Resolving an incongruity in the equivalence principle: revisiting the foundations of gravity

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Abstract

In the context of the equivalence principle, we resolve the lack of full correspondence in the behavior of light paths between accelerating and stationary gravitational frames. As a consequence, we postulate a moving 'Acceleration Field Space' (AFS), complementary to general relativity's metric space. Free-falling objects that are mathematically considered as coming from infinity and travel along geodesics can be regarded as 'stationary' in AFS, while the space itself moves past metric-stationary objects. Light always travels at the vacuum speed $\boldsymbol{c}$ with respect to AFS. Clock recordings for light events are aligned in both the AFS and metric spaces, although spatial distances differ. We demonstrate that AFS behaves as a medium that influences redshift through its acceleration, distinguishing it from the ether concepts of the pre-relativity era. We also show that AFS is independent of arguments relying on the behavior of light. Unlike equal length paths in the metric description, in AFS, upward radial light path distances are greater than downward. We demonstrate that within AFS, gravitational time dilation can be interpreted as equivalent in mechanism to the cosmological redshift effect. This allows AFS to unify two previously distinct phenomena under a single theoretical construct: gravitational redshift, and cosmological redshift. We make a prediction linking black holes, dark matter and all gravitating bodies in the universe, to the density of dark energy. The proposed framework revises our understanding of spacetime structure and provides a single conceptual foundation for all three forms of the equivalence principle. We discuss the theoretical implications and testable predictions of the AFS model. Our results highlight the potential of AFS to enhance the metric space description, providing an intuitive understanding of gravitational phenomena, while remaining consistent with experimental results.

Keywords: general relativity, gravitational time dilation, acceleration field spacetime, light paths, escape velocity, redshift unification

1 Introduction

The description of spacetime encapsulated in Einstein's theory of general relativity (GR), underpins our current understanding of the universe, a four-dimensional deformable continuum in which events are described.

The previous classical view of space and time begins from Aristotle, with refinements by Newton [1, 2], in which space and time were conceptualized as separate, absolute, and unchanging entities. Then in 1908, following the advent of special relativity (SR), which introduced the properties of length contraction and time dilation, Minkowski proposed that space and time be combined into a unified four-dimensional continuum, deformed by the Lorentz transformations [3]. This revolutionary idea actually built on an earlier work by Hamilton in 1843, who suggested that space and time could be combined within his four-dimensional quaternions [4], as well as Poincaré in 1905, who noted that the Lorentz transformations imply a four-dimensional spacetime [5]. Finally, GR developed by Einstein in 1915, extended Minkowski's concept of spacetime by treating it as a curved manifold influenced by the presence of matter and energy. In GR, gravity is not a Newtonian force but a manifestation of the curvature of spacetime, in which particles follow geodesics [6] and has now been extensively confirmed by numerous experiments [7].

In addition, the advent of quantum mechanics led to the proposal of a quantum theory of gravity, in which spacetime is no longer a smooth continuum but a foam-like structure at the smallest scales. This quantum foam is believed to be composed of tiny Planck-scale fluctuations, which give rise to a discrete nature of space and time [8].

Now, in order to introduce our approach, we begin by noting that while GR is fundamentally a coordinate independent theory, several different coordinate systems have been found to improve understanding of the physics. The first solution found to Einstein's field equations were the Schwarzschild coordinates [9]. However, these coordinates have a discontinuity across the event horizon, and so alternate coordinate systems were sought. Then, the Gullstrand-Painlevé coordinates, were independently proposed by Painlevé in 1921 [10] and Gullstrand in 1922 [11], leading to the river model of gravity. This conceptualizes space flowing like a river through a flat background, with objects moving within this space according to special relativity. In a spherical black hole, for example, space falls in at the Newtonian escape velocity, ultimately reaching the speed of light at the horizon. Their key innovation was introducing a cross term that distinguishes these coordinates from standard Schwarzschild coordinates. These coordinates, are not only regular across the horizon but also describe a free-fall inertial observer within flat space. As these coordinates describe an inflow of space at the local escape velocity, they are intuitive for radial timelike geodesics [12]. Later, other coordinates were developed, with various benefits, such as the Eddington–Finkelstein coordinates in 1958 [13, 14], Lemaître coordinates in 1932 [15] and Kruskal–Szekeres coordinates in 1960 [16]. Unruh's 1981 paper [17] introduced analog gravity by mapping black hole event horizons to sonic horizons in fluid flows, establishing a key connection to the river model of gravity, independent of the Gullstrand-Painlevé formulation. More modern interpretations inspired by Unruh were advanced by Hamilton and Lisle [18] and Braeck and Grøn [19], noting that the flowing spacetime perspective naturally aligns with the Gullstrand-Painlevé metric, although treating it more as a pedagogical device, rather than seeing it as a fundamental description. Einstein himself rejected the Gullstrand-Painlevé solution during a 1922 debate at the Collège de France due to controversy over the non-quadratic cross term [20]. Although he initially viewed these terms as problematic, he ultimately regarded the Painlevé and Gullstrand coordinates merely as coordinate changes, perhaps underestimating their possible physical significance. In more recent treatments, Chakrabarti and Soumya [21] go beyond mere pedagogical explanations, generating quantifiable predictions regarding non-singular gravitational collapse. Reviewing the historical development of this approach, it appears that Einstein's initial rejection may have significantly contributed to its slow adoption and lack of development.

This paper differs from the aforementioned approaches, which all extend solutions to Einstein's equations and then draw analogies to known physical quantities such as rivers or sound. Instead, we adopt a first-principles approach grounded in established physics to develop a fundamental model of moving space, placing it on a par with the metric space description of GR. Our approach, founded on the equivalence principle, firstly identifies a lack of full congruence in the behavior of light, when comparing frames under gravity and acceleration. Through resolving this discrepancy, we derive a flowing space model of gravity. Here, gravity is viewed as the inward flow of spacetime, akin to a river sweeping along matter. We find our result also naturally aligns with the Gullstrand–Painlevé coordinates, providing a novel yet clear framework for understanding gravitational phenomena. From the perspective of a free-falling observer, we derive the key principles of general relativity along with some original interpretations and outcomes. We will now endeavor to show that our approach has explanatory power for why inertial and gravitational mass are equal, as well underpinning the equivalence principles, and unifying all forms of redshift.

While this approach may appear somewhat novel, we identify various phenomena where the concept of flowing space is already exploited, such as in cosmological expansion and gravitational frame dragging. Our paper thus takes these applications further by modeling all gravitational effects in terms of a moving space frame. Regarding the property of frame dragging, even though our approach assumes the simplified case of radial geodesic, we note that it has been shown that frame dragging can be modeled with purely radial geodesics provided a twist term is added to the moving space [22]. Hence, the flowing space model with radial geodesics, as developed here, has fundamental validity.

2 Thought experiment one: light behavior

2.1 Inertial observers

Consider an inertial rocket R, in free space away from gravitational sources. It comprises one-way mirrored walls so that observers outside can see what is occurring inside, but inside observers cannot see outside. Let two observers A and B be inside the rocket. Observer A is fixed at the top and B fixed on the floor. Let there also be two outside free float inertial observers C and D, where C is proximal to A and D proximal to B. The observers C and D remain inertial at all times and are used to observe events at A and B inside the rocket. Initially, since the rocket has not accelerated, all observers are stationary with respect to each other and R. A and B use laser light to both synchronize their respective clocks and determine the length of R to be $L = ct$, in accordance with special relativity (SR). This corresponds to the distance between A and B, as well as the external inertial observers C and D. See Fig. 1.

