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Inertial frames and breakthrough propulsion physics

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A R T I C L E I N F O

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A B S T R A C T

The term “Breakthrough Propulsion Physics” comes from the NASA project by that name which examined non-rocket space drives, gravity control, and faster-than-light travel. The focus here is on space drives and the related unsolved physics of inertial frames. A “space drive” is a generic term encompassing any concept for using as-yet undiscovered physics to move a spacecraft instead of existing rockets, sails, or tethers. The collective state of the art spans mostly steps 1–3 of the scientific method: defining the problem, collecting data, and forming hypotheses. The key issues include (1) conservation of momentum, (2) absence of obvious reaction mass, and (3) the net-external thrusting requirement. Relevant open problems in physics include: (1) the sources and mechanisms of inertial frames, (2) coupling of gravitation to the other fundamental forces, and (3) the nature of the quantum vacuum. Rather than following the assumption that inertial frames are an immutable, intrinsic property of space, this paper revisits Mach's Principle, where it is posited that inertia is relative to the distant surrounding matter. This perspective allows conjectures that a space drive could impart reaction forces to that matter, via some as-yet undiscovered interaction with the inertial frame properties of space. Thought experiments are offered to begin a process to derive new hypotheses. It is unknown if this line of inquiry will be fruitful, but it is hoped that, by revisiting unsolved physics from a propulsion point of view, new insights will be gained.

1. Introduction

A “space drive” is a notional device for propelling a spacecraft using only the interactions between the spacecraft and its surrounding space, without needing to transport and expel propellant. While the scientific principles from which to engineer such effects have not been discovered, the presumed benefit, when compared to rockets, is that such a device could deliver a greater total mission Δv for a given amount of energy. For interstellar missions the performance gain is about 100 orders of magnitude. The potential benefit when compared to space sails, is that the spacecraft can maneuver independently without any dependency on incoming photons. Another possible benefit is that the physics discoveries necessary to enable such devices would have other utilities – perhaps providing an acceleration field inside a spacecraft (mimicking a gravitational field) for long-duration crew health.

Perhaps the earliest space drive concept to appear in scientific journals was “negative matter” propulsion in 1957 [1]. Other concepts and analysis followed. The most substantive of these were assessed by comparing their critical make-break issues to open questions in physics to determine next-step research questions [2]. Thereafter, 24 examples of space drive concepts were categorized by their physics discipline and then compared in terms of their development status, key issues, and inferred reaction mass [3]. A key table from that publication is included at the end of this report, as Table 1, with updates based on recent progress on the “Mach Effect Thruster” [4] and recent publications on the “EmDrive” [5,6].

From this prior work, it was found that a common ambiguity to most space drive concepts is ensuring conservation of momentum relative to inertial frames. Inertial frames are the reference frames upon which the laws of motion and the conservation laws are defined, yet it is still unknown what causes inertial frames to exist and if they have any deeper properties that might prove useful [7].

Given its key relevance and unknowns, this paper focuses on the physics of inertial frames. First, the main findings of the preceding space-drive work are reviewed, including: the anticipated energy benefit, problem statement, general lines of inquiry, and a review of inertial frame physics. A series of thought experiments are then offered, using a Machian perspective of inertial frames, to illustrate a process to develop new hypotheses. Several different mathematical representations could be posited from this exercise, whose consistency with physical observables could be checked afterwards.

2. Anticipated energy benefit

In principle, the potential benefit of a space drive can be shown by

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Table 1
Compilation and comparison of space drive inquiries, reprinted and updated from Ref. [3] with permission. The shaded cells represents nonviable concepts.

