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How Gravitational Time Dilation Affects the Flow of Time on Different Astrophysical Entities: Exoplanets, Stars and Compact Objects

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Abstract

One of the most prominent features that can be derived from Einstein's General Theory of Relativity is gravitational time dilation. It defines how mass curves spacetime influences the passage of time for different observers. The main consequence of this phenomenon is that time runs slower in regions where the gravitational field is stronger. This effect is more pronounced in the case of the closest neighborhoods of compact celestial bodies, such as neutron stars, black holes and white dwarfs, where gravitational forces are extremely strong and spacetime is significantly distorted. This understanding opens the door to studying physics in extreme cosmic environments**,** finding application in the development of GPS technology, and the influence of relativistic effects on light, motion and cosmic evolution.

Keywords/Terms: Gravitational time dilation; General theory of relativity; Spacetime curvature; Black holes; Neutron stars; White dwarfs; Gravitational field strength; Time flow; Relativistic effects; Einstein’s relativity; Astrophysical entities; Compact objects; GPS accuracy; Atomic clocks; Event horizon; Gravitational redshift; Spacetime distortion; Temporal relativity; Massive bodies; Kepler-277b; Kepler-277c

1 Introduction

1.1 The Issue with Interpreting Time on Different Planets

Gravitational time dilation has been one of the biggest obstacles in figuring out how time functions on different planets. Observations of time can differ depending on gravitational strength. This means that a second on a very heavy planet might not be the same second on Earth (NASA GSFC, 2023). Without the right instruments to detect and take into account such changes, time measurements in different gravitational areas become quite uncertain. The problem of time is at the center of concern for scientists and space-farers, who use time as a tool for orientation, communication and research (NASA JPL, 2024).

Gravitational time dilation is the phenomenon where time is slower in a stronger gravitational field and faster in a weaker one. Massive things warp the very fabric of spacetime around them, which in turn changes the rate of time flow. For example, time running on the surface of a planet or next to a compacted star, will be slower compared to a clock that is located far away in space (NASA GSFC, 2023). This effect has been confirmed experimentally through the Hafele–Keating experiment of 1971, where atomic clocks flown aboard airplanes demonstrated measurable time differences due to gravity and velocity (Hafele and Keating, 1971). Additionally, it has continually been verified through the relativistic corrections that were required for the operation of GPS satellites, whose orbiting clocks run faster than those on Earth due to weaker gravity (Ashby, 2003).

This effect of gravitational time dilation depends heavily on the mass and density of the objects. For instance, close to a black hole, the effect is extremely powerful. On the other hand, it is only a little bit on Earth. Celestial objects exist in outer space, such as stars, black holes, galaxies, neutron stars and planets, and other cosmic structures, such as nebulae, star clusters and planetary systems (NASA GSFC, 2023).

Planets that do not belong to our Solar System are named as exoplanets. These are planets that revolve around a star other than the Sun (NASA Exoplanet Archive, 2023). As different planets possess different masses, densities and orbital conditions, gravitational time dilation could considerably alter time on these planets compared to Earth (ESA, 2023). Some examples are Proxima Centauri b, TRAPPIST-1 e, Kepler-186 f and LHS 1140 b (NASA Exoplanet Archive, 2023). Compact objects represent a category of celestial bodies that are small in size. In saying that, they have high density and are massive for their size. This group includes leftovers of stars, such as white dwarfs, neutron stars, black holes and the supermassive black holes that lie in the centers of galaxies. The compact objects are not regular planets or average stars that have not collapsed, nor are they diffused clouds of gas. Instead, they are the end stages of stellar evolution with intense gravitational fields (NASA GSFC, 2023).

There are several benefits in terms of detecting and employing gravitational time dilation. Firstly, time dilation creates prediction and synchronisation of clocks and signals to a higher level of accuracy (NASA JPL, 2024). This is crucial for satellite navigation systems, such as GPS and interplanetary missions. For instance, NASA’s plan to create a Coordinated Lunar Time (NASA GSFC, 2024). Furthermore, knowing time dilation in different gravitational situations allows scientists to figure out the difference in time between various planets, moons or around different stars This information is critical for advancing space exploration, enhancing communication and conducting research in the field of gravitational physics (NASA GSFC, 2023). In regard to space exploration, accurately accounting for variations in gravitational time can enable mission planners to synchronise the clocks of spacecraft, improve navigation precision and guarantee that long duration missions maintain accurate timing, despite the fluctuations in gravitational forces. In terms of communication, comprehending time dilation assists in minimising signal-timing inaccuracies between spacecraft, satellites and ground stations. This is vital for data transmission, command sequencing and coordinating autonomous systems during deep-space missions.

Nevertheless, there are limitations and a need for improvement in the development of gravitational time dilation research. The effects of gravitational time dilation on many planets of moderate mass are very tiny and difficult to detect. Thus, the accuracy of clocks and measuring instruments becomes very important. It is highly challenging to model the exact gravitational potential of a planet. This is because various aspects need to be taken into account, such as rotation, mass distribution and atmosphere. In addition, scientists need to figure out how time dilation influences different altitudes or orbital positions. Besides that, our knowledge of physics might have to be changed for areas with extreme gravitational fields. For example, near black holes or neutron stars. It is difficult to verify experiments in those kinds of strong-field environments. Finally, the effort to create universal and at the same time flexible reference systems, which will allow implementation of time dilation corrections in different planetary environments, is still going on (NASA GSFC, 2023).

To conclude, the investigation of how gravity influences the flow of time is a great example of how theoretical physics is interconnected with practical technology and exploration. Research has highlighted that time is not a fixed and universal measure. It is closely related to space, mass and motion. Knowing about gravitational time dilation and realising that it is different from one planet to another, is the key to future space missions, inventions and even our deeper understanding of the universe (NASA GSFC, 2023).

In Section 2 of this research paper, a comprehensive literature review is carried out. It outlines experimental evidence for gravitational time dilation, and exoplanet case studies will be examined. Section 3 discusses the methodology regarding the quantitative analysis and relevant physical assumptions. In Section 4, the results of this analysis are presented. In section 5, conclusions are drawn in connection to theoretical development of space time using time dilation.

2 Literature Review

2.1 The Significance of Research about Gravitational Time Dilation

Comparing gravitational time dilation across exoplanets, stars and highly compact objects aids in demonstrating how relativity operates at vastly different mass and density scales. Gravitational time dilation is an effect which results from Einstein’s General Theory of Relativity. According to his theory, time slows down in strong gravitational fields. That is where spacetime is more curved due to gravity (NASA, 2020). This is because mass and energy curve spacetime’s geometry in the process. The time that goes by is different depending on where the observer is in relation to the gravitational field (Misner et al., 2023; NASA; n.d). Since then, scientists have employed gravitational time dilation to investigate how time behaves in the vicinity of cosmic bodies, such as exoplanets and stars, and compact objects, such as neutron stars and black holes (ESA, n.d).