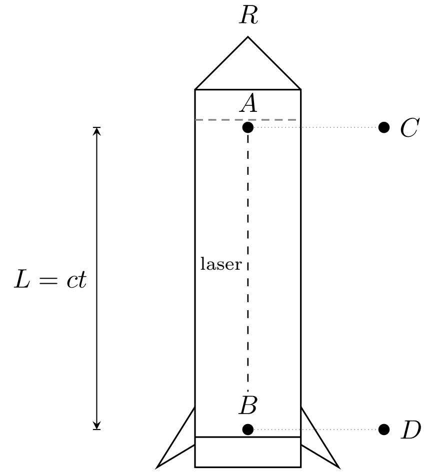

Fig. 1 Inertial rocket R in free space far from gravitational sources. Observers A and B are fixed at the top and floor of R respectively; the external free-float inertial observers C and D are proximal to A and B. The walls of R are one-way mirrored, so C and D can observe events at A and B but not vice versa. Before the rocket accelerates, all observers are mutually at rest, and the length $L = ct$ is determined by A and B via laser synchronisation.

2.2 Internal accelerated observer's A and B's, view

Moments later, setting the time to $t = 0$, R begins uniform acceleration ($v \ll c$) and simultaneously, laser pulses propagate upward from the floor and downward from the ceiling, with the previously synchronized digital clocks at each location recording the arrival times. From standard relativity we know clock A at the ceiling records redshifted light emitted from B (from the rocket floor) and therefore perceives time as running slower on the floor. Likewise, observer B receives blue-shifted light from A and concludes that time at the ceiling runs faster. By invoking the equivalence principle (EP), Einstein then inferred that time will run slower deeper within a gravitational field.

2.3 External frame view C and D and the principle of PLSD

We now ask: what do outside observers C_a and D_a record[1] for the laser light behavior as seen inside the rocket during its acceleration? The inertial observer C_a being external

[1]The addition of a subscript a, simply refers to C and D being in free space observing an accelerating frame. This notation change will be useful later when we switch the observers into the equivalent free fall frame of gravity where we can use the subscript g instead of a.

and adjacent to the rocket's top, acts as a positional marker for where the light pulse originated at A. Now since C_a sees, the rocket's floor upward accelerate towards the downward traveling light, C_a will observe a shortened light length path from the rocket ceiling to the floor by $\frac{1}{2}at^2$. Therefore, C_a will measure a propagation distance $L_d = L - \frac{1}{2}at^2$, where L_d refers to the downward direction. We note that although D_a is at a distance L from C_a, since it is in the same inertial frame as C_a, it will agree with the light length that C_a measures. Similarly, D_a will find the upward light to move a distance of $L_u = L + \frac{1}{2}at^2$, as the ceiling appears to be moving away from the emitted pulses at B, where L_u refers to the upward direction.

We now wish to take special note of these differing length observations between the accelerating frame observers A and B at fixed positions inside the rocket, and the inertial outside observers C_a and D_a. Despite this being straight forward to understand in this acceleration case, let us give this a name: the 'principle of length and space disparities' (PLSD).

2.4 Observer-dependent origins of emitted light

As noted, since A and B remain at fixed and separated positions in the rocket, then A will always record successive light pulses originating from a fixed position. In contrast, while C_a also identifies the first pulse with the same position in space as A, however on account of the rocket moving upward and so away from C_a, C_a will attribute each subsequent pulse to a point progressively different to the original light pulse origin. The same relationship holds between B and D_a. Using C_a and D_a as distinct placeholders for the spatial origin of the light will become important later when we consider the gravitational context.

2.5 Time equivalence

Since the light distances measured by the inertial observers C_a and D_a satisfy $L_d < L_u$, then the floor clock registers a light arrival event before the ceiling clock. Hence we see that while the top and bottom arrival times match the clock times of A and B, the physical explanations are quite different. It follows that A and B interpret the result as differing clock rates, while C_a and D_a interpret this as due to differing light distances. Hence for $v \ll c$, we see that the SR convention $L = ct$ still holds for C_a and D_a. We will designate these differing reasons for equal times, the special name: 'time equivalence' (TE). We note there is nothing paradoxical, regarding these two sets of viewpoints.

2.6 Considering a separate free fall observer inside the accelerating rocket

Let there be an inertial observer C'_a, adjacent to C_a but inside the rocket. Then for downward light, PLSD should also hold. When the rocket is in an inertial state, place C'_a inside a rectangular box that is also within the rocket but detached from it. This box is aligned with the axis of the rocket with length $L' = ct'$, where $L' < L$. At the instant the rocket begins to accelerate, with the box and C'_a remaining inertial, a laser beam is shone downward from the top of the box. Now, since the rocket's floor accelerates upward to meet the box, the light need only traverse the reduced distance L' at the instant the rocket floor coincides with the end of the box. As far as C'_{a} can ascertain by this measurement, the light only travels the distance $L' < L$ in this time. This satisfies the condition that all observers inside the box record the shorter distance that the laser travels, which aligns with the shorter distance that C_{a} and D_{a} measured, by using the bottom clock for the light event arrival of the light. Hence C_{a} and D_{a} or C'_{a} are equivalent frames for such measurements.

2.7 PLSD in gravity: resolving an apparent discrepancy with the accelerated frame

By the equivalence principle, an inertial observer C'_{a} inside an accelerating rocket is indistinguishable, locally from freely falling observer C'_{g} in gravity. Hence, in gravity, we would expect to obtain the same results for C'_{g} as C'_{a}. Given this, we now reach our first important conclusion: in the free fall frame of C'_{g} downward light in gravity, must also travel a shorter path length, to the rocket floor, than L, by the amount $L_d = L - \frac{1}{2}at^2$. We therefore conclude that, relative to C'_{g} the light moves toward the floor at $c + at$ and in a manner consistent with the accelerated case. However, we are now confronted with a lack of correspondence with respect to our acceleration frame: given that the floor of the rocket remains stationary, then as seen by C'_{g}, how does the downward light traverse the shorter distance L_d and still reach the floor ?

2.8 Resolving the issue with AFS

At first glance, one might conjecture that permitting light to exceed the speed c *through space* could resolve this discrepancy. Yet, such a proposition not only contradicts the principle of light's constancy but also undermines the equivalence principle, as no such phenomenon manifests in an accelerating context. Thus, we must seek an alternative explanation. The solution becomes evident once we reconsider our assumptions about the nature of space in this scenario. If we posit that the space through which light propagates is itself moving toward the floor of the rocket, at any instant by the velocity at, then the dilemma immediately resolves itself. In essence, in the context of gravity, we can envision the space in which light travels as moving past the stationary rocket, thereby shortening the required light travel distance. This concept of a moving space, we now introduce as our *Acceleration Field Space*, which we refer to now as AFS.

It follows from this that within the space-time metric g_{uv} of general relativity light moves the metric length of L, but in the AFS space it moves the length $L_d = L - \frac{1}{2}at^2$. Hence light moves different lengths in spacetime, depending on the frame in which you measure it in. From this it immediately follows that upward light travels the longer metric distance L by the amount $L_d = L + \frac{1}{2}at^2$. This result in gravity now aligns exactly with the acceleration case.

2.9 Preliminary comments

2.9.1 Equivalence Principle as a Kinematic Constraint on Spacetime

This result reveals that the equivalence principle operates as a deeper structural constraint on spacetime itself: it demands that both the accelerating observer and the observer at rest within a gravitational field share a common dynamical relationship with spacetime namely, that both are, in a fundamental sense, in motion through it. The equivalence principle thus does not merely relate two physical scenarios; it exposes an underlying kinematic unity that transcends the apparent dichotomy between acceleration and gravitation.

2.9.2 Disagreement on the origin of light signals in gravity

Referring back to our section 'Observer-dependent origins of emitted light', these considerations reveal an unexpected phenomenon in AFS space. Although the positions from which light originates, as seen by the observers frames C_a and D_a, align with those in the rocket's frame, the equivalence principle implies a striking consequence under gravity: that is since the corresponding observers C_g and D_g, fall with the AFS space, their subsequent observations diverge. In particular, since C_g and D_g measure these upward-propagating light pulses to have originated from positions adjacent to D_g, then by the time the light pulses reach the top of the rocket, the original starting position in space, as seen by D_g, is now below the rocket's location. Hence D_g will measure the light path to be longer by the distance, $L_d = L + \frac{1}{2}at^2$. Conversely, downward-propagating pulses appear to have traveled an overall shorter path, $L_d = L - \frac{1}{2}at^2$. Hence D_g will measure the light path to be longer by the distance, $L_d = L + \frac{1}{2}at^2$. Conversely, downward-propagating pulses appear to have traveled an overall shorter path, $L_d = L - \frac{1}{2}at^2$. Hence, by the time each light ray reaches its destination, observers C_g and D_g conclude that the downward propagating light, originated from a position lower within the rocket than the inside observers claim, while the upward-propagating light originated from a position below the rocket entirely—a region entirely inaccessible to direct observation by those inside.