Line of Inquiry		Form	Key Issue or Next Step	Reaction Mass	Net External Thrust	Since (Yr)	Literature Search Author Suggestion	Starting Reference
Common Misinterpretations	Stiction Drives	Devices	Misinterpreting the effect of static and dynamic friction	Floor	–	1959	“Dean Drive”	[2]: p. 249–254
	Gyroscopic Antigravity	Devices	Misinterpreting torques as linear forces	–	No	1973	Laithwaite	[2]: p. 254–259
	Lifters et al.	Devices	Misinterpreting ion wind as and an antigravity effect	Air	–	1920s	Biefeld–Brown	[2]: Ch. 8–9
	Enhanced Photon Momentum	Theory + Experiment	Incorrect combination of incompatible formalisms	–	No	1949	Slepian, Corum, Brito	[2]: Ch. 10
Fundamental Forces	“Antigravity”	Slang	Clarifying semantics	–	–	1900?1932?	Mader, Greg, Walsh	[51,52]
	“EmDrive”	Experiment	Improve fidelity of experimental data	?	?	2002	Shawyer	[5,6]
	Gravity-Shielding Superconductor	Experiment	Misinterpretation of observations	–	–	1992	Podkletnov	[2]: p. 140–242 [53,54]
	Electro-Gravitation	Experiment	Improve statistical significance of data	?	?	1991	Yamashita	[2]: Ch. 7
	Atomic Gravity	Anecdotal experiment	Advance to assessable equations with derivations	?	?	1950s	Alzofon	[2]: p. 221
	“Graviphoton”	Speculation	Derive testable equations	?	?	1996	Heim, Dröscher	[2]: p. 218–221
	Tachyon Drive	Speculation	Requires neutrinos to become tachyons	Neutrinos	Yes	1996	John Cramer	[55]
Inertial Reference	Higgs Mechanism	Theory	Apply theory & experimental data to propulsion	?	?	1962	P. W. Anderson, Higgs	[15,16]
	Modified Inertia Rockets	Speculation	Assess energy conservation and time-rate changes	Propellant	Yes	2009	Millis	[2]: p.138–143
	Negative Mass Propulsion	Speculation, Theory	Seek theoretical and experimental evidence for/against negative inertia	(internal)	Yes	1957	Bondi, Forward	[2]: p. 160–162, 180–184
	Mach-Effect Thrusters of Woodward	Theory + Experiment	Increase magnitude of effect and publish more detailed experimental data	Inertial frame	Being tested	1990	Woodward	[2]: p. 156 [2]: Ch. 11 [4,8,56–58]
	Anomalous Frame Dragging	Experiment	Subsequent experiments found no effect	–	–	2001	Tajmar	[2]: p.243 [59,60]
	Frame Coupling Propulsion	Speculation	Derive testable equations	Inertial frame	?	1996	Millis	[2]: p. 134–137, 160–165
Quantum Spacetime	Quantum Energy Sail	Speculation	Derive testable equations	Quantum energy	If flux sustained	1996	Millis	[2]: p. 152–154
	Vibrating Mirror Propulsion	Theory + Experiment	Explore variations having greater effect	Photons	Yes	2004	Maclay & Forward	[2]: Ch. 12 [21–23]
	Gravity/Curvature & Quantum Vacuum	Theory	Confirm & configure into propulsive embodiment	–	–		Maclay, Pinto, Calloni	[2]: p. 213–218 [30,42]
	Inertia by Vacuum or Unruh Effect	Speculation	Derive testable equations	–	–	1994, 2008	Haisch, McCulloch	[2]: Ch. 13 [37,61]
Riemannian Spacetime	Gravitational Dipole Generator	Theory	Explore variations for greater effect	Mass of Generator?	Yes	1963	Forward	[2]: p. 185
	Levi-Civita Effect	Theory	Rearrange into propulsive embodiment and explore variations for greater effect	–	–	1917	Levi-Civita	[2]: p. 198
	Space Strain, Metric Engineering	Theory	Explore variations, Examine time-rate-of-changes	Spacetime	–	1988 1994	Minami, Puthoff	[2]: Ch. 15 [20,62,63]
	Gravitational Wave Propulsion	Theory	Less efficient than a photon rocket, at best	Gravitons	Yes	1973 1997	Bekenstein, Bonner	[2]: p. 201

comparing the kinetic energy for just the vehicle (analogous to an ideal space drive) to the energy required for a rocket. eq. (1) shows the energy, E_D, required for a rendezvous mission using an ideal space drive (simply kinetic energy), while eq. (2) shows the energy approximation, E_R, for the rocket. These equations assume 100% efficiency for both systems and where thrusting times are much shorter than trip times [2]: p. 145. These are not optimized equations, but rather introductory examples to illustrate the differences.