The first evidence of the effect was demonstrated in an experiment by Pound and Rebka in 1959. They measured the gravitational redshift of gamma rays over a 22.5-meter height in Harvard University. The results of the experiments that they performed were consistent with Einstein's assertion that photons lose energy when they are against gravity. Thus, they directly verified that time is slower in the regions of higher gravitational fields (Pound & Rebka, 1959; Harvard Gazette, 1996). Followed by this, Hafele and Keating (1971) furthered this proof by taking atomic clocks aboard commercial airplanes on a trip around the globe. They discovered that the clocks on the planes showed different times than the ones on the ground, and the difference was exactly what relativity had predicted. In this way, the researchers confirmed that time dilation can be caused by speed and gravity (Hafele and Keating 1972; U.S. Naval Observatory, 2021).

Currently, engineers make corrections for gravitational time dilation as part of their normal work for the Global Positioning System (GPS). Since the satellites are in a weaker gravitational field, their clocks are ticking faster compared to the ones that are on Earth. They make relativistic corrections of around 45 microseconds per day to keep the GPS accurate. This is an example of Einstein's theory being applied in the real world (Ashby, 2003). Moreover, astronomical research has been a source of evidence for the concept through the detection of gravitational redshift near compact cosmic entities. Walter Adams was the first person to detect such an effect in 1925, by the redshifted spectra of Sirius B. This was the first physical confirmation of relativity's forecasts in the gravitational field of a white dwarf (JB Holberg, 2010). The most recent evidence is from the area around the supermassive black hole Sagittarius A*. The star S2 changes its speed, and the light coming from it gets altered during its closest orbit to the black hole. This is evidence that spacetime is bending in an extremely strong gravitational field (Abuter et al., 2018).

2.2 Exoplanetary Systems and Host Stars

The first exoplanetary system under review is Proxima Centauri b. It orbits the red dwarf Proxima Centauri about 4.24 light-years from Earth (NASA Exoplanet Archive, 2012). It was discovered in 2016 by using the HARPS spectrograph from the European Southern Observatory. It is the closest known exoplanet to our Solar System (Anglada-Escudé et al., n.d). The planet has a minimum mass of roughly 1.07 times that of Earth and lies within the star's habitable zone, with an orbital period of 11.2 days (NASA, n.d).

Formation models propose that Proxima Centauri b likely formed from the protoplanetary disk of its M-type star through core accretion and later migrated due to stellar tidal forces (Dressing & Charbonneau, n.d). The host star is a small M5.5V red dwarf, with only 12% of the Sun's mass. It frequently emits X-ray and ultraviolet flares that can strip planetary atmospheres (France et al., n.d; NASA, 2004). Since Proxima Centauri b orbits at just 0.048 AU, its surface experiences much higher gravitational potential concerning the star's mass. As a result, there is measurable though still tiny gravitational time dilation compared to Earth's surface (NASA, n.d). Time runs imperceptibly - more slowly on Proxima Centauri b compared to Earth. This illustrates that gravitational time dilation serves as a good means for measuring time differences between planetary environments.

The second exoplanetary system studied - TRAPPIST-1 e, orbits the ultra-cool M8V dwarf TRAPPIST-1, 39.5 light-years away in Aquarius (NASA, 2013). It was found by the Transiting Planets and Planetesimals Small Telescope. The TRAPPIST-1 system hosts seven Earth-sized planets, four of them either within or close to the habitable zone (Gillon et al., 1956). TRAPPIST-1 e has a radius of 0.92 $R_\oplus$ and a mass of 0.692 $M_\oplus$ in an orbit at 0.029 AU. This architecture provides an equilibrium temperature that could support liquid water if the atmosphere is appropriate (Agol & Mangel, 2011). Planetary formation models demonstrate that the planets formed through pebble accretion within the inner disk, and then possibly migrated closer to the star as the disk dissipated (Luger et al. 1997).

Pebble accretion is the accumulation of particles. It ranges from centimeters up to meters in diameter. This is into planetesimals in a protoplanetary disk that is enhanced by aerodynamic drag from the gas present in the disk. This drag reduces the relative velocity of pebbles as they pass by larger bodies, preventing some from escaping the body's gravity. Low brightness and dense gravitational potential of the host star mean that stronger spacetime curvatures occur closer to the surface of such stars compared to the Sun (Ames, 1939). In this respect, more significant gravitationally induced time dilation is expected for closely bounded star-planet systems, where the time difference grows by closer orbits. Though small, such relativistic effects could also be gauged through relativistic potential equations. These confirm that gravitationally induced time dilation is a constant physical metric for star-planet systems.

Kepler-186 f is the first Earth-sized planet discovered within the habitable zone of a star, found by NASA's Kepler mission in 2014 (NASA, 2014). Kepler-186 f orbits its host, a K-type main-sequence star at 492 light-years from Earth, with an orbital period of about 129.9 days (Quintana et al., 1998). Kepler-186 f has a radius of 1.17 $R_\oplus$ and is likely rocky (NASA Exoplanet Archive, 2015). Its formation follows conventional protoplanetary accretion models wherein dust and planetesimals merged in the inner disk of the host star (Burke et al., 2013). Its host, Kepler-186, has a mass of 0.54 $M_\odot$ with a surface gravity lower than the Sun. Thus, it presents moderate gravitational curvature. Time dilation at the stellar surface and on Kepler-186 f's orbit is correspondingly weak compared to M-type systems, yet it can still be detected by using relativistic equations (NASA Goddard, n.d). Predictability of such effects supports that gravitational time dilation is superior in computing time differences. This is because it will come directly from the spacetime metrics rather than through observational estimates.

The fourth case is LHS 1140 b, in orbit around an M-dwarf star which is 49 light-years away in the constellation of Cetus. In 2017, the MEarth Project discovered a super-Earth with a mass of 6.6 $M_\oplus$ and a radius of 1.73 $R_\oplus$. It orbits its star every 24.7 days at 0.0936 AU from it (Dittmann et al., 2022). Observations with the Hubble and JWST telescopes display a possible water-rich atmosphere (NASA JPL, n.d). Its host star is an M4.5V dwarf that presents extreme stable brightness and low flare activity compared to other M stars. This constitutes a relatively stable gravitational environment (Kane et al., 1994).

Due to its larger planetary mass and closer orbital radius, LHS 1140 b experiences slightly stronger relativistic time dilation than Earth. This may impact internal geophysical processes, such as the rate of mantle convection, over cosmic time frames (NASA Exoplanet Science Institute, 2020). In all these systems, gravitational time dilation has remained the preferred metric. This is due to the fact that it is derived from the curvature of spacetime and is invariant from local chemical or orbital conditions.