2.9.3 What all observers agree on: conclusions of the acceleration case for light

From the above acceleration case, we conclude that using light and despite different path lengths occurring for different observer sets A,B and C_a, D_a, all record identical clock readings. Now by the EP we expect this 'time equivalence' to hold in gravity as well as between A,B and C_g and D_g. In addition, PLSD provides a new conceptualization of gravity. So that we need a redefinition of what a geodesic is. That is in the frame of C_g and D_g a geodesic is the movement 'with' an AFS space, while in the frame of A,B it is the motion 'through' metric space.

2.9.4 The distance light travels up exceeds the distance traveled down

If space flows downward under gravity, as this model proposes, then light climbing against that flow travels a longer effective path than light moving with it. Consequently, upward-directed pulses take more time and cover a greater distance through AFS than downward-directed ones. Upward propagation through the AFS space produces the familiar redshift, while downward directions produce blueshift. This perspective provides a simple kinematic account of gravitational time dilation and frequency shifts consistent with general relativity.

3 Thought experiment two: equivalence principle without light

The above conclusion of a falling AFS space was based on the behavior of light. We now provide alternate confirmation of this result.

Let us suppose that an accelerating rocket R_a, in flat space far from gravity, moves towards a test mass m a distance H away, at some point P in outer space. Now, we can assume that since Newton's first law applies to m, then for R_a to reach m at P it must move through space between it and P a distance H. Now this observation that R_a needs to traverse the distance H to reach m is so apparent that declaring it as a principle of nature may seem unnecessary. However, for the sake of our discussion, let us proceed to state it as such and call it the law of R_a *traversing space distance* (TSH), H. We denote this with $R_a \equiv \Upsilon \equiv$TSH.

We now ask, if O is some observer both stationary and in close proximity to m, can O perform any local experiment, to distinguish if R_a is truly accelerating or stationary in gravity? By the EP we answer in the negative. This is because O could be in free fall under gravity and the rocket R_a be hovering, at a fixed position r, in some gravitational field with m also falling toward R_a. If indeed O is in gravity, then we can now label the rocket as R_g and ask a pivotal question: Since observer O is in free fall in a gravitational field, does $R_g \equiv \Upsilon$ also apply to the rocket? That is, does R_g traverse a distance H through space so that $R_a \equiv \Upsilon \equiv R_g$? If we are to hold to the EP at the most fundamental level we must answer in the affirmative. But the same obvious objection, as above with light, now arises: how can this be if the rocket remains stationary in gravity?

In order for R_g to move the same distance H through space to reach m, we find we are left with no other answer, than to propose that m and the entire space it occupies, is moving towards R_g. That is all of Lorentzian spacetime, is in free fall and so moving past the 'stationary' rocket. This conclusion emphasizes parsimony and demonstrates internal consistency, achieving the highest degree of spacetime symmetry regarding acceleration and localized gravitational effects, precisely the structural coherence required by the EP. In the accelerating case, the rocket moves toward an inertial mass m, which, according to Newton's first law of inertia, remains in its state of motion—whether moving or stationary—unless acted upon by a net force. Similarly, in the gravitational case, m maintains its state of motion within space, thus adhering to Newton's first law, while the entire spacetime moves radially downward.

Having reached this fundamental conclusion, we still need to clarify what this symmetry demonstrates with respect to the metric space g_{uv} of Einstein's general theory of relativity. We will examine first, the gravitational case. We begin by asking: 'what do we mean by saying the rocket is stationary?' The rocket is obviously stationary with respect to the source mass that is responsible for the gravitational field, but less obvious is that it is also stationary with respect to the metric space of general relativity, where the g_{uv} is fixed at each position r. Hence if m, the space point P and this dual Lorentzian space-time, all fall a distance H with respect to the rocket then they will also with respect to the metric space g_{uv}. That is $g_{uv} \implies \Upsilon$. Let us now see how this maps to acceleration. Consider the inside frame of a windowless accelerating rocket. Now, by the EP an observer inside occupies and is stationary with respect to, a pseudo metric space[2]. Additionally since an inside observer O' has no experimental way to determine if they are in a local gravitational field, then if they were to drop a test mass m, then at an instant later m will be in a separate flat Lorentzian space, which the rocket is accelerating through. Now in the frame of the rocket there will also exist a pseudo metric space stationary with respect to O'. That is, the pseudo metric space is in symmetry with gravity $R_n \equiv \Upsilon$, where $n \in \{a, g\}$.

3.1 Classical conceptual bias—finding true invariants

Let us now address potential bias that might arise from classical views of motion and appear to conflict with the concept of a falling VFS. Classical physics was primarily founded on the laws of motion that Newton developed. The following simple example, shows how a classical bias can cloud the physics.

Consider a small steel ball in space far from gravity. Now let it be enclosed in a large box. Let the box be accelerated with respect to the ball. We now ask, has the act of accelerating the box changed the state of the ball in anyway? Ignoring quantum level effects, we answer in the negative. What we have done according to our classical understanding of physics is to only change the state of motion of the box, so that it accelerates with respect to a 'stationary' ball. Hence to an observer O inside the box, who knows that the box is being accelerated far from gravity, will look at the ball and although observes it accelerating 'down' within the box, will not consider it to be moving through space, rather the box is accelerating through 'space' towards the ball.[3]

Suppose the box is now placed on the surface of the Earth so that it is stationary with respect to the surface and let O know this. Now let the ball be dropped so that O observes exactly the same as in the accelerated case. What is O entitled to say? The common answer is: since the box is not moving through space, then it is the ball that

[2]'Pseudo' means here flat but non-inertial. Strictly speaking, during acceleration while inertial effects arise from coordinates, not curvature, the EP makes no such physical distinction locally inside the rocket. The Riemann tensor vanishes, yet the metric components depend on position, producing nonzero Christoffel symbols, $\Gamma_{uv} \neq 0$ (inertial forces). Hence in gravity the metric can be locally flat, but globally curved. In acceleration this leads to the interpretation of it as a pseudo-coordinate-dependent tensor, meaning it encodes curvature, but can be transformed locally to flat form in Rindler coordinates. While this is mathematically correct, for our particular purpose, we are focusing on the metrics manifesting as fixed, when inside the frames, and not the particular nuanced differences of the actual metrics in each frame.

[3]We could have, in the acceleration case, chosen the true symmetry to lie with the ball suddenly accelerating towards the box when the box was attempted to be accelerated. However there is no known mechanism in physics for this and furthermore it would imply the whole universe would suddenly accelerate with respect to the floor of the box. A very unlikely scenario.

is now falling through space towards the floor. Although this answer seems correct, it reveals a flaw in physical reasoning that arises from a false assumption underlying classical thought.

The assumption is that in the gravitational field, since the metric distance between the ball and the bottom of the box decreases, then this is equal to the ball's distance traveled through space. While it is true that the measured distance between the ball and the floor does decrease, the equivalence principle implies this need not mean a decrease in the ball's distance through space. We propose that, just as in the case of acceleration, the ball remains stationary in space even as its separation in distance from the floor diminishes. How are we to then explain this?

We propose that in the case of gravity, for the ball to remain stationary in space, then the space itself carries the ball towards O. This interpretation extracts a deeper symmetry and invariance in the inertial state of the ball in both cases, as opposed to an apparent one, under the paradigm of classical mechanics.