$$E_D = (2)\frac{1}{2}m\Delta v^2 \tag{1}$$

$$E_R = \frac{1}{2}mv_{\mathrm{ex}}^2\left(e^{(2)\frac{\Delta v}{v_{\mathrm{ex}}}} - 1\right) \tag{2}$$

where:

E = kinetic energy required, J
m = mass of ship, kg
Δv = required delta-v for one maneuver, m/s
v_{ex} = rocket exhaust velocity, m/s

Two things are important to note regarding the energy differences. First, the energy for a rocket is an exponential function of Δv, whereas the energy of an ideal space drive is a squared function of Δv. This by itself is significant, but it is important to point out that a rocket and a space drive treat additional maneuvers differently. For a rocket, additional maneuvers require increases to Δv, again part of the exponential function. For a space drive, however, the additional maneuvers are in terms of additional kinetic energy, a linear function. For example, a rendezvous mission requires both an initial acceleration and final deceleration. Notice the location of the factor, "(2)," for this dual thrusting in both equations. In the space drive equation the factor of 2 is applied to the required kinetic energy for one thrusting. In the case of the rocket, however, the factor of 2 must be directly applied to the Δv, which is in the exponent.

For low Δv missions, the difference is insignificant. For high Δv missions, the difference is substantial. For example, consider a probe mass $\approx 10^3$ kg (Voyager), an Isp $\approx 10^4$ s (advanced ion thruster), and a flight time of 100 years to rendezvous with Alpha Centauri (4.3 ly distant) which equates to a $\Delta v \approx 10^7$ m/s for each thrusting (accel, decel). Entering these values into both equations results in a space drive energy $\approx 10^{17}$ J and rocket energy $\approx 10^{111}$ J, a difference of 94 orders of magnitude.

These comparisons are only to illustrate the gains sought, not an assertion of definitive results.

3. Problem statement

The first step of the scientific method is to define the problem. To that end, the critical issues for a space drive are compiled into a problem statement. This not only serves as a checklist to assess proposed solutions, but also to shed light on where to concentrate research attention.

Simply put, a space drive requires a controllable means to induce a unidirectional motion of the vehicle relative to the surrounding space, without expelling a reaction mass, and simultaneously satisfying conservation laws. Regardless of which concept is explored, a mechanism must exist that can affect a property of matter or energy in spacetime and that satisfies these conditions:

- Satisfies conservation of momentum
- Satisfies conservation of energy
- Satisfies the net external force requirement, inducing unidirectional motion of the vehicle
- The propulsive effect must be controllable
- The physics proposed for the propulsive mechanism and for the properties of matter and spacetime must be completely consistent with empirical observations of nature

3.1. *Conservation of momentum and energy*

With the exception of transportation methods based on the formalism of Riemannian geometry (warp drives and wormholes), other methods of propulsion satisfy Newtonian and relativistic mechanics. This means that the momentum change of the vehicle must be equal to and opposite to the momentum imparted to a reaction mass, to satisfy conservation of momentum.

Another possible exception to propulsive momentum conversation deals with Wanser's analysis of Woodward's Mach Effect Thruster [8]. Other than citing this possibility, it will not be further described here. The physics of the Mach Effect Thruster is an ongoing complex investigation, whose operating details are still open for interpretation.

In the general case of space drives, there is no *obvious* source of reaction mass. Naively, space appears empty. However, options for further investigations exist as discussed in Section 5.

Conservation of energy is mentioned for two reasons. The first is for consistency with fundamental physics. The second is to encourage space drive proposals to explicitly address how the energy delivered to the space drive will result in a change in the kinetic energy of the vehicle.

Since these conservation laws are defined relative to an inertial frame, and since the origin of inertial frames is still an open area in physics, this makes the phenomena of inertial frames an important focus of study as discussed in Section 6.