2.3 Compact Objects and Relativistic Comparison

In contrast to exoplanets and regular stars, compact objects, such as neutron stars and black holes, have extreme gravitational potentials that strongly enhance time dilation effects. A neutron star, typically with 1.4 $M_\odot$ compressed into a radius of about 10 kilometers, generates surface gravitational fields exceeding 10^{11} times that of Earth (NASA, 2011). Under these conditions, time dilation becomes huge: a clock on the surface of a neutron star would tick much more slowly than one well outside, resulting in measurable redshifts for radiation emitted from the surface of a neutron star (Özel & Freire, 2012). This provides direct experimental confirmation of the general relativistic prediction that time slows under strong gravity and helps confirm the theory's relevance across astrophysical scales.

Consequently, black holes provide the most extreme gravitational time dilation. This is where their event horizon and the curvature of spacetime reaches infinity. For a faraway observer, time practically comes to a standstill (NASA, 2023). This effect has been continuously verified by simulations and through spectral analysis of matter falling into black holes (Teukolsky, 1979). For this purpose, the super-massive black hole Sagittarius A* located at the galactic center, with a mass of 4.3×10^6 M⊙, offers realistic means of measuring such effects through its orbiting stars. Their motion illustrates relativistic time dilation (Gravity Collaboration et al., 2018). These measurements have made clear the fact that gravitational time dilation is not a purely theoretical concept. It is rather one that can be measured in extreme astrophysical environments.

In comparison, exoplanets, such as Proxima Centauri b or LHS 1140 b, are expected to exhibit time dilation that is millions of times weaker than these compact objects. Yet the same relativistic equations describe both cases (NASA, 1919). This universality reinforces gravitational time dilation as the most dependable paradigm for assessing the flow of time in diverse gravitational settings. Though other yardsticks, such as orbital mechanics or thermodynamic timescales, may be used to estimate relative durations. None of them are intrinsically linked with the geometry of spacetime like gravitational time dilation (Misner, et al., 1973). Nonetheless, modeling gravitational time dilation is problematic due to the uncertainties of measuring exoplanet and star mass, radius and density (NASA Exoplanet Archive, 2024). Due to observational limits, particularly for far-away systems, such as Kepler-186 f, there are errors in the relativistic potential of similar magnitude that will carry over into the calculations (Tarter et al., 2007). In addition, magnetic fields, stellar rotation and frame-dragging effects introduce small corrections to local spacetime curvature. Thus, affecting the evaluation of time rates. Frame dragging is an astrophysical phenomenon that is predicted by Einstein's theory of general relativity, where a massive rotating object ‘drags’ the fabric of spacetime around it (Lense & Thirring, 1918).

The values should be improved by missions, such as the James Webb Space Telescope and PLATO through stellar parameter refinement, and relativistic modeling by using general and special relativity combined in multi-body simulations (ESA, 2023; NASA, 2024). Through these means, time differences between planetary surfaces and interstellar reference frames will be calculated more exactly. Additionally, theoretical development proceeds in the analysis of time dilation in close proximity to compact objects. Quantum gravitational effects may even alter the expected behaviour of time near singularities (Hossenfelder, 2018). Increased observational sensitivity from the Event Horizon Telescope, supplemented by new X-ray facilities, such as Athena, will further firm up the empirical grounding of gravitational time dilation tests around the boundaries of existing knowledge. These, when put together with the study of exoplanets, may point toward the unification of a relativistic model that defines the time evolution at every mass-density scale of celestial bodies (ESA, 2023).

2 Methodology

This research, in the realm of time dilation as induced by gravity, undertakes theoretical and analytical research based on the basic concepts of General Relativity. The analysis is based on the Schwarzschild solution of Einstein's field equations that describes the geometry of spacetime surrounding a spherically symmetric, non-rotating mass. From this model, the research paper will take into consideration how time changes with distance from massive objects, such as planets, stars and compact remnants. This section undertakes to explain the scientific background, mathematical foundation, assumptions made and the computational process towards the quantification of the time dilation effect.

3.1 Theoretical Framework

Gravitational time dilation is a consequence of the General Theory of Relativity. This theory posits that gravity is not a force across a distance. It is a consequence of the geometry in spacetime wrought by mass and energy. In essence, what this theory says is that time does not flow consistently between different gravitational potentials. The bigger the gravitational field, the more spacetime bends, and time moves more slowly compared to an observer who is further away from the source of gravity.

This is done through the relation obtained from the Schwarzschild metric, which describes the spacetime geometry outside a spherical, non-rotating mass. The mathematical relation between proper and coordinate time can be stated as:

$$t' = t\sqrt{1 - \frac{2GM}{rc^2}}. \qquad (1)$$

In this equation, proper time t′ is the time measured close to the massive body, and coordinate time t is the time measured far from the mass, where the gravitational effects can be considered to be negligible. The gravitational constant, G, is $6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$ and the speed of light, c, is $3 \times 10^8 ms^{-1}$. These are the constants to be used when describing the effect of gravitational potential upon time.

3.2 Conceptual and Physical Assumptions

To make the analysis easier, a few assumptions are made. First, the mass is taken to be perfectly spherical and non-rotating, for which no additional effects, such as frame-dragging or distortions due to angular momentum would arise. This assumption again justifies the use of Schwarzschild geometry in such configurations. Secondly, it is assumed that all observations are performed outside the physical surface of the mass to avoid areas of infinite curvature or singularities.

This simplification is justified by two well-known theorems - both of which are equally valid in both classical and relativistic physics. For Newtonian gravity, it is Newton's Shell Theorem that states a spherically symmetric object acts on external objects as though all of its mass were concentrated at the center. General Relativity, which is extended by Birkhoff's Theorem, states that any spherically symmetric solution of the vacuum field equations must be stationary and be the Schwarzschild solution. Together, these considerations justify treating a star, planet or other spherical body for calculating gravitational time dilation, as if it were a point mass at the center.

3.3 Parameters and Definitions

In equation (1), M is the total mass of an object that acts as the source of a gravitational field, and r stands for radial distance from its center. If this distance becomes very large, the fraction with the gravitational constant and mass becomes much smaller. Hence the expression inside the square root approaches one. This is to say that a faraway observer who perceives almost zero gravity sees no effect of time dilation whatsoever. In saying that, if this observer comes closer to the mass, the expression inside the square root diminishes. This means that their clock runs slower compared to the one at a large distance.

An important value here is the Schwarzschild radius. This radius denotes the distance from the center of the mass at which, for a theoretical observer who is closer to the mass, time would appear to stop, or more precisely - proper time will approach zero. This means that at this radius, the boundary of a black hole is reached. Therefore, beyond which nothing, not even light, can escape the gravitational field. This can be found by setting the term inside the square root to zero, resulting in the Schwarzschild radius:

$$r_{Schwarzschild} = \frac{2GM}{c^2}\,. \qquad (2)$$

For the Sun, this radius is roughly three kilometers, compared to its photospheric radius of seven hundred thousand kilometers. This demonstrates that the Sun's gravitational field is too weak. This means it is not dense enough to form a black hole.