3.2 Distinction from the ether concept

The ether concept was a hypothetical medium that was posited to permeate all of space, through which light waves were thought to propagates, similar to how sound needs air and water waves need water [23]. The ether was thought to provide a privileged reference frame against which absolute motion could be measured. The most famous attempt to measure the ether was the Michelson-Morley experiment (1887), which tried to detect Earth's motion through the ether by measuring differences in light speed in different directions. Experiments were expected to reveal variations as Earth moved through this stationary medium, creating an 'ether wind'. However, experiments found no difference, with light apparently traveling at the same speed in all directions [24]. This null result, repeated many times, was a major puzzle that eventually helped lead Einstein to special relativity (1905), which eliminated the need for the ether entirely. Nevertheless, Einstein's Leiden lecture in 1920 described the metric field $g_{\mu\nu}$ as varying from place to place, determined by material phenomena, allowing the transmission of inertial and electromagnetic effects, although never assignable to an independent state of motion [25]. In the AFS model, spacetime is likened to a flowing river that moves objects along—not as a physical substance, but as a dynamic geometric field structure. Unlike the static ether concept, the varying 'flow' rates in the AFS model correspond to the curvature of metric spacetime in GR. Crucially, this represents the flow of space itself, rather than a flow through space. Objects falling from infinity, which we typically think of as following geodesics, the straightest paths in curved spacetime, are actually stationary within this flowing spacetime, which in this model we interpret as gravitational attraction.

The concept of AFS, as it only responds to acceleration, will naturally return a null result for the Michelson-Morley experiment, as this experiment is at constant speed.

3.3 Unifying the three aspects of the equivalence principle

The AFS paradigm inherently embodies all three forms of the EP, dissolving them into a single fundamental framework of a unified concept of moving space. These principles are:

1. The Weak Equivalence Principle (WEP), first articulated by Galileo Galilei through his experiments with falling bodies, states that all test masses accelerate equally in a gravitational field, irrespective of their mass or composition. This principle is seamlessly integrated within the AFS framework, where every mass—regardless of its size—dropped from the same height in a gravitational field accelerates uniformly. This uniform acceleration arises not from the properties of the masses themselves, but from the consistent relationship that all mass holds with the AFS and the dynamics of the AFS space.

2. The Einstein Equivalence Principle (EEP), introduced by Albert Einstein in 1907, posits that the results of any local non-gravitational experiment conducted in a freely falling frame are independent of both the frames and its position in spacetime, incorporating local Lorentz and position invariance. This theory simplifies the understanding of experiments—such as dropping an apple inside an accelerating rocket—by illustrating that one cannot distinguish between this scenario and being in a gravitational field. In the framework of AFS, acceleration and gravity are unified into a single field within the frames, allowing the EEP to emerge as a natural consequence of this integrated perspective.

3. Strong Equivalence Principle (SEP). Conceptually extended by Einstein but formalized in modern form by Robert Dicke [26], particularly in the context of scalar-tensor theories and precision tests of general relativity. This follows from the fact that all objects are 'stationary' in AFS. The concept of a moving space leads us to another intriguing outcome: it revolves around the notion of 'being stationary in space'. This idea is fundamentally rooted in the concept of inertial mass rather than gravitational mass. By highlighting this distinction, we can merge various interpretations of the EP into a singular concept of inertia.

In essence, while moving space might suggest a dynamic environment, the focus shifts to the stability of objects within that space. This perspective allows us to reconcile different theoretical frameworks, emphasizing that the essence of inertia, based only on Newton's first law, can unify our understanding of motion and rest, transcending the classical distinctions that have traditionally divided gravitational forces from inertial effects.

3.4 Some implications

3.4.1 The set of infalling spaces

We recognize the difficulty of truly defining the properties of such a space, as being proposed. However, we provide a list of its essential properties, and in order not to overly speculate, for the moment we have to be satisfied with this limited explanation. Assuming the aforementioned conclusion is valid, then the set of infalling space-times are equivalent to and map exactly, to the set of all conventional flat geometries—such as Euclidean or Minkowski spacetime, including those with quantum fluctuations. Hence while we will refer to AFS as well as 'AFS space,' we intend the term 'space' here to denote the familiar concept of the set of all spaces, including all known quantum fields. In contrast, since the interior spacetime perceived by stationary observers in R_g above are static and governed by the general relativity (GR) metric $g_{\mu\nu}$ this spacetime does not belong to the class of infalling space-times. Rather, the ensemble of infalling space-times traverses the manifold of all GR metric space-times $g_{\mu\nu}$. Given the preliminary nature of this proposal, further investigation into the properties of this space is required and will be addressed in a future paper.

3.4.2 Comparative path lengths for light and mass in AFS versus metric spacetime

We wish to now briefly clear up the difference in distances traveled in a AFS space, for light versus mass. In the light case above, we found the downward distance traveled in AFS space is shorter than in metric space, while upward motion is comparatively longer. By contrast, the mass m and point P description reveal that the AFS distance coincides with the metric spacetime distance. Additionally, it should not be difficult to see that horizontally, light bends in metric space by the amount given by GR.

3.5 The Gullstrand–Painlevé coordinates and AFS

We will now show that AFS model, fits with an already standard treatment by way of the Gullstrand-Painlevé metric [12]. The solution of Einstein's field equations around a stationary, non-rotating mass is the Schwarzschild metric

$$ds^2 = \left(1-\beta^2\right) c^2 dt^2 - \left(1-\beta^2\right)^{-1} dr^2 - r^2 d\Omega^2, \tag{1}$$

where we have defined

$$\beta = \frac{v_e}{c} = \sqrt{\frac{r_s}{r}}, \tag{2}$$

where v_e is the escape velocity at a distance r, so β is the standard relativistic escape velocity as a fraction of c. While $r_s = \sqrt{\frac{2GM}{c^2}}$ is the Schwarzschild radius. We use S.I. units for c, as this adds clarity to our arguments for the moving space. Now, making the coordinate transformation $dt = dT - \frac{\beta}{1-\beta^2}$, the line element becomes

$$\begin{aligned} ds^2 &= \left(1-\beta^2\right) c^2 dT^2 - 2\beta c dT dr - dr^2 - r^2 d\Omega^2 \\ &= c^2 dT^2 - \left(dr + \beta c dT\right)^2 - r^2 d\Omega^2, \end{aligned} \tag{3}$$

which are the Gullstrand–Painlevé coordinates. The spatial component $dr + \beta c dT = dr + v_e dT$, describes a flow of space-time towards the gravitating mass. The local time coordinate T is now equal to the proper time of a free-falling observer from infinity, and at constant time with $dT = 0$, the space is flat, as reflected in a unit coefficient on dr^2. The line element is also regular across the event horizon, with the inflow rate reaching the speed of light at the event horizon, and increasing steadily towards the singularity $r = 0$.

Now, light or electromagnetic radiation (EM) satisfies $ds^2 = 0$, so that Eq. (3) produces the factorized equation $\left(cdT + (dr + \beta c dT)\right)\left(cdT - (dr + \beta c dT)\right) = 0$, indicating two solutions. Dividing through by dT, we find

$$v_{\mathrm{EM}} = \frac{dr}{dT} = c\,(\pm 1 - \beta) = \pm c - v_{\mathrm{esc}} = c\left(\pm 1 - \sqrt{\frac{r_s}{r}}\right). \tag{4}$$

Hence, at the event horizon, with $r = r_s$, we can see that the outbound light is zero, as it is balanced by the similar inflow of AFS, thus providing a natural explanation for the event horizon. We note that the inbound light has a velocity of $2c$, in these coordinates[4].

The Gullstrand-Painlevé coordinates in this theory describe a space equivalent to the AFS, with the velocity of inflowing AFS at a given radius r and thus also corresponding to a free-fall observer in gravity, within a flat space. For an observer falling from infinity, they are at rest with respect to this space as it moves towards the centre of the mass. Hence, moving in from infinity, they have effectively traveled zero distance in the AFS. Reversing their direction, they will travel further than the distance dr, as there is an extra distance traveled through the AFS.

