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P5_4 The Relatively Special Voyager 1 Clock

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Abstract

We calculate the extent of the effects of special relativity on the Voyager 1 space probe by calculating the difference in time between an atomic clock in a stationary frame on Earth and one on the Voyager 1. We determine that there would be a difference of 2.19 s. We also calculate the change in length to be 1.08×10^{-9} m and the change in mass to be 1.4 μg. We also discuss the possible pitfalls of our assumptions.

Introduction

NASA's Voyager 1 space probe was launched in September 1977 and has since travelled over 150 AU from Earth making it the furthest venturing space probe in history [1]. In the process of crossing the heliopause, Voyager 1 travelled at a top speed of over 17,000 ms^{-1} [2]. This means Voyager 1 is also one of the fastest man-made objects. Special relativity means the faster an object travels through space the slower it moves through time. Meaning a clock left on the stationary frame of Earth would record time passing faster than a clock on Voyager 1. The probe is only travelling at a small fraction of the speed of light but has been travelling for over 45 years so it's conceivable that this small effect has caused a measurable difference. These effects of special relativity can also be applied to the Voyager's length and mass.

Calculating Average Velocity

We know how far from the Earth the Voyager 1 probe has travelled and we know how long it has taken to get there. The probe has travelled 2.37×10^{13} m from Earth in 1.42×10^{9} s [2][3]. Using these values and equation 1 an average velocity can be calculated.

$$\bar{v} = \frac{x_{tot}}{t} \tag{1}$$

This results in an average velocity of 16,630 ms^{-1}.

Calculating Time Dilation

It is important to define the different reference frames before calculating the effects of special relativity. The Earth is in the 'S frame' and is the stationary frame of reference. The Voyager 1 is in the inertial 'S$'$ frame.' We use the time dilation equation to work out the time interval in the S frame.

$$\Delta t = \gamma \Delta t' \tag{2}$$

where γ is the Lorentz Factor, which is defined as:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \tag{3}$$

Using the value for average velocity, $\bar{v}$ = 16,630 ms^{-1}, we obtain a Lorentz Factor of 1.000000002. Therefore, using a rearranged form of equation (2), $\Delta t' = 1422999998$ s. In order to obtain the difference in recorded time between a clock in the S frame and a clock in the S′ frame $\Delta t'$ must be subtracted from Δt using equation (4).

$$\delta t = \Delta t - \Delta t' \tag{4}$$

We calculated a δt of 2.19 s. This means that the atomic clock on Voyager 1 is over two seconds behind an atomic clock on Earth.

Calculating Length Contraction

Special relativity also affects the length of an object. When an object travels at a significant fraction of the speed of light its length appears contracted to a stationary observer or the relative stationary length. As the probe would be contracted parallel to its direction of travel it is important to use the correct dimensions. Though at its longest length the space probe is almost 4 m [4] in length it is orientated so that the antenna is facing away from its direction of travel and back to Earth. This means that the correct length to use when calculating its degree of length contraction is 0.54 m [5],

$$\Delta x = \gamma \Delta x' \tag{5}$$

Using the Lorentz Factor calculated previously $\Delta x'$ is calculated to be 0.5399999989 m. This means that the length of the space probe has decreased by 1.08×10^{-9} m.

Calculating Relativistic Mass

Special relativity also affects the mass of an object. As an object's velocity increases so does it's mass. At increasingly large velocities approaching the speed of light the mass of an object will tend to infinity. Voyager 1 had a recorded mass of 721.9 kg [5]. This mass was recorded in the rest frame of Earth prior to launch.

$$m = \gamma m_0 \tag{6}$$

We calculated a relativistic mass of 721.9000014 kg. This means the mass of the Voyager 1 has increased by 1.4 μg.

Discussion and Conclusions

These changes in age, size and mass are small. The most significant change is the difference in time between the two clocks. This is because this difference is always increasing so although Voyager 1 is travelling a small fraction of c it has been travelling for over 45 years. The changes to the probe's length and mass are much lesser as they are constant at constant velocity.

When undertaking these calculations it was assumed that the distortion of space-time due to the Sun and planets Voyager has passed on its travels have had no relativistic effects on the probe. However, this is not true and, though small, these effects should be calculated in future studies. Also, it has been assumed that the Voyager 1 probe travelled in a straight line from Earth to its current position. However, this is not true and Voyager 1 has had to slingshot around planets to leave the solar system. This increase in path would affect these calculations. However, we believe the values we have obtained would be of a similar order of magnitude.

In conclusion, we calculated a time difference of 2.19 s, a change in length of 1.08×10^{-9} m and the change in mass to be 1.4 μg.

References

[1] `https://voyager.jpl.nasa.gov/mission/timeline/#event-a-once-in-a-lifetime-alignment` [Accessed 10 October 2022]

[2] `https://voyager.jpl.nasa.gov/mission/status/` [Accessed 10 October 2022]

[3] `https://www.timeanddate.com/date/durationresult.html` [Accessed 10 October 2022]

[4] `https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1977-084A` [Accessed 11 October 2022]

[5] Kohlhase, C. E., and P. A. Penzo, Voyager mission description, Space Sci. Rev., (1977).