3.4 Analytical and Computational Procedure

This method includes the time dilation factor calculation for different types of astrophysical objects at several distances from their centers. The examples below use standard values for mass and radius: the Earth's mass is 6×10^{24} kg and the radius of 6400 km. Whereas the Sun's mass is 2×10^{30} kg. For compact objects, such as white dwarfs, neutron stars and black holes, the radius is much smaller and the mass much larger. Thus, resulting in a far stronger gravitational time dilation.

Another way accuracy is attained is through the use of both exact and approximate methods. For those areas where the gravitational field is weak, for example near the surface of Earth or other planets, a linear approximation can be used to simplify the calculations. This approximation is based on the assumption that the factor containing the gravitational constant, and mass is sufficiently small that the square root may be expanded as a simple subtraction. However, in regions where a stronger gravitational field exists, such as near neutron stars and black holes-full, exact relationships must be employed. This is because approximation would introduce significant errors.

A large dataset of exoplanets and their host stars was taken from the NASA Exoplanet Archive (NASA Exoplanet Archive, 2023). Prior to analysis, this dataset was cleaned in the following manner: all observed exoplanets (approximately 30,000 listed in the table) with some missing data have been removed and duplicate rows for multiple measurements of the same planet have been removed. The 1st entry for each unique planet being kept. This has resulted in a final collection of 1,288 exoplanets with measurements of mass and radius, and their host stars' masses and orbital distances. The results of this analysis are presented in Section 4.

3.5 Uncertainties and Limitations

All the physical quantities that enter the calculation, such as mass, radius and gravitational constant, have some associated uncertainty. These are propagated through the calculation to provide an estimate of possible errors in the final time-dilation factor. As the gravitational constant and the speed of light are by now very well-established and accurately measured values, the largest uncertainty usually comes from the estimated mass, or radius of the celestial object under study. This methodology only considers gravitational effects.

Other relativistic effects of motion, such as kinematic time dilation, due to Special Relativity are excluded. In addition, rotational and magnetic field effects are ignored, since these would require a more complicated metric than considered here. It is known as the Kerr solution and is beyond the scope of the present study.

3.6 Summary of Methodological Approach

In general, the theoretical setting of this paper is based on the theory of General Relativity by Einstein, while the Schwarzschild solution has been applied to quantify time dilation near huge masses. Comparing different masses and distances in such an analysis increases the level of understanding of the relation of gravitational strength to the rate at which time flows. In addition, the use of Newton's Shell Theorem and Birkhoff's Theorem has ensured that the model remains physically valid for all spherical objects. In extreme cases, such as black holes, a natural limit was provided by the Schwarzschild radius, where time in effect stops in the frame of a distant observer.

The systematic calculations and assumptions give a coherent physics-based methodology for describing how gravity can change time. These results provide the basis for a discussion of the implications, and interpretation of gravitational time dilation effects in a wide variety of astrophysical environments.

4 Findings and Discussions

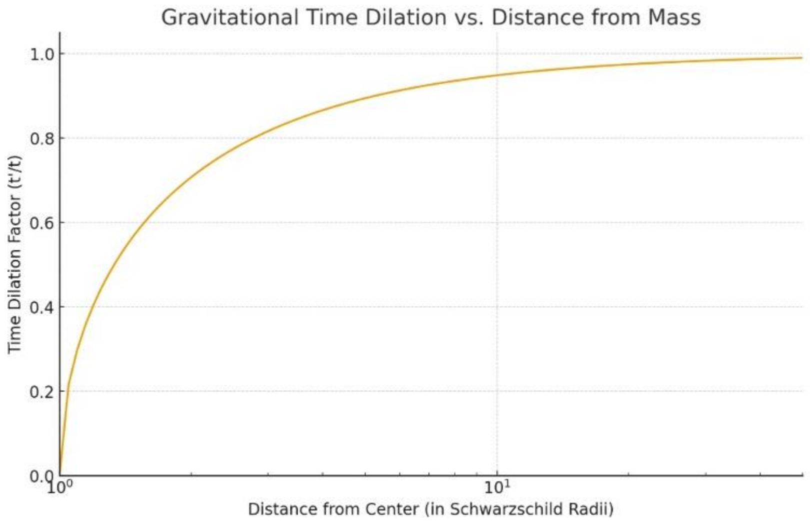

Figure 1 — Distance from a mass, in Schwarzschild radii, vs. gravitational time dilation factor (t'/t). When a distance of one Schwarzschild radius is reached, time appears to stop to an external observer, i.e. $t'/t \to 0$.

Fig. 1 demonstrates how gravitational time dilation depends on the distance from a celestial body in units of the Schwarzschild radius. Note that we can combine equations (1) and (2) to re-express the gravitational time dilation factor as:

$$t' = t\sqrt{1 - \frac{r_{Schwarzschild}}{r}}. \qquad (3)$$

This relation is directly plotted in Fig. 1. The closer you get to a massive object, the more spacetime curves. This causes time to pass slower compared to what a distant observer would experience. This result shows that according to Einstein's general theory of relativity, time dilation is more significant if close to a dense and compact mass. This effect is exaggerated in proximity to the event horizon of a black hole (ESA, 2019; NASA GSFC 2023).

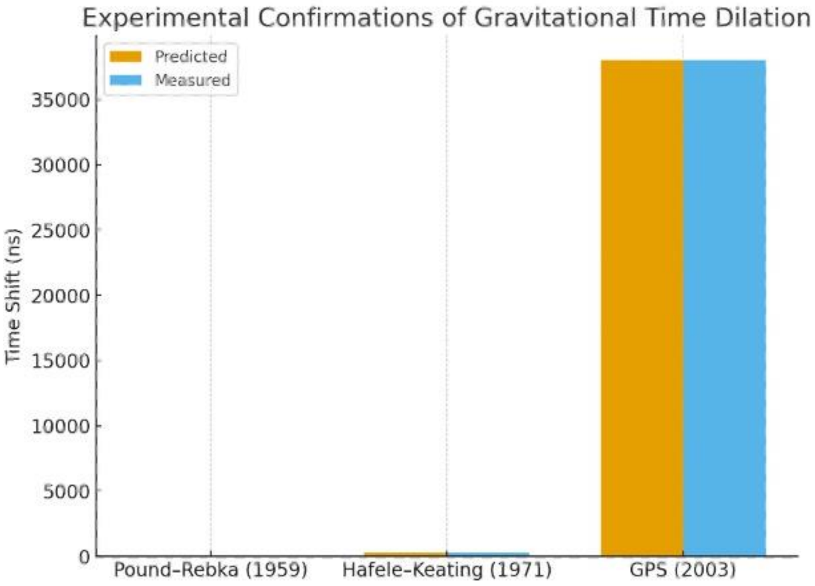

Figure 2 — Experimental confirmations of gravitational time dilation, details of which are given in the text.