Hence what is usually considered as a simple mathematical coordinate transformation, we show from physical arguments that the Gullstrand–Painlevé coordinates are correctly describing the physical inflow of space from infinity, against the backdrop of the metric tensor g_{uv} and the static Schwarzschild coordinates. Thus we can view the AFS around a gravitating mass as a vector field describing the velocity of the infalling space, where the gradients in this field impute acceleration. In the AFS model of gravity, space flows inward toward a central mass M with a velocity

$$\boldsymbol{v}(r) = -\sqrt{\frac{2GM}{r}}\,\hat{r},$$

where

- $\boldsymbol{v}(r)$ is the velocity of AFS space.
- $\hat{r}$ is the radial unit vector in spherical coordinates.

The flow speed approaches c at the Schwarzschild radius $r_s = 2GM/c^2$.

This vector field describes a stationary, spherically symmetric inflow of AFS space, mathematically consistent with the Painlevé–Gullstrand coordinates used in the river model. This AFS model describes curvature effects as arising from differences in the acceleration field of space at differing r.

3.6 AFS and metric spaces as dual descriptions of differing spatial dimensions

Lets us now see how AFS is also a different description of spatial dimensions in gravity compared to the standard GR representation. The AFS description, represented by the Painlevé-Gullstrand coordinates, provide a metric where the time coordinate t is synchronized with the proper time of distant observers, whereas in asymptotically flat

[4]This does not mean light is moving through space at $2c$, which would violate special relativity, rather the space is able to move up to a limit of c at the event horizon, while light moves within this space at speed c.

(SR-like) spacetime, the spatial part incorporates a 'flow' or 'shift'. This means the two frames agree on the global time t (shared between the GR interior and SR exterior at infinity), but disagree on spatial measurements due to the inflow term. Now using the $(+,-,-,-)$ signature convention (where $ds^2 > 0$ for timelike intervals and $ds^2 = d\tau^2$ along a worldline for proper time τ), the invariant interval is:

$$ds^2 = d\tau^2 = \left(1 - \frac{2GM}{rc^2}\right) c^2 dt^2 - 2\sqrt{\frac{2GM}{r}}\, dt\, dr - dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta\, d\phi^2, \quad (5)$$

where G is the gravitational constant, M is the black hole mass, and c is the speed of light. This can be rewritten in an expanded form to highlight the velocity shift:

$$ds^2 = d\tau^2 = c^2 dt^2 - \left(dr + \sqrt{\frac{2GM}{r}}\, dt\right)^2 - r^2 d\theta^2 - r^2 \sin^2\theta\, d\phi^2. \quad (6)$$

Here, the term $\sqrt{\frac{2GM}{r}}\, dt$ (or $\beta\, c\, dt$, with $\beta = \sqrt{\frac{2GM}{rc^2}}$) is the 'shift vector' in the metric. It represents the differential velocity between the frames, as it describes the speed of AFS resulting from its movement from infinity. It also matches the escape velocity at the position r:

- In the SR frame at large r, $\beta \to 0$, so the metric reduces to Minkowski: $ds^2 = c^2 dt^2 - dr^2 - r^2 d\Omega^2$.
- In the GR frame closer in, the shift introduces a cross-term ($-2\beta c\, dt\, dr$) that couples time and space, meaning spatial displacements dr are 'dragged' by the time evolution dt with velocity $-\beta c$ (inward). This is the mathematical encoding of the frames not matching in velocity.

Agreement on Time: The coordinate t is the proper time for observers at infinity (SR frame) and is synchronized across the entire spacetime. Both frames 'agree' on t as the global time parameter, but they disagree on spatial measurements and velocities.

4 Applications

4.1 Escape velocity as the natural speed of 'space'

Let us see what the escape velocity $v_{\text{esc}} = \sqrt{2MG/r}$ means for AFS in this model. It can be considered as the instant velocity required by any mass m to overcome the equal and opposite downward velocity v_d, of the AFS space at position r with a_d acceleration, that is $v_d = v_{\text{esc}}$.

Now in the model of space we are presenting, AFS began its fall towards the mass M, at a position where space is nearly flat in GR terms. However, for more practical purposes, if M is the Earth and we use the common escape velocity of 11.2 km/s, then we can take this as the speed v_d of our AFS at the surface of the Earth in the fixed position r.

Now for the mass m to leave the Earth at the escape velocity, it must also leave according to the usual escape velocity of $v = \sqrt{2MG/r}$, equal to 11.2 km/s. However, the ejecting mass has to also travel through the infalling space as it leaves the Earth, and so the distance traveled through the AFS will be greater than simply the metric distance given by GR. For the special case of a projectile fired from the surface of the Earth at the escape velocity, its velocity will always be equal and opposite to the inflowing space velocity, and hence the distance traveled through AFS will be about double the metric space distance[5]. This also simply explains why light is trapped at the event horizon—the light is still traveling at the speed c within its local region of space, however, the space itself is moving inward towards the black hole at c.

Now, ignoring the velocity dependence of gravity [27] and the tidal forces to the first order, the acceleration field is independent of the velocity of the field at that position r. Hence consider a mass m_1 that begins its fall from infinity toward a source mass M. If at position r_1 it encounters another mass m_2, which is also dropped at that location, then although m_1 is stationary in AFS at r_1 while m_2 is not, both masses will still accelerate in gravity at the same rate for $v \ll c$. We note that when we refer to m_1 as stationary in AFS, we mean that it is moving at the same speed as the AFS itself. For instance, if we measure an object to have an infalling speed of 11.2 km/s at the surface of the Earth, we can therefore classify it as stationary in AFS. Hence while this view of space posits that any object falling in gravity is moving with the AFS, this does not mean it does so at the same speed of the AFS. This only occurs for free fall objects that originate from infinity.

4.2 Gravitational time dilation and moving AFS space

In special relativity (SR), the time dilation, based on a relative velocity v in flat space, is given by

$$\frac{t}{t_0} = \frac{1}{\gamma} = \sqrt{1 - \frac{v^2}{c^2}}, \tag{7}$$

where γ is the relativistic gamma factor. Again $v = v_d = g_d t$ and so substituting in the escape velocity from Eq. (2), describing the inflow velocity of space, we find

$$\frac{t}{t_0} = \sqrt{1 - \frac{2GM}{rc^2}}, \tag{8}$$

where t_0 is the time of the observer at infinity, this is the equation for the gravitational time dilation. Hence, we can view gravitational time dilation in this model as being due to light propagating against the flow of space, which lengthens its travel time, which is equivalent to a retarded clock, as assumed in SR. Thus Eq. (8) also describes the gravitational redshift from a massive body.

4.3 Distances in metric versus AFS space

We can easily derive the first order gravitational redshift, $\omega = \omega_0(1 - gL/c^2)$ for inside the rocket and therefore for gravity, from the non-relativistic Doppler effect,

[5]Space flow speed inward: $v_{\text{space}(r)} = \sqrt{2GM/r}$. Escape trajectory speed outward: $v(r) = \sqrt{2GM/r}$. Total speed relative to inflowing space necessary to escape: $v_{\text{rel}(r)} = v_{(r)} + v_{\text{space}(r)} = 2\sqrt{2GM/r}$.
By $dr/dt = v(r) = \sqrt{2GM/r}$, then $dt = dr/v(r)$ and so $S = \int v_{\text{rel}} dt = \int 2\sqrt{2GM/r} \cdot (dr/\sqrt{2GM/r}) = \int 2dr = 2L$.

$\omega = \omega_0(1 - v/c)$, by letting $v = at$, where $v \ll c$, and $t = L/c$, where L is the length light travels in AFS space. Also we can write $v = c(1-\omega/\omega_0)$, where ω_0 represents the angular frequency of the wave as emitted by the source in its own rest frame. Hence we can use the Doppler shift equation to calculate relative motion between source and observer. But since in this theory, $v = \sqrt{2MG/r}$ represents the velocity of AFS space at the position of the metric radius r, we can equate

$$v(r) \;=\; \sqrt{\frac{2GM}{r}} \;=\; c\left(1 - \frac{\omega(r)}{\omega_0}\right), \tag{9}$$

and then integrate the velocity to get the distance through AFS space that light travels in weak fields. For light leaving Earth's gravity, this is the distance light traveled in AFS space, which can also be estimated by gravitational redshift.