3.2. *Net external force requirement*

A space drive must move the vehicle relative to the surrounding space, rather than just inducing forces internal to the vehicle. A common mistake, especially with naive electromagnetic schemes, is to have thrusting methods where the forces act between internal parts of the vehicle. This is analogous to pushing on a dashboard from inside a car in an attempt to move the car. Instead, a genuine space drive will have to induce forces between the vehicle and something in its surrounding, external space. Further, that "something in the surrounding space" must act as a reaction mass.

A possible exception and alternative research path involves the possibility of negative inertia and "negative mass propulsion." The physics of negative gravitational mass and negative inertial mass were introduced in 1957 by Bondi [1], and then detailed as a propulsion concept in 1990 by Forward [9]. The concept involves placing a hypothetical negative mass behind a normal mass, where their combined interactions cause both to accelerate in the same direction. A crucial feature is that the negative mass is assigned the property of *negative inertia*. For this particular concept, the forces do occur between parts of the vehicle instead of interacting with the surrounding space – an exception to the net external thrust requirement. A variety of experiments, some involving neutrons, are reporting evidence of an "*effective* negative inertia" [10–12].

3.3. *Controllable propulsive effect*

It must be possible to turn on and off the propulsive effect. The propulsive effect must be able to operate in any direction. It must also be accessible while the vehicle is both accelerating and coasting.

Though it may seem premature to go into this level of detail before any potential thrusting effect has been discovered, such details help guide the advancement of speculations into equations. The equations should address energy conservation, operation in both accelerated and non-accelerated reference frames, and the time-rate-of-change properties of the chosen physical phenomena.

4. General lines of inquiry

The first step of the scientific method – defining the problem – leads naturally to setting the context for the subsequent step of collecting and analyzing the data. To assist that information collection, the basic questions become:

- What phenomena are indigenous to space?
- Can *unidirectional* forces be induced by interacting with any of these indigenous phenomena?
- Are the forces and the amount of accessible reaction mass sufficient to propel a spacecraft?

With the exception of the first question, the others are not routine inquires of general physics. Even though general physics works to understand the constituents of space and the properties of spacetime, these inquires are often in the context of the origin and fate of the universe. The point here is that, by introducing a different problem (specifically non-rocket propulsion), additional lines of inquiry are opened. It is hoped, by looking where others have not, that new discoveries will be made. The pursuit of propulsion physics is not just for propulsion, but also another approach to make further progress in physics, even if the desired propulsion breakthroughs cannot be achieved.

Another question is where to look for relevant developments. If the known laws of physics already allowed for space drives, then space drives would most likely already exist. The strategy employed by the NASA Breakthrough Propulsion Physics project was to look for the overlap between unanswered questions in physics and the critical make-or-break issues of the desired breakthroughs [2], Ch. 22. In that theme then, the most pertinent questions in physics are those which are still the least understood.

5. Potential sources of indigenous reaction mass

The term, *indigenous* reaction mass, is chosen to describe phenomena that are natural constituents of space that might serve as a reaction mass for space drives. This includes the observed and inferred *mass* as well as sources of *energy* in space. It also includes the very 'substance' of spacetime itself.

As a cursory comparison, the known possibilities are listed below along with their estimated equivalent mass densities (if known). For items in the form of *energy*, an effective *mass* density is calculated using the $E = mc^2$ relationship [2]: p. 131:

- Cosmic Microwave Background (10^{-31} kg/m^3)
- Dark Matter (10^{-27} kg/m^3)
- Dark Energy (10^{-26} kg/m^3)
- Hydrogen (protons) in open space (10^{-21} kg/m^3)
- Virtual Particle Pairs (depends on energy applied)
- Higgs Vacuum Field
- Predicted Total Cosmological Vacuum Energy (10^{-26} to 10^{98} kg/m^3)
- Spacetime itself (10^{-26} to 10^{98} kg/m^3)

Most of these constituents do not have sufficient mass density to be an effective reaction mass unless the thrusting device spanned an enormous surface area. In the theme of focusing on the physics that are the least understood, the interesting possibilities include virtual particle pairs, the Higgs mechanism, the quantum vacuum, and the very nature of spacetime itself.