Fig. 2 represents some of the most renowned experiments in history that have dealt with time rationing between theory and practice are represented by the figure below. The Pound-Rebka experiment in 1959 measured the gravitational redshift of photons on Earth. The Hafele-Keating experiment in 1971 confirmed time differences using atomic clocks on airplanes. Presently, GPS satellites have to continually adjust for relativistic effects to maintain accuracy. These results together present a suite of tests that confirm Einstein's predictions under both ground and space conditions (Pound & Rebka, 1959; Hafele and Keating 1972; Ashby, 2003).

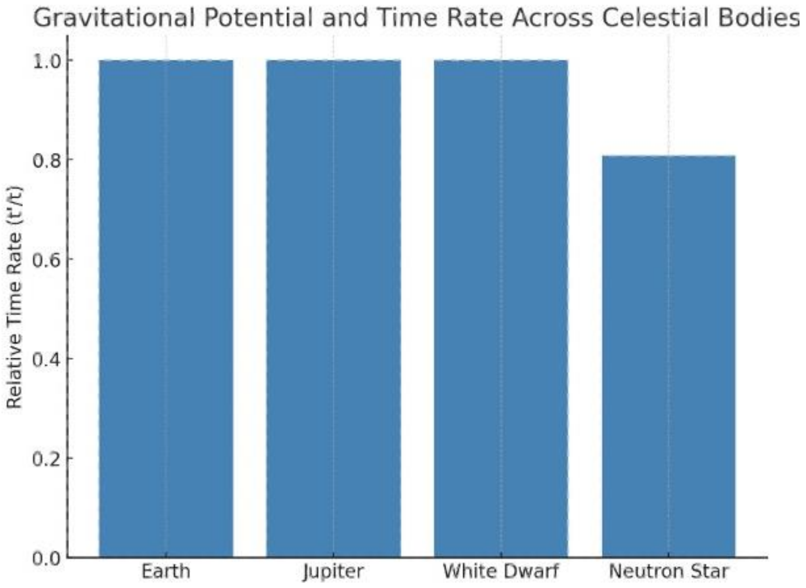

Figure 3 — Time dilation effect across celestial bodies, as calculated from equation (1).

Fig. 3 is a comparison of the impact of gravitational potential on time rates of various celestial bodies. In general, objects with higher mass and density, such as a white dwarf, a neutron star, or a black hole, have deeper gravitational wells. Therefore, time is slowed down a lot compared to the Earth or Jupiter. This figure goes a step further to show that compactness is what contributes most to the huge time dilation effect, not just the mass (Misner et al., 1973; NASA GSFC, 2023; ESA, 2023). The strong time dilation effect for the neutron star stresses that incorporating a full general relativistic treatment is necessary when analysing their properties.

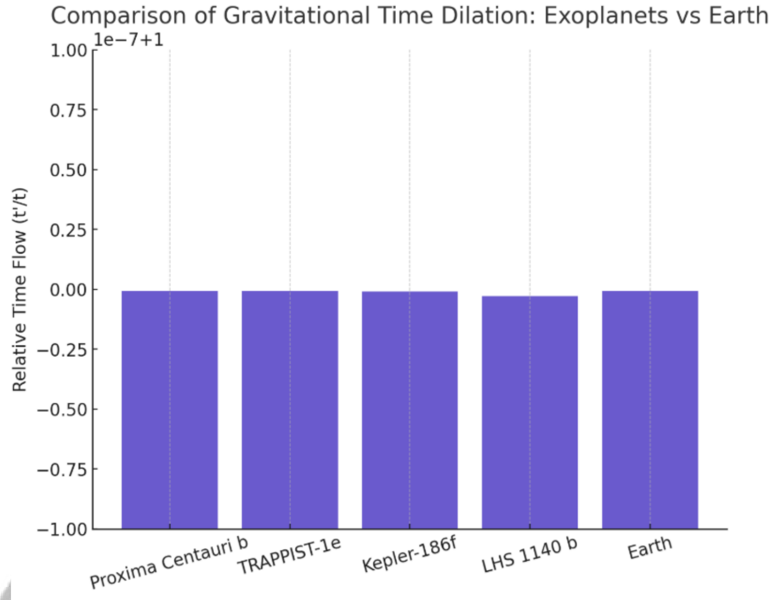

Figure 4 — Comparison of gravitational time dilation: exoplanets vs. Earth.

Fig. 4 shows time flowing relative to the exoplanets mentioned in the article: Proxima Centauri b, TRAPPIST-1e, Kepler-186f and LHS 1140 b, in comparison to the Earth. The differences stem from the variations of the planets' masses and radii, which change the local gravitational potential. Although time dilation differences are minuscule, they demonstrate that gravity would still have a minor influence on timekeeping and the harmony of any future missions, or colonies on these planets (NASA Exoplanet Archive, 2023; ESA, 2023).

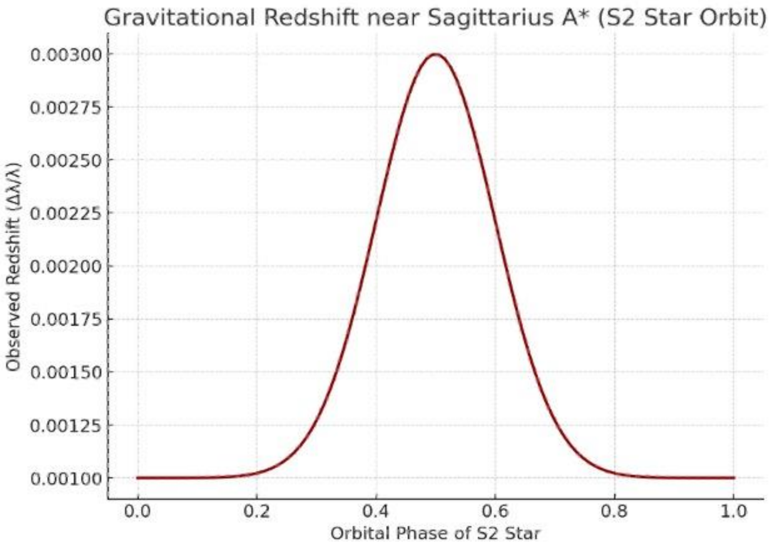

Figure 5 — Gravitational redshift observed near Sagittarius A* as the star S2 made a close orbit around the supermassive black hole.

Fig. 5 shows the gravitational redshift that was observed for the S2 star as it made a close approach around the supermassive black hole Sagittarius A* at the center of the Milky Way. When the star moves to its closest approach, the light coming from it gets redshifted more and more. Thereby, providing direct evidence for gravitational time dilation and spacetime curvature in a strong-field regime. The observations constitute one of the most exacting tests of general relativity in the vicinity of a black hole (Gravity Collaboration et al., 2018; ESO, 2018).

