to make such calculations, but, like Alice and Betty, we can inspect the empirical results for clues as to how time works.

The opposite signs of the two results suggests that the rate at which time flows depends on the motion of the observer. The east-going clock was moving in the same direction as the earth's rotation, so its velocity relative to the earth's center was greater than that of the ones that remained in Washington, while the west-going clock's velocity was correspondingly reduced.[2] The signs of the $\Delta t's$ show that the moving clocks were slower.

Note

These differences in velocity are not simply something that can be eliminated by choosing a different frame of reference, because the clocks' motion isn't in a straight line. The clocks back in Washington, for example, have a certain acceleration toward the earth's axis, which is different from the accelerations experienced by the traveling clocks.

On the other hand, the asymmetry of the results, with $|\Delta t_E| \neq |\Delta t_w|$, implies that there was a second effect involved, simply due to the planes' being up in the air. Relativity predicts that time's rate of flow also changes with height in a gravitational field. The deeper reasons for such an effect are given in section 1.5.

Although Hafele and Keating's measurements were on the ragged edge of the state of the art in 1971, technology has now progressed to the point where such effects have everyday consequences. The satellites of the Global Positioning System (GPS) orbit at a speed of $1.9 \times 10^3 m/s$, an order of magnitude faster than a commercial jet. Their altitude of 20,000 km is also much greater than that of an aircraft. For both these reasons, the relativistic effect on time is stronger than in the Hafele-Keating experiment. The atomic clocks aboard the satellites are tuned to a frequency of 10.22999999543 MHz, which is perceived on the ground as 10.23 MHz. (This frequency shift will be calculated in example 11).

Muons

Although the Hafele-Keating experiment is impressively direct, it was not the first verification of relativistic effects on time, it did not completely separate the kinematic and gravitational effects, and the effect was small. An early experiment demonstrating a large and purely kinematic effect was performed in 1941 by Rossi and Hall, who detected cosmic-ray muons at the summit and base of Mount Washington in New Hampshire. The muon has a mean lifetime of 2.2 μs, and the time of flight between the top and bottom of the mountain (about 2 km for muons arriving along a vertical path) at nearly the speed of light was about 7 μs, so in the absence of relativistic effects, the flux at the bottom of the mountain should have been smaller than the flux at the top by about an order of magnitude. The observed ratio was much smaller, indicating that the "clock" constituted by nuclear decay processes was dramatically slowed down by the motion of the muons.

Gravitational red-shifts

The first experiment that isolated the gravitational effect on time was a 1925 measurement by W.S. Adams of the spectrum of light emitted from the surface of the white dwarf star Sirius B. The gravitational field at the surface of Sirius B is $4 \times 10^5 g$, and the gravitational potential is about 3,000 times greater than at the Earth's surface. The emission lines of hydrogen were red-shifted, i.e., reduced in frequency, and this effect was interpreted as a slowing of time at the surface of Sirius relative to the surface of the Earth. Historically, the mass and radius of Sirius were not known with better than order of magnitude precision in 1925, so this observation did not constitute a good quantitative test.

The first such experiment to be carried out under controlled conditions, by Pound and Rebka in 1959, is analyzed quantitatively in example 7.

The first high-precision experiment of this kind was Gravity Probe A, a 1976 experiment[3] in which a space probe was launched vertically from Wallops Island, Virginia, at less than escape velocity, to an altitude of 10,000 km, after which it fell back to earth and crashed down in the Atlantic Ocean. The probe carried a hydrogen maser clock which was used to control the frequency of a radio signal. The radio signal was received on the ground, the nonrelativistic Doppler shift was subtracted out, and the residual blueshift was interpreted as the gravitational effect effect on time, matching the relativistic prediction to an accuracy of 0.01%.

Note

Vessot at al., Physical Review Letters 45 (1980) 2081

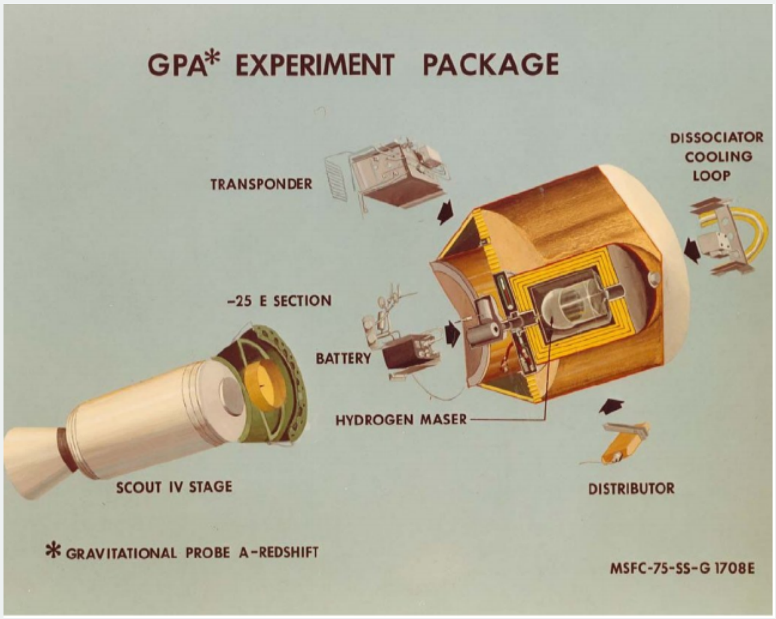

Figure 1.2.2 - Gravity Probe A.