5.1. Virtual particle pairs

The idea of using virtual particle pairs (e.g. quark-antiquarks or electron-positrons) as a propulsive reaction mass has been suggested at least as far back as 1997 [13]. If virtual particle pairs can be converted into tangible matter, then the accessible mass will be limited to the energy applied. If a velocity is imparted to this mass, then the more complete version of Einstein's energy equation, eq. (3), should be used to determine how much energy is required to create an amount of reaction mass, *m*, at a relative velocity, *v*, to the spacecraft [14]:

$$E = \frac{mc^2}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \tag{3}$$

where:

E = energy required J
m = reaction mass created, kg
c = light speed, 3×10^8 m/s
v = reaction mass velocity relative to craft, m/s

5.2. Higgs mechanism

The Higgs vacuum field, Higgs boson, or more generally the Higgs mechanism, is a theoretical construct related to the mass of the quarks and leptons in the universe [15]. It is listed here as a placeholder. To date, no propulsion speculations have been published that are based on the Higgs mechanism. It should be noted that the mass of the Higgs boson is about 10^{-25} kg, two orders of magnitude greater than a proton [16].

5.3. Quantum vacuum energy

The quantum vacuum is a significant ongoing topic in physics [17,18]. Estimates for its effective mass density (energy density), span 10^{-26} to 10^{98} kg/m^3, depending on the upper cut-off frequency assumed in the calculation. The lower estimate is based on equating the quantum vacuum to Dark Energy, while the highest is based on the Plank Frequency, 10^{23} Hz – the highest frequency considered physically possible.

Forces between objects and the quantum vacuum have been measured, but the forces are small (10^{-9} N) and act symmetrically on both sides of a "Casimir cavity" [19]. To be useful for propulsion, unidirectional forces and of a greater magnitude are needed.

There have been several articles that consider the propulsive implications of the quantum vacuum. A general description of approaches and issues is offered by Puthoff [20], and a specific propulsion concept was introduced by Maclay [21]. This propulsion concept started as a thought experiment about a dynamical Casimir effect, which was experimentally demonstrated later by others [22]. The propulsion efficiency of this concept is still very low. The ratio of the change in kinetic energy verses the energy consumed is only 10^{-26} [23]. These inquiries remain an open area of study.

Because these approaches are already under study, they will not be further explored here, except in the context of theories that attempt to link inertia to the quantum vacuum, as discussed in Section 6.5.

5.4. Spacetime itself

The notion of using spacetime itself as a reaction mass is just conjecture at this time. The issues include estimating its effective reaction mass density, and then how to interact with that effective mass to create unidirectional motion.

Absent of any theories from which to estimate its effective mass density, a provisional guess is that spacetime might span the same range of uncertainty as the quantum vacuum energy, 10^{-26} to 10^{98} kg/m^3. The possible connection between the quantum vacuum and inertia is discussed in Section 6.5. A prior mass density estimate by this author [2], p. 137 was found to be in error.

6. Physics of inertial frames

An inertial frame is a property of spacetime where accelerated motion of matter is measureable – the reference frame for Newton's and the relativistic forms of $F = ma$, and the related conservation laws.

Given the existence of one inertial frame, any number of other inertial frames exist, where the necessary condition is that they move at constant velocity relative to the original frame (up to lightspeed). This equivalence of multiple inertial frames is an anchoring assumption in special and general relativity. A general term for this is Lorentz invariance.

Considering the equivalence principle, where gravitational and inertial mass are considered equivalent, the properties of spacetime that give rise to gravitation are likely related to inertial frames.

There are at least two perspectives on the origins of inertial frames; that inertial frames are just an intrinsic, unalterable property of space, or that they are a function of the distribution of the surrounding matter in space. The former perspective is consistent with Riemannian geometry, while the latter is based on Mach's principle.