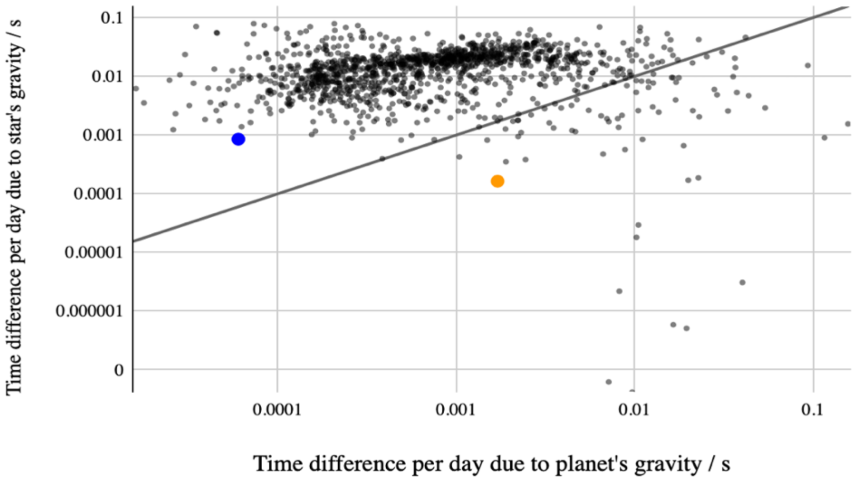

Figure 6 – Comparison of the effects of gravitational time dilation from a selection of exoplanets (on their surface) and from their host stars (at the exoplanets' orbital distances). The grey diagonal line indicates equally strong effects from the planet and host star. A sample of 1,288 exoplanets have been analysed from the NASA Exoplanet Archive and values for Earth are displayed in blue and those for Jupiter in orange.

Fig. 6 underlines a comparison of gravitational time dilation which is caused by exoplanets themselves and by their host stars at the planets' orbital distances, using data from 1,288 exoplanets. Each orange point represents one planet - with the x-axis showing the time difference per day due to the planet's gravity, and the y-axis showing the time difference per day due to the star's gravity. The diagonal grey line indicates where both effects would be equal. Most points lie above this line, showing that for most exoplanets, the star's gravitational influence on time dilation is stronger than that of the planet. This indicates that the star's gravitational potential dominates the curvature of spacetime at the planet's orbit, producing the larger share of the total time-dilation effect. For the planet, this means its own gravitational contribution is comparatively minor. Thus, becoming significant only for the most massive or extremely compact worlds.

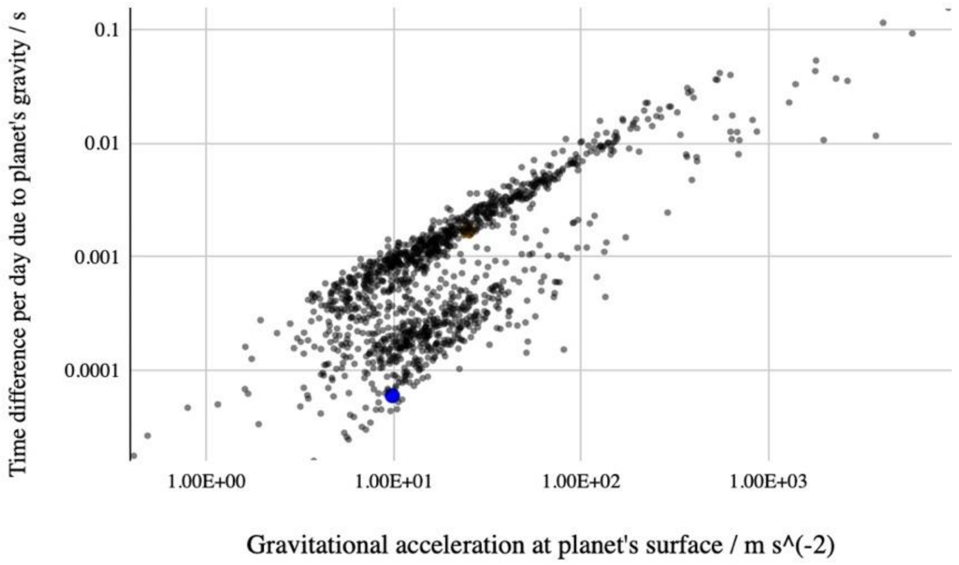

Figure 7 – Gravitational time dilation effect from a selection of exoplanets compared to their surface gravity. Earth and Jupiter are plotted using the same colours as in Fig. 6. Note the bimodality in the exoplanet distribution, with gas giants and rocky planets forming two distinct regions. This indicates that planets with stronger surface gravity experience a deeper gravitational potential, leading to greater daily time-dilation shifts. It shows that relativistic effects scale directly with the planet's compactness.

Fig. 7 demonstrates how gravitational time dilation varies with surface gravitational acceleration across a diverse range of confirmed exoplanets. The data stresses a notable positive correlation: increased surface gravity leads to greater daily time-dilation differences. Therefore, it aligns with the relativistic relationship to gravitational potential. The positive correlation means that as surface gravity increases, relativistic time dilation strengthens accordingly. This relationship causes clocks on high-gravity planets to run noticeably slower than those on low-gravity ones. Two main groupings are observable, representing low-density gas giants and higher-density terrestrial planets. This reflects their unique mass–radius relationships. Earth and Jupiter are included for comparison, maintaining the same color scheme from previous figures, and are positioned in line with their respective types. The upper edge of the distribution is influenced by the density of massive close-in exoplanets. It illustrates that even slight changes in radius can significantly enhance relativistic effects. This results in measurable differences in the passage of time across exoplanets, with dense or compact worlds exhibiting the strongest relativistic slow-down. It pinpoints surface gravity as a key driver of planetary time-dilation effects.

For a planet of mass M and radius R, its surface gravitational acceleration can be approximated as:

