Exploring the Twin Paradox: From Einstein's Theory to NASA's Twin Astronauts

Seyed Mohammad Javad Mortazavi (PhD)[1], Payman Rafiepour (PhD)[2], Seyed Alireza Mortazavi (MD)[3], Lembit Sihver[4,5,6,7]*

[1]Ionizing and Non-Ionizing Radiation Protection Research Center (SUMS), Shiraz University of Medical Sciences, Shiraz, Iran
[2]Department of Nuclear Engineering, School of Mechanical Engineering, Shiraz University, Shiraz, Iran
[3]AMVLS College, The University of Glasgow Glasgow, Scotland, UK
[4]Department of Radiation Dosimetry, Nuclear Physics Institute of the CAS, Prague, Czech Republic
[5]Technische Universität Wien, Atominstitut, Vienna, Austria
[6]Department of Physics, East Carolina University, Greenville, NC, USA
[7]Royal Military College of Canada, Kingston, ON, Canada

*Corresponding author: Lembit Sihver
Technische Universität Wien, Atominstitut, Vienna, Austria
E-mail: lembit.sihver@tuwien.ac.at

Received: 8 August 2023
Accepted: 15 August 2023

According to the Einstein's special theory of relativity in physics, the twin paradox, which explores the concept of time dilation, is a thought experiment involving identical twins. One of the twins' journeys into space in a high-speed spacecraft and returns to Earth to find that the twin who stayed at home has aged more than the twin who made the high-speed journey in space. This seemingly contradictory result can be explained by the fact that time passes more slowly for an object in motion than for one at rest, a consequence of Einstein's theory of special relativity. Thus, the passage of time is relative to the observer's frame of reference and is affected by their relative motion.

This Paradox has been a popular topic of discussion and exploration in scientific and popular culture since Einstein first proposed it in 1905. In recent years, NASA has conducted a unique experiment involving twin astronauts Mark and Scott Kelly, with Scott spending a year aboard the International Space Station (ISS) while Mark remained on Earth. The NASA twin study was a research project conducted by NASA to investigate the effects of spaceflight on the human body, including the comparison of physiological changes in two identical twins, one of whom went into space while the other stayed on Earth. The study also involved time dilation and special relativity to some extent, as the twin who traveled to the ISS did experience that time passed slower for him due to his high-speed relative to the twin on Earth.

The time dilation Scott Kelly experienced during his 1-year space journey, relative to his twin brother Mark Kelly on Earth, can be estimated. According to special relativity, time dilation occurs when an object is moving at high speeds relative to another object or is in a strong gravitational field.

During Scott Kelly's 1-year stay on the International Space Station, he traveled at an average speed of ~17,500 miles per hour (mph) (~28,150 kilometers per hour) relative to the Earth. This high speed causes a noticeable time dilation effect, where time appears to slow down for Scott relative to Mark on Earth.

Scott Kelly's mission was a year-long mission, which began on March 27, 2015, and ended on March 1, 2016. During this mission, Kelly spent 340 consecutive days in space aboard the ISS, setting a record for the longest single spaceflight by an American astronaut. There have been other astronauts who have spent about one year in space. One example is Russian cosmonaut Valery Polyakov, who holds the record for the longest continuous stay in space by any human (having spent 437 days in space in 1994-1995). Other astronauts who have spent close to a year in space include Russian cosmonaut Sergei Krikalev (who spent 311 days in space in 1992-1993 and 803 days over six spaceflights in total) and NASA astronaut Peggy Whitson (who spent 289 days in space in 2016-2017 and a total of 665 days over three spaceflights).

The time dilation effect can be calculated using the formula: $t=\frac{t_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$,

where t is the time elapsed for Scott in space, t_0 is the time elapsed for Mark on Earth, c is the speed of light in vacuum, and v is the relative speed between the twins.

Using this formula and assuming an average speed of 17,500 mph for Scott during his year in space, we can estimate that Scott experienced a time dilation of about -2.9×10^{-5} seconds per day he spent in space. This means that over the course of his year-long mission, Scott experienced a total time dilation of approximately 0.01 seconds (-2.9×10^{-5} seconds per day×340 days=-9.9×10^{-3} seconds, or roughly 0.01 seconds). Hence, while the time dilation effect was very small, it is still measurable. However, it is not likely that this very small-time dilation can have important implications for space travel and future missions to more distant parts of our solar system.

However, one of the key findings of the NASA Twins Study was that Scott Kelly experienced changes in his DNA, e.g., telomere elongation, that were not observed in his twin brother, providing significant insights into the effects of space travel on human health. The changes of telomere length in space are not unexpected. They might be a form of adaptive response to key space stressors such as radiation.