6.1. *Inertial frames in Riemannian geometry*

Riemannian geometry describes how spacetime is distorted in the presence of mass or energy. Its foundation is constructed to provide frame-independent representations [24]. Though seldom stated explicitly, this formalism assumes that inertial frames are an intrinsic, unalterable property of spacetime.

The Riemannian formalism is rooted in the perspective that conservation laws apply *locally*, and that assemblages of many local increments of spacetime, even when distorted, will *implicitly* satisfy conservation of momentum as a whole. Imbedded in the solutions of the field equations are the necessary conditions for conservation laws. This is related to Noether's theorem which shows the consistency of physical laws from one place to another leads to conserved quantities overall, including conservation of momentum [25].

The difficulties with the Riemannian formalism appear when attempting to address momentum conservation more globally. For example, there is no means in this formalism to explicitly demonstrate that the motion of an object, using warp drives or wormholes, will satisfy global conservation of momentum over its initial and final locations [26]: p. 499–500.

6.2. *Mach's principle*

"Mach's principle" (a term coined by Einstein in 1918) asserts that the inertial properties of matter are actually due to the surrounding mass in the Universe [27]. "Inertia here because of matter there." In contrast to the Newtonian concept of "absolute space," Mach was attempting to find a *relational* definition for inertia, where acceleration would only have meaning relative to the location of other masses.

Einstein, using Riemannian geometry, attempted to incorporate the notion of Mach's principle, or "relative inertia," into General Relativity, but did not succeed [7].

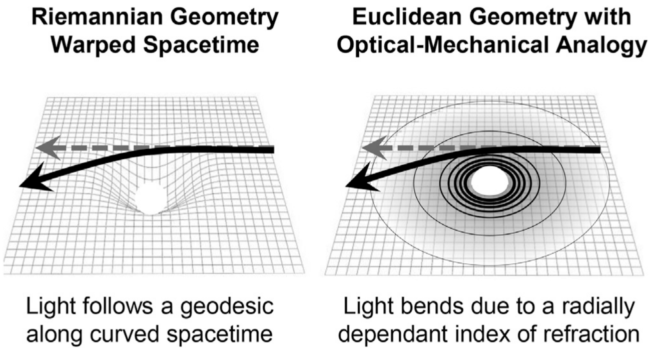

Fig. 1. Deflection of light near a gravitating body described in different general relativity formalisms.

There have been several different attempts to advance Mach's principle into a mathematical description, some of which have been dismissed. An extensive reference about Mach's principle, complete with transcribed conference discussions, was compiled by Barbour & Pfister in 1995 [7]. On page 530 of that reference, 21 different formulations of Mach's principle are listed. One noteworthy debate arose when Rindler asserted that a Machian view of the Lense-Thirring effect predicted the wrong direction [28], to which Bondi and Samuel showed that another version of Mach's principle predicted the correct direction [29].

Ironically, a literal interpretation of Mach's principle implies an *absolute* reference frame, coincident with the mean rest frame for all the matter in the Universe [7]. This is because the location of that inertial frame tracks directly with the position of that matter. At first glance this notion of such a *progenitor* inertial frame (*the* frame created by, and referenced to, the mass distribution) might appear to violate Lorentz invariance. Even if a progenitor frame were an absolute reference frame in that Machian sense, Lorentz invariance would still be satisfied across all the other inertial frames (moving at constant velocity to the progenitor frame).

A natural phenomena that has been observed to be coincident with the mean rest frame of the universe is the cosmic microwave background. This property is detectable by Doppler shifts when moving through this background [30]. Discovered in 1964, this microwave background (interpreted to be a remnant of the big bang) was unknown when much of the debate about Machian perspectives in general relativity were underway (1905–1920s).

If the Machian perspectives of inertial frames are true, could there then be a connection between the cosmic microwave background and a progenitor Machian frame (in addition to cosmic microwaves being a remnant of the big bang)? Another open question is, how does this track with the expansion of the universe (or the Hubble redshift observations from which the expansion was first hypothesized)?