4.3.1 The AFS space interpretation of GPS clock synchronization

We have the time taken for a photon leaving the Earth's surface (propagating against the downward flow of space), up to the GPS orbit

$$t_{\mathrm{GPS}} = \int_{r_E}^{r_{\mathrm{GPS}}} \frac{dr}{c - v_{\mathrm{AFS}}} = \int_{r_E}^{r_{\mathrm{GPS}}} \frac{dr}{c - \sqrt{\frac{2GM}{r}}}, \tag{10}$$

where the radius of the Earth $r_E = 6{,}371$ km, and the distance to the GPS satellite orbits $R_{\mathrm{GPS}} = 20,200$ km.

This gives an extra time of flight 1.2 microseconds, which is equivalent to an extra distance of 360 m. Note that these values are slightly approximate as we have ignored atmospheric effects.

In the AFS space view, this implies that when we send a signal from the Earth up to a GPS satellite, that the later clock reading is not due to its clock running faster in a weaker gravitational field (as in the conventional view), but a longer travel time for light. Hence in AFS space, we can deem the GPS clocks to be running at the same rate as those on the Earth, and so they could all be synchronized together on the Earth, before launching. Hence, this provides an alternate synchronization procedure for GPS clocks. Also, from the AFS perspective, since there is a shorter downward elapsed time (attributed to a reduced travel distance), this could perhaps be exploited to improve GPS timing and positioning.

As a further example, if we take the distance from Earth to the James Webb telescope to be 1.5 million km in coordinate space, then the upward distance light travels through AFS space is the extra amount of approximately 6.82 km. Conversely it travels less by this same amount in the opposite direction (see Appendix 6). This property of distance through AFS space as a function of direction, has implications for how we might consider the true size of the universe. The length through coordinate space is currently calculated to be 13.8 billion light years, however, this could vary for different directions with respect to AFS space.

4.4 A possible connection to dark energy

The AFS treatment that explains gravitational redshift as due to light moving against an infalling AFS space, this would seem to natural link to the expansion of the universe and cosmological redshift and so to the universe's overall energy density. Assuming that the space of AFS is the same space of the expanding universe, it is therefore not inconceivable that the infalling AFS space of gravity, might have the effect of 'diluting' the energy density of space in the universe at large, affecting its expansion.

There is new emerging observational data suggesting a potential deceleration in the rate of cosmic expansion. For example recent findings from the DESI (at sigma 4.2) [28], indicate that the universe's expansion rate is currently slower than it was several billion years ago. The data implies a temporal decline in the dark energy density, which now appears to be approximately 10% lower than its value 4.5 billion years ago. Further studies need to be undertaken to help confirm this prediction. Fortunately, there is a forthcoming increase of cosmological datasets, driven in 2025–26, by the observational platforms of the Euclid mission, and the Vera C. Rubin Observatory. It is also believed that mass, or matter, played a crucial role in slowing the expansion of the universe during the matter-dominated era [29]. Building on this, alongside the previously discussed concept of an unseen gravitational mass increase [30], these mechanisms could collectively indicate that dark energy is linked to AFS. If future findings from DESI correlate with the total mass of the universe across different epochs, this would provide a compelling test and validation of the theory. Although the property of a moving space is not unlike that of an expanding space, applying the detailed calculation would still be non-trivial.

4.5 Implications for charges in gravity

There are continuing debates regarding the radiating of charges in gravity. However, this framework offers a clearer approach. For example, according to standard electromagnetic theory, a charge q, with an acceleration a, radiates power according to the Larmor formula

$$P = \frac{\mu_0 q^2 a^2}{6\pi c}, \tag{11}$$

with the speed of light $c = 3.0 \times 10^8$ m/s, magnetic permeability of the vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m. We see that radiation is assumed detected in an inertial frame.

Now, by the equivalence principle, the inertial frame in gravity is the free-fall frame so it is this frame that measures the radiation. The AFS framework provides a physical framework as to *why*. Accelerating a charge through space is associated with an inertial frame. In the AFS model, remaining stationary in a gravitational field still constitutes acceleration through space, associated with a local gravitational force exactly equivalent to the inertial force. Therefore AFS provides not merely the prediction that a free-falling observer will detect radiation from a charge held stationary in gravity, but the underlying reason: the free-falling observer, being inertial, is stationary in AFS space. It follows directly that this observer will measure the stationary charge as radiating.

4.6 Inertial and gravitational mass a single phenomenon

In the AFS framework, a mass accelerating through space and space accelerating past a stationary mass are, by symmetry, physically indistinguishable. The first gives rise to what we call inertial force, the second, gravitational force. Both reduce to a single mechanism: the relative acceleration between a mass and the local flow of space.

This eliminates the need to posit two distinct properties that happen to be numerically equal. Inertial and gravitational mass share a common origin, making their equivalence a necessary consequence of the framework rather than an empirical coincidence. Since the mechanism is purely kinematic, we would expect it to extend to quantum scales.

5 Discussion

There have been other models of gravity as a river of space falling freely. Most derive their arguments from the Gullstrand–Painlevé coordinates, usually as pedagogical aids and have varying interpretations of what the coordinates represent.

For example, Hamilton and Lisle developed a river model of non-rotating black holes by also expressing the Schwarzschild metric in the Gullstrand-Painlevé coordinates [18]. However, in their model, space is pictured as a river flowing through a flat background coordinate system. In our description, we do not engage with any background space in relation to the AFS space. Instead, we conceptualize the AFS space as flowing independently while remaining consistent with the metric space.

Our starting point is also different from the Gullstrand-Painlevé coordinates. Starting from a fundamental position, that is, the EP and using only a novel application of it, we reveal a non correspondence in the behavior of light in gravity. By a resolution of this, we propose that gravity comprises an additional 'dual' AFS space to that of the metric space of GR. This then informs a direct interpretation of the physical meaning of the Gullstrand-Painlevé coordinates. This was shown also for example by the in-equidistant length that masses move in both acceleration and in AFS space in gravity. The same holds for light. We therefore established AFS from a first principles approach, without any additional assumptions or propositions. Additionally, once length is defined as $L = ct$, it follows by simple analysis that vertical lengths in the up and down directions in metric space differ to those in the AFS space. This shows that what we mean by length in gravity is frame dependent.

Despite these comments, we should ask the question: what do we mean by the concept of a AFS that moves? The problem under consideration presents significant challenges within theoretical physics and, arguably, carries philosophical implications that extend beyond the scope of this paper. To ease this understanding let us quickly review the history of how astronomers realized the expansion of the universe. This was not the motion of galaxies through space, but space-time itself expanding. The recognition of this emerged from the interplay of theoretical and observational advances in relativistic cosmology. Solutions to Einstein's field equations demonstrated that homogeneous and isotropic universes need not remain static but could evolve dynamically, admitting models of expansion or contraction, as shown by Friedmann (1922) [31] and

Lemaître (1927). Lemaître further connected this theoretical framework to astronomical data by relating the recession velocities of extragalactic nebulae to their distances, anticipating the linear law later observationally confirmed by Hubble (1929). This synthesis established that cosmic expansion was not the motion of galaxies through space but rather the stretching of spacetime itself, a view formalized in the relativistic cosmological models that underpin modern cosmology [32, 33]. Note that with respect to escape velocity and how we interpret it in this theory, that is, in cosmology the distance a galaxy moves away at the speed of light, is the Hubble radius: $R_H = c/H_0$, approximately 14 billion light-years, where H_0 is the Hubble constant. Beyond this 'horizon', galaxies recede faster than light and this is not possible if they are moving through space, but only if space itself is expanding faster than light. The gravitational model of space–time developed in this paper is dual to the usual metric picture in which space–time is stretched or warped. In the AFS framework, expansion of the universe is described as a movement of space–time through which light still propagates at c.