$$g_{surface} = \frac{GM}{R^2}. \qquad (4)$$

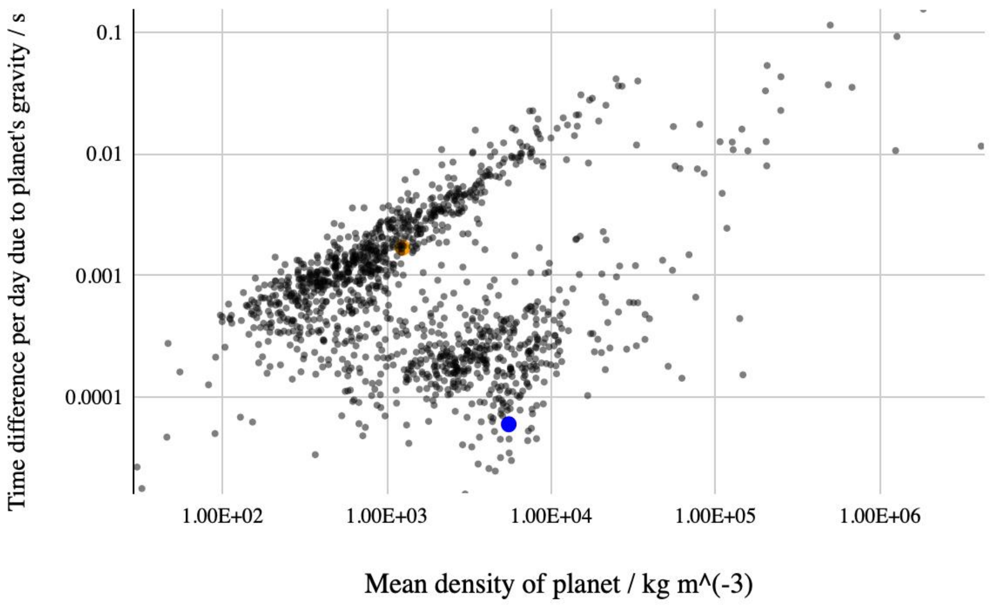

Figure 8 – Gravitational time dilation effect from a selection of exoplanets compared to their mean density. Earth and Jupiter are plotted using the same colours as in Fig. 6. Note the bimodality in the exoplanet distribution, with gas giants and rocky planets forming two distinct regions.

Fig. 8 shows how gravitational time dilation changes among a selection of confirmed exoplanets based on their average density. The graph demonstrates a clear split: low-density gas giants occupy one area, while higher-density terrestrial planets occupy another. This split results from the different mass-radius relationships of these two groups, which follow distinct mass – radius relationships: gas giants gain mass without substantial decreases in radius. On the other hand, terrestrial planets become markedly smaller as density increases. These contrasting trends produce the clear separation in gravitational potential, and therefore in time-dilation strength.

The amount of time dilation grows as density increases. This reflects the stronger gravitational fields that are found in more compact planetary interiors. Earth and Jupiter, illustrated with the same color scheme as in Figure 6, fall within their respective population branches. They serve as reference points for understanding the wider distribution of exoplanets. The segment with higher density highlights ultra-dense super-Earths and transitional high-gravity planets, where the importance of relativistic effects is increasing. This leads to systematically stronger relativistic time-dilation in the high-density branch, where compact planets generate much deeper gravitational wells. As a result, ultra-dense super-Earths and transitional high-gravity planets exhibit noticeably amplified relativistic effects.

For a planet of mass M and radius R, its mean density can be approximated as:

$$\bar{\rho} = \frac{M}{V} = \frac{M}{\frac{4}{3}\pi R^3}. \qquad (5)$$

This assumes spherical symmetry, a reasonable assumption for this analysis.

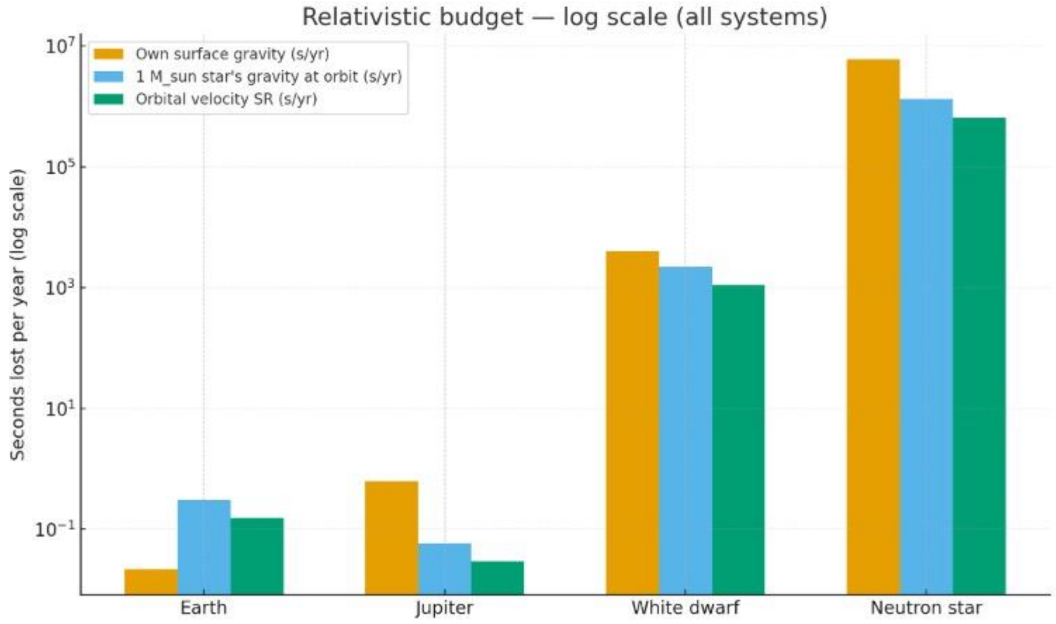

Figure 9 – Relativistic budget for selected astrophysical bodies, showing annual time lost due to surface gravity, stellar gravitational potential at orbit, and orbital special-relativistic effects.

Fig. 9 illustrates the annual contributions to time dilation for Earth, Jupiter, a typical white dwarf, and a neutron star. These contributions are categorised into the surface gravitational potential, the gravitational potential from the star at orbital distance, and orbital special-relativistic effects. They are all presented on a logarithmic scale. As these astrophysical objects orbit their host/companion star, their orbital speeds can be sufficiently large to induce another time dilation effect from special relativity as compared to a stationary observer. (NASA, 2011; Özel & Freire, 2012) The orbits can be approximated as circular and estimate the orbital speeds as

$$v_{circ} = \sqrt{\frac{GM}{R}}. \quad (6)$$

Here, M is the total mass of the orbital system and R is the separation between the orbiting components. Then, we can input this calculated speed into the special relativistic time dilation formula that is given below. Next, compute time losses as before:

$$t' = \frac{t}{\sqrt{1 - \frac{v^2{}_{circ}}{c^2}}}. \quad (7)$$

The planetary cases show annual offsets that are less than one second, with the gravitational influence of the host star being the primary factor. White dwarfs exhibit time-dilation effects that are several orders of magnitude greater, mainly due to their significant surface gravity. Neutron stars enter a highly relativistic phase, where all three components surpass 10^5 s yr^{-1}, with surface gravity being the overwhelming factor. This scaling highlights the rapid and nonlinear enhancement of relativistic effects as compactness increases. Therefore, underscoring the importance of employing a comprehensive relativistic approach in the modeling of compact objects (Adams, 1925; JB Holberg, 2010).