Though we think of an inertial frame as being homogenous and isotropic, that interpretation refers to local regions of spacetime. If an inertial frame is indeed created by surrounding matter, then in principle, the properties of an inertial frame will vary if that distribution of matter is altered. Does this mean then, that the motion of *local* masses will have a *perceptible* affect on their *local* inertial frame? Sciama, who posited a version of Mach's principle based on gravitational effects, showed that the contributions of nearby masses would be insignificant when compared to the larger inertial frame from the greater distant matter [31,32].

6.3. *Euclidean geometry and the Optical–Mechanical analogy*

Although some Machian hypotheses have been formulated using Riemannian geometry, or at least using the tensor representations inherent with Riemannian geometry, many other versions are formulated in Euclidean geometry. As stated before, Riemannian geometry is more consistent with assuming that inertia is an intrinsic, unalterable property of space. The Machian versions assume that an object's inertia is relative to the distribution of masses throughout the universe. Such distributions are easier to model in Euclidean geometry.

When switching to Euclidean geometry, it is necessary to use a different way to represent the connections between gravitation and electromagnetism, such as light bending in a gravitational field. One of the approaches is the "optical–mechanical analogy," where space is treated as having a variable index of refraction that is a function of a gravitational scalar potential. Though most articles attribute this idea to Eddington [33], others cite that the idea goes as far back as Descartes (1637) [34]. A succinct summary of the evolution of these ideas was offered by Ye [35], which lists the different formulations including the following for the relative index of refraction for space around a gravitating body of mass, M, from de Felice eq. (4) [36] and Puthoff eq. (5) [37]:

$$n = \frac{\left(1 + G\frac{M}{2rc^2}\right)^3}{\left(1 - G\frac{M}{2rc^2}\right)} \tag{4}$$

$$n = e^{\left(2G\frac{M}{rc^2}\right)} = 1 + 2G\frac{M}{rc^2} + \cdots \tag{5}$$

where:

n = index of refraction of space, $f(r,M)$
c = light speed, 3×10^8 m/s
G = gravitational constant, 6.7×10^{-11} m^3/kg s^2
M = mass of gravitating body, kg
r = radius from center of gravitating body, m

It has been shown that these optical–mechanical analogs correctly model the deflection of light in a gravitational field, radar echo delay, and gravitational redshift [36,38]. It has also been shown that the optical–mechanical analogy accurately describes the motion of particles with mass in a spherically symmetric field [39].

Regarding light bending in the presence of a gravitating body, the Riemannian version treats light as following a geodesic in curved spacetime (see Fig. 1, left) and where the Euclidean version describes light bending because of a radius-dependant gradient in the index of refraction in flat space (see Fig. 1, right).

To explain this analogy further, consider the basic relation of distance traveled over time, $d = vt$, where in this case that velocity is the speed of light. In the Riemannian version, the speed of light is held as the universal constant, which means space (d) and time (t) get warped in the presence of gravity. In the Euclidean version, space is considered flat (unchanged d), and then both the speed of light and the measurement of time are affected by gravitation. Again, both formalisms accurately model physical observables.

6.4. *Riemannian vs Euclidean propulsion speculations*

To convey how the two different formalisms affect contemplations of space drives, consider this analogy of moving an automobile across a landscape. The *Riemannian* approach of *spacetime warping* is analogous to reshaping (or moving) sections of the *landscape* so that the automobile will roll passively down hill (or will be carried by the moving landscape) in the desired direction. This requires substantial energy expenditures. The Euclidean perspective, on the other hand, entertains the possibility of inducing net forces between the vehicle and spacetime itself, analogously to how an automobile's tires push against the ground, allowing the vehicle to move locally under its own power. In both cases the reaction mass is the ground, but how to explicitly describe that critical issue is different in each formalism.