The subsequent discovery of late-time acceleration through Type Ia supernovae reinforced the paradigm of expanding space, now understood to be governed by both matter-energy content and a dark energy component [34, 35]. The fact that this notion of infalling Minkowski space has come out of the EP, which GR and the expanding universe is also based on, should not therefore be totally surprising.

Hence, while general relativity regards gravitational redshift as a distinct physical phenomenon separate from other forms of redshift effect, we contend that light emitted from an object within a gravitational field—interpreted through the lens of AFS—exhibits redshift characteristics akin to those observed in the expanding universe, rather than merely reflecting a pure velocity difference. Hence this provides a unified description of seemingly disparate causes for redshift.

Another aspect of spacetime that remains inadequately understood is that of curved spacetime. This however does not stop one from using it mathematically to predict such things as the bending of light. In this theory the idea of ordinary space actually falling a cordinate distance r, is not proposed as a mathematical construct, but as an intrinsic physical property of gravity. Now leading on from such vexing questions and perhaps the opposite of what is outside of the expanding space of the universe, is what happens to the infalling space in gravity as it converges to the central point of a mass? We can suggest that it meets its opposite counterpart. After that we can only speculate.

The AFS framework lends theoretical support for the mechanism that stellar objects could have an unexpected rapid mass accumulation, especially during the early epochs of cosmic evolution. This ability to provide a supportive explanation for independent predictions of rapid mass increase, provides an additional layer of support for the underlying theory.

By linking the energy density of the universe to the infall of AFS space around all masses, it is compelling to propose this as a potential reason for the observed decrease in dark energy density. A recent study [28] supports this prediction, but further investigation is necessary.

Furthermore, since AFS is a theory of moving space-time, this forces a distinction between 'space-time' and 'distance'. This then raises questions such as: what is the medium through which space–time moves, or is there one? These are topics for future research.

5.1 AFS and Frame Dragging: the Rotational Extension

The Accelerated Flow of Space framework belongs to a mathematical lineage in which gravitation is represented as a flow of space through a flat background, extending from Painlevé [36] and Gullstrand [37] to its rotating generalisation in Doran [22] and the unified river model of Hamilton and Lisle [38]. AFS recovers the velocity component of this formalism while making explicit its acceleration characteristics via the equivalence principle.

A crucial test of any flow-based picture lies in its treatment of rotating sources, where Lense and Thirring [39] predicted the dragging of inertial frames — a structure naturally expressed in the gravitoelectromagnetic formalism [40, 41]. Within AFS, the flow would remain radial in mean direction but inherit a local rotational character that Lorentz-rotates the tetrad of an observer carried by it. Empirically it has been confirmed by Gravity Probe B [42] measuring a drift of $-37.2 \pm 7.2\,\mathrm{mas\,yr^{-1}}$ against the general-relativistic prediction of $-39.2\,\mathrm{mas\,yr^{-1}}$; LAGEOS satellite analysis [43] independently confirmed the effect at the ten-percent level; and the binary pulsar PSR J1141−6545 [44] provides astrophysical confirmation in a strong-field regime. The AFS picture is consistent with these observations, provided its rotational extension can reproduce this behaviour, it is planned to be developed in a subsequent paper.

6 Conclusion

By applying the equivalence principle to light paths in a stationary gravitational field, we uncovered an apparent physical inconsistency in the way light travels in gravity compared to acceleration. The simplest resolution is an independently infalling spatial frame (AFS), which complements the metric description of general relativity—–a result confirmed also by a light-independent derivation and validated within Gullstrand–Painlevé coordinates.

The AFS model treats gravitational redshift, cosmic expansion, and all three forms of the equivalence principle as facets of one underlying mechanism, ‘movement through space’. In AFS, freely falling objects are at rest, light propagates at constant c, and local clocks run uniformly across local radial distances; what appears as time dilation in the metric picture reduces to a positional time offset, ‘Time Equivalence.’ The complementary AFS and metric viewpoints also reveal a genuine dimensional distinction between the two descriptions, with directionally asymmetric light propagation in AFS providing the physical basis.

Because AFS space infalls toward all masses, the framework predicts this as a possible cause of some decreasing effects on the energy density of dark energy, possibly detectable by DESI and future missions. Once a moving space is admitted, a satisfying gravitational explanation emerges as being infalling space towards mass, creating a radial acceleration. This same unity necessarily forbids any distinction between inertial and gravitational mass, thereby providing a fundamental mechanism for the equivalence principle, which is rendered not as an independent axiom, but a derived consequence of the deeper structure from which all the described phenomena depend.

We leave as a topic for future research, the generalization of radial geodesics in AFS with a twist component, in order to describe frame dragging effects.

Declarations

- **Funding:** We would like to gratefully thank the Australian Space Agency (MTMDFG000016 and MTMDFG000075) and the Australian Research Council (FL240100217) for funding support.
- **Conflict of interest / Competing interests:** The authors declare that they have no competing interests.
- **Data availability:** No new data were generated or analysed in support of this research.
- **Author contributions:**
  DB: Conceptualization, Investigation, Methodology, Validation, Formal analysis, Manuscript writing, Proof reading and editing.

  JC: Investigation, Methodology, Validation, Formal analysis, Proof reading and editing.

  DA: Investigation, Methodology, Validation, Supervision, Proof reading and editing.

Appendix A: Light distance in metric versus AFS space

We have the two expressions for the same local velocity :

$$v(r) \;=\; \sqrt{\frac{2GM}{r}}, \qquad v(r) \;=\; c\left(1 - \frac{\omega(r)}{\omega_0}\right). \tag{A.1}$$

These equations give

$$1 - \frac{\omega(r)}{\omega_0} \;=\; \sqrt{\frac{2GM}{r\,c^2}} \;=\; \frac{K}{\sqrt{r}}, \tag{A.2}$$

where the Schwarzschild radius $K = \sqrt{\frac{2GM}{c^2}}$. We can then form the redshift radius identity

$$\left(1 - \frac{\omega(r)}{\omega_0}\right)\sqrt{r} \;=\; \sqrt{\frac{2GM}{c^2}} \;=\; K. \tag{A.3}$$

Define the normalized AFS distance

$$d \;=\; \int_{r_0}^{R} \frac{v(r)}{c}\, dr \;=\; \int_{r_0}^{R} \left(1 - \frac{\omega(r)}{\omega_0}\right) dr. \tag{A.4}$$

Using $1-\omega(r)/\omega_0 = K/\sqrt{r}$,

$$d \;=\; \int_{r_0}^{R} \frac{K}{\sqrt{r}}\,dr = K\left[2\sqrt{r}\,\right]_{r_0}^{R} \;=\; 2K\left(\sqrt{R}-\sqrt{r_0}\right). \tag{A.5}$$

Substituting either endpoint form of Eq. (A.3), into Eq. (A.5) yields two equivalent expressions:

$$d = 2\left(1-\frac{\omega(R)}{\omega_0}\right)\sqrt{R}\,\left(\sqrt{R}-\sqrt{r_0}\right), \tag{A.6}$$

$$d = 2\left(1-\frac{\omega(r_0)}{\omega_0}\right)\sqrt{r_0}\,\left(\sqrt{R}-\sqrt{r_0}\right). \tag{A.7}$$

Numerical evaluation for Earth (both ways)

Route A: using $K=\sqrt{2GM/c^2}$.

$$\frac{2GM}{c^2} \approx 8.873\times 10^{-3}\text{m}, \qquad K=\sqrt{\frac{2GM}{c^2}} \approx 9.422\times 10^{-2}\,\text{m}^{1/2},$$

$$\sqrt{R} \approx 3.040\times 10^{4}\,\text{m}^{1/2}, \qquad \sqrt{r_0} \approx 2.524\times 10^{3}\,\text{m}^{1/2}.$$

Then

$$d \;=\; 2K\left(\sqrt{R}-\sqrt{r_0}\right) \;\approx\; 2\times(9.422\times 10^{-2})\times(2.7876\times 10^{4}) \;\approx\; 5.25\times 10^{3}\text{m}.$$

Route B: using the endpoint ratio at R.

$$1-\frac{\omega(R)}{\omega_0} = \sqrt{\frac{2GM}{R\,c^2}} = \sqrt{\frac{8.873\times 10^{-3}}{9.24\times 10^{8}}} \approx 3.10\times 10^{-6}.$$

Then

$$d \;=\; 2\left(1-\frac{\omega(R)}{\omega_0}\right)\sqrt{R}\left(\sqrt{R}-\sqrt{r_0}\right) \;\approx\; 2{\times}3.10{\times}10^{-6}{\times}3.04{\times}10^{4}{\times}2.79{\times}10^{4} \;\approx\; 5.25\times 10^{3}\text{m}.$$

Consistency: Both routes give $d \approx 5.25$km, confirming the symmetry.