Regarding the NASA Twin Study, we have previously reported that the elongation of telomeres may be ascribed to a well-established biological adaptive response to the space environment [1]. Interestingly, some studies show that neither the inhabitants of high background radiation areas of Ramsar, Iran [2] nor Kerala, India [3] show telomere length alterations, while the NASA Twin Study [4] clearly represents a significant change that may be related to the presence of high linear energy transfer (LET) relativistic particles in space. Although protons are relatively known as low-LET particles, high charge and energy (HZE) particles have high energies and high Linear Energy Transfer (LET) values [5]. Therefore, despite the low abundance, HZE particles traversing a cell nucleus induce almost irreparable DNA damages because of a very high rate of energy deposition in living cells [6].

In their e-letter published in Science, Mortazavi et al. raise some concerns about the NASA Twins Study, which analyzed the biological effects of a year-long spaceflight on a male astronaut compared to his monozygotic twin [7]. The authors of the e-letter suggest that the study did not fully address the potential impact of space radiation, particularly HZE particles, on telomere length and telomerase activity. They also raise the possibility that telomere elongation during space flight could be an adaptive response to the space environment but also increase the risk of cancer of an astronaut in long-term missions [8]. Additionally, they suggest that the study could provide insight into the difference between low-dose exposures to low- vs. high-LET radiation.

Authors' Contribution

SMJ. Mortazavi and L. Sihver designed the study. P. Rafiepour and SAR. Mortazavi reviewed the literature and prepared the reports. SMJ. Mortazavi and L. Sihver drafted the manuscipt. All authors read and approved the manuscript.

Conflict of Interest

SMJ. Mortazavi, as the Editorial Board Member, was not involved in the peer-review and decision-making processes for this manuscript.

References

1. Bevelacqua JJ, Welsh J, Mortazavi SMJ. Comments on "Association of telomere length with chronic exposure to ionizing radiation among inhabitants of natural high background radiation areas of Ramsar, Iran". *Int J Radiat Biol.* 2020;**96**(6):707-8. doi: 10.1080/09553002.2020.1739770. PubMed PMID: 32134704.
2. Movahedi A, Mostajaboddavati M, Rajabibazl M, Mirfakhraie R, Enferadi M. Association of telomere length with chronic exposure to ionizing radiation among inhabitants of natural high background radiation areas of Ramsar, Iran. *Int J Radiat Biol.* 2019;**95**(8):1113-21. doi: 10.1080/09553002.2019.1605460. PubMed PMID: 31038377.
3. Das B, Saini D, Seshadri M. Telomere length in human adults and high level natural background radiation. *PLoS One.* 2009;**4**(12):e8440. doi: 10.1371/journal.pone.0008440. PubMed PMID: 20037654. PubMed PMCID: PMC2793520.
4. Garrett-Bakelman FE, Darshi M, Green SJ, Gur RC, Lin L, Macias BR, et al. The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight. *Science.* 2019;**364**(6436):eaau8650. doi: 10.1126/science.aau8650. PubMed PMID: 30975860. PubMed PMCID: PMC7580864.
5. Kamsali N, Chakravarty SC, Basuvaraj PK. Investigation of HZE particle fluxes as a space radiation hazard for future Mars missions. *Heliyon.* 2019;**5**(12):e02972. doi: 10.1016/j.heliyon.2019.e02972. PubMed PMID: 31867459. PubMed PMCID: PMC6906680.
6. Asaithamby A, Chen DJ. Mechanism of cluster DNA damage repair in response to high-atomic number and energy particles radiation. *Mutat Res.* 2011;**711**(1-2):87-99. doi: 10.1016/j.mrfmmm.2010.11.002. PubMed PMID: 21126526. PubMed PMCID: PMC3318975.
7. Mortazavi SMJ, Bevelacqua JJ, Welsh. 2019. Comment on: Garrett-Bakelman FE, Darshi M, Green SJ, Gur RC, Lin L, Macias BR, et al. The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight. *Science*. [Online]. Comment posted on 31 May 2019. [Accessed 12 April 2019]. Available from: https://www.science.org/doi/10.1126/science.aau8650..
8. Bevelacqua JJ, Welsh J, Mortazavi SAR, Keshavarz M, Mortazavi SMJ. Space Medicine: Why Do Recently Published Papers about Telomere Length Alterations Increase our Uncertainty Rather than Reduce it? *J Biomed Phys Eng.* 2021;**11**(1):103-8. doi: 10.31661/jbpe.v0i0.2005-1115. PubMed PMID: 33564645. PubMed PMCID: PMC7859374.