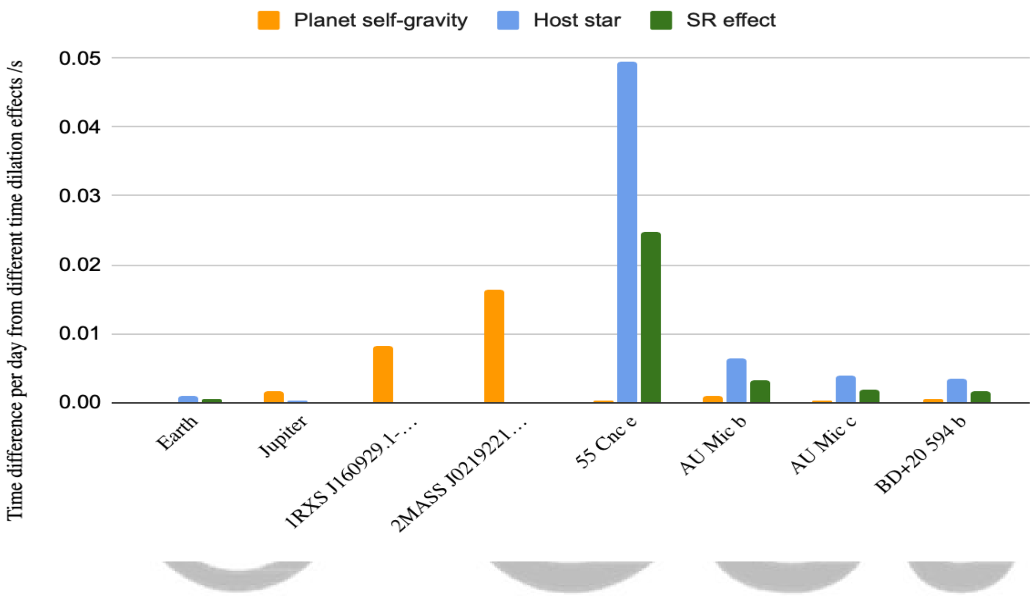

Figure 10 – Relativistic budget for selected exoplanets, showing annual time lost due to surface gravity, stellar gravitational potential at orbit, and orbital special-relativistic effects. The data has been processed identically to that of Figure 9. Additionally, comparisons to Earth and Jupiter have been presented.

Fig 10 represents the overall relativistic impact on selected exoplanets, with Earth and Jupiter shown for comparison. It details the daily time lost due to the planets' self-gravity, the star's gravitational effects, and special relativistic influences from their orbital motions. The graph highlights that planets in close orbit, especially 55 Cnc e, experience much greater contributions from both stellar and special relativistic factors compared to Earth or Jupiter. In contrast, systems like AU Mic and BD+20 594 show moderate, yet noticeable effects. This supports the earlier conclusion that the level of relativistic time dilation varies widely among different planetary systems and is particularly strong for exoplanets in tight orbits.

5 Conclusion

The idea of gravitational time dilation is one of the most influential discoveries in modern physics. From its theoretical elaboration in 1916 to the verification done through careful experiments and astronomical observations, it reflects the mix of mathematical beauty that relativity represents with empirical reality. Einstein's General Theory of Relativity revolutionised our understanding of gravity: not as a force, but as the bending of space and time due to mass and energy. It followed from this that time would flow differently according to gravitational potential (Carroll, 2019).

The first observational hint came at the beginning of the twentieth century when Adams (1925) detected the gravitational redshift of light from Sirius B, which is a white dwarf star. In this way, it was shown for the first time that light loses energy and time runs more slowly in strong gravitational fields. However, only in 1959 did scientists confirm this effect on Earth. Pound and Rebka conducted an important experiment with gamma rays at Harvard University, measuring the gravitational redshift over a vertical distance of 22.5 meters. Their findings tallied with Einstein's prediction exactly, and underlined that even near the surface of Earth, time itself is measurably affected by gravity (Pound & Rebka, 1959).

The experiment's accuracy improved significantly in the succeeding decades. In 1972, Hafele and Keating flew atomic clocks on scheduled airliners and compared times with ground-based stationary clocks. The results highlighted that the differences were consistent with what both special and general relativity predict: clocks run a bit faster at higher altitudes. These experiments validated that gravitational time dilation is measurable and not simply theoretical (Hafele & Keating, 1972; U.S. Naval Observatory, 2023).

By the late twentieth century, Einstein's theory became integral to practical technology. The Global Positioning System relies on time corrections for both gravitational and speed-related effects. Satellites in orbit experience weaker gravity, causing them to tick faster compared with ground-based clocks. Without these adjustments according to relativity, positional errors would add up to almost ten kilometers a day. Some examples include - Ashby, 2003; NASA JPL, 2024. The ongoing precision of GPS serves to illustrate that relativity affects cosmic scales and our daily lives.

Over the last several decades, experiments have become increasingly precise. Advances in atomic clock technology, particularly at the NIST, allow the measurement of time differences for changes in height of less than a meter. Results confirm that gravitational time dilation is happening continuously and predictably, even with tiny changes in potential (NIST 2022). The consistency of these results with those specified by Einstein underlines how impressively exact general relativity and modern timekeeping are.

On an astronomical scale, gravitational time dilation is observed in regions dominated by large masses and densities. The observation of compact objects, such as white dwarfs, neutron stars and black holes highlighted that gravity can bend both light and time. The 2018 GRAVITY Collaboration observations of the star S2 orbiting the supermassive black hole in the Galactic Center provided direct evidence for the relativistic redshift near the event horizon, as predicted by the Schwarzschild metric. These findings were enabled by missions from ESA and NASA and prove once more that Einstein's equations are still valid under very strong gravitational conditions. The same dynamical principles apply, albeit on a much-reduced scale, in planetary and exoplanetary contexts.

Planets around massive stars have reduced proper time compared to distant observers. These latter differences pile up at a rate of only microseconds per year. In saying that, they are nonetheless measurable with appropriate relativistic modeling. With JWST and PLATO, respectively, astrophysicists are now able to fold relativistic corrections into orbit and atmosphere data. Therefore, applying Einstein's framework to far worlds beyond those in the Solar System. Regarding compact objects, such as neutron stars, the curvature of spacetime becomes so strong that time slows down considerably. Theoretical models by Misner, Thorne and Wheeler (1973) and Wald (1984) illustrate that time for an object falling into a black hole stands still near the event horizon of such a black hole. Relativistic effects follow in the matter and radiation within accretion disks, which are of crucial importance to understand high-energy phenomena in astrophysics. From Einstein's original equations through the sub-meter accuracy of today's atomic clocks, the confirmation of gravitational time dilation represents one hundred years of intellectual and experimental work.

It reaches from the smallest measurements of the lab to the very largest in the universe in a demonstration that time is inextricably linked with the geometry of the universe. To conclude, a combination of theory and evidence has transformed our understanding of physics and technology, underlining how important relativity is in terms of exploring and measuring the universe. Finally, gravitational time dilation is much more than a scientific curiosity. It speaks volumes about deep links between matter, energy and time itself. From Adams's early study of Sirius B, the findings by the GRAVITY Collaboration on black holes, to the continuous accuracy of satellite systems, each represents a basic truth. Time is not absolute but comes with a gravity-shaping effect. As tools of measurement and observation continue to increase, studying time dilation will be important for the understanding of spacetime and the structure of our universe.

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