Extra distance for outward propagation

From $v(r) = \sqrt{\frac{2GM}{r}}$, $\Delta r = r_2 - R$, R is Earth's radius, and r_2 is the final radial distance from Earth's center and starting from the integral for the extra distance $ct - \Delta r = \int_R^{r_2} \frac{v(r)}{c-v(r)}\,dr$.

Step-by-step derivation of the antiderivative

1. Express $v(r)$ in a convenient form:
   Let $b = \sqrt{2GM}$, so $v(r) = \frac{b}{\sqrt{r}}$.
   The integral becomes
$$\int \frac{\frac{b}{\sqrt{r}}}{c - \frac{b}{\sqrt{r}}}\, dr.$$
2. Use a substitution to simplify:
   Let $u = \sqrt{r}$, so $r = u^2$ and $dr = 2u\, du$.
   Then $v(r) = \frac{b}{u}$, and the integral is:
$$\int \frac{\frac{b}{u}}{c - \frac{b}{u}} \cdot 2u\, du = \int \frac{b}{c - \frac{b}{u}} \cdot 2\, du = \int \frac{2b}{\frac{cu-b}{u}}\, du = \int \frac{2bu}{cu - b}\, du.$$
3. Simplify the integrand:
$$\frac{u}{cu-b} = \frac{1}{c} \cdot \frac{cu - b + b}{cu - b} = \frac{1}{c}\left(1 + \frac{b}{cu-b}\right) = \frac{1}{c} + \frac{b}{c(cu-b)}.$$
   Hence:
$$2b \int \left(\frac{1}{c} + \frac{b}{c(cu-b)}\right) du = 2b\left(\frac{1}{c}\int du + \frac{b}{c}\int \frac{1}{cu-b}\, du\right).$$
4. Integrate each term:
$$\int du = u, \qquad \int \frac{1}{cu-b}\, du = \frac{1}{c}\ln|cu - b|.$$
   Putting it together:
$$2b\left(\frac{u}{c} + \frac{b}{c}\cdot\frac{1}{c}\ln|cu-b|\right) + C = \frac{2bu}{c} + \frac{2b^2}{c^2}\ln|cu-b| + C.$$
5. Evaluate the definite integral from $u = \sqrt{R}$ to $u = \sqrt{r_2}$:
   Since $cu - b > 0$ for the relevant range (as $v(r) \ll c$ far from any event horizon analog), drop the absolute value:
$$\left[\frac{2bu}{c} + \frac{2b^2}{c^2}\ln(cu-b)\right]_{\sqrt{R}}^{\sqrt{r_2}} = \frac{2b}{c}(\sqrt{r_2} - \sqrt{R}) + \frac{2b^2}{c^2}\ln\left(\frac{c\sqrt{r_2} - b}{c\sqrt{R} - b}\right).$$
   This is the closed-form expression for the extra distance.

Numerical example (JWST at L2)

Use the following values (standard for Earth, with $r_2 = 1{,}500{,}000$ km as the radial distance to the James Webb Space Telescope at the Sun–Earth L2 point):

- $GM = 3.986004418 \times 10^5\ \mathrm{km}^3/\mathrm{s}^2$
- $c = 299{,}792.458$ km/s
- $R = 6{,}371$ km
- $r_2 = 1{,}500{,}000$ km

1. Compute $b = \sqrt{2\,GM}$:
   $2GM = 7.972008836 \times 10^5$
   $b = \sqrt{7.972008836 \times 10^5} = 892.86107$ (units consistent as $\mathrm{km}^{3/2}/\mathrm{s}$).
2. Compute $\sqrt{R}$ and $\sqrt{r_2}$:
   $\sqrt{R} = \sqrt{6{,}371} = 79.8185$
   $\sqrt{r_2} = \sqrt{1{,}500{,}000} = 1{,}224.7449$
3. Compute the first term: $\dfrac{2b}{c}\big(\sqrt{r_2} - \sqrt{R}\big)$:
   $\sqrt{r_2} - \sqrt{R} = 1{,}224.7449 - 79.8185 = 1{,}144.9263$
   $\dfrac{2b}{c} = \dfrac{2 \times 892.86107}{299{,}792.458} = \dfrac{1{,}785.7221}{299{,}792.458} = 0.0059565$
   First term $= 0.0059565 \times 1{,}144.9263 = 6.8198$ km.
4. Compute the second term $\dfrac{2\,b^2}{c^2}\ln\!\left(\dfrac{c\sqrt{r_2} - b}{c\sqrt{R} - b}\right)$:
   $b^2 = 892.86107^2 = 797{,}200.8836$
   $\dfrac{2\,b^2}{c^2} = \dfrac{2 \times 797{,}200.8836}{299{,}792.458^2} = \dfrac{1{,}594{,}401.7672}{89{,}875{,}517{,}874} \approx 1.774 \times 10^{-5}$
   Now the argument of the log:
   $c\sqrt{r_2} = 299{,}792.458 \times 1{,}224.7449 \approx 367{,}169{,}275,$
   $c\sqrt{r_2} - b \approx 367{,}169{,}275 - 892.86107 \approx 367{,}168{,}383,$
   $c\sqrt{R} = 299{,}792.458 \times 79.8185 \approx 23{,}928{,}998,$
   $c\sqrt{R} - b \approx 23{,}928{,}998 - 892.86107 \approx 23{,}928{,}105.$
   Ratio $= \dfrac{367{,}168{,}383}{23{,}928{,}105} \approx 15.345, \quad$ and $\quad \ln(15.345) \approx 2.7308.$
   Second term $= 1.774 \times 10^{-5} \times 2.7308 \approx 4.844 \times 10^{-5}$ km (negligibly small).
5. Sum the terms for the extra distance:
   Extra = first term + second term $\approx 6.8198 + 0.0000484 = 6.8198$ km.
6. Compute the total real distance traveled through AFS space (ct):
   Coordinate distance $\Delta r = r_2 - R = 1{,}500{,}000 - 6{,}371 = 1{,}493{,}629$ km.
   $ct = \Delta r + \text{extra} \approx 1{,}493{,}629 + 6.820 = 1{,}493{,}635.820$ km.

Deficit distance for inward light propagation—James Webb Space Telescope to Earth

Using the analogous reasoning for light moving radially inward (downward) from $r_2 = 1{,}500{,}000$ km to $R = 6{,}371$ km, the proper distance traveled through the AFS of space is shorter than the coordinate distance $\Delta r = 1{,}493{,}629$ km by the deficit amount

$$\int_R^{r_2} \frac{v(r)}{c + v(r)}\, dr.$$

The closed-form expression for this deficit, derived similarly via substitution $u = \sqrt{r}$, is:

$$\frac{2b}{c}\left(\sqrt{r_2} - \sqrt{R}\right) - \frac{2\,b^2}{c^2}\ln\left(\frac{c\sqrt{r_2} + b}{c\sqrt{R} + b}\right),$$

where $b = \sqrt{2GM}$.

Using the same values as previously, this evaluates to approximately 6.82 km. Thus, the light has moved approximately 6.82 km *less* through the AFS of space, for a total distance of approximately 1,493,622 km.

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