6.5. *Inertia, gravity, and the quantum vacuum*

Another line of inquiry is to link inertial and gravitational properties to the quantum vacuum. In 1968, Sakharov posited a connection between gravitation and the quantum vacuum [40]. In 1998, Rueda & Haisch posited that inertial forces are due to an electromagnetic drag force relative to the quantum vacuum [41]. In 2002, Puthoff described general relativity in terms of a polarizable vacuum [37]. And in 2010, Maclay showed a correlation between changes in the quantum vacuum energy to changes in gravitational potential energy [42]. This is a topic of continued study.

Though uncommon, the explicit role of inertial frames is occasionally questioned in quantum theory. One such example is by Dickson [43], who explores how the uncertainty relationships of quantum theory might be affected by inertial frame properties. Interestingly, this exploration explicitly describes inertial frames using Galilean (Euclidian) transformations. The viability of Mach's principle and attempts to link inertia or gravitation to the quantum vacuum remain open.

6.6. *Lingering unknowns*

Though various approaches for describing the relations between spacetime, electromagnetism, inertia, and gravity can accurately model many phenomena, none of them accurately describes all the phenomena. This includes the observations that led to the *dark matter* hypotheses [44,45], observations that led to the *dark energy* hypothesis [46–48], and others. Since none of the theories fully account yet for all natural observations, new physics awaits discovery.

7. Propulsion specific inquires

Amid the possibility for new discoveries, the tactic used here is to entertain approaches that would be advantageous to the goal of creating a space drive. This includes seeking a way for the propulsive forces to be imparted to the surrounding matter of space. It must be stressed that this is a "what-if" exercise instead of asserting that such effects are possible. It will be a separate step to see if any resulting formalisms match physical observables.

To proceed, a Machian viewpoint is assumed, but with a change in perspective. Usually the formalism of Mach's principle describes how an *object's* inertia is related to the distribution of surrounding matter. The alternative here is to split this into two distinct steps. First, the distribution of matter is used to define the *properties of the inertial frame* and then, separately, the properties of that inertial frame are used to describe the motion of matter and light in that frame.

Consider again the very measure of inertia, $F = ma$. Note that this equation has terms for mass, space, and time, suggesting that inertia is a *relationship* between mass and spacetime, not solely a property of mass.

To more explicitly associate an inertial frame to the surrounding matter (which implies a positional reference frame coincident with the mean rest frame of the universe), Euclidean geometry and the mathematics of fields and scalar potentials will be a starting point.

Since Euclidian geometry is used, the optical–mechanical analogy is adopted to describe gravitational affects on electromagnetism.

8. Cursory thought experiments

To evolve these "what-if" assumptions into testable theories, a series of thought experiments are presented. At this stage, these experiments are incomplete and offered to illustrate a process for rethinking the fundamental physics of inertial frames from first principles. There is no assertion at this time that these exercises provide accurate representations of the physical universe. That remains to be seen once such thought experiment's are advanced into testable mathematical representations.

The approach taken here is different from prior versions of Mach's principle, such as those by Sciama, where the inertia of a test particle is described in terms of a direct interaction with surrounding matter [31]. Instead, these exercises entertain the viewpoint that the presence of surrounding matter *imbues space with inertial frame properties*, and then as a separate step, those inertial frame properties affect the motion of mass and light inside that frame. This change is intended to allow exploring notions for how a space-drive might interact with inertial frames.

A consequence of this approach is that the characteristics of an inertial frame are considered *variable* – dependent on the distribution of the surrounding matter that gives rise to that frame. Hence, any changes to the distribution of the surrounding matter will alter the properties of its inertial frame. Then as a separate analysis, it will be necessary to specify how the altered properties of the inertial frame might affect the motion of mass and light within that frame. This notion of a *variable* inertial frame is a departure from familiar teachings, but a necessary "what-if" for these space drive exercises.

With each step in this exercise, there is more than one way hypothesize its constructs. As the sequence of thought experiments progress, these options permutate into a wide range of possible concatenated derivations. Absent of any insights for which versions to choose, a systematic yet arduous approach would be to advance each of these permutations into testable mathematical representations, and then see if any of these accurately match physical observables. For this example exercise, provisional hypotheses are made with each step while alternatives are mentioned later.

8.1. Step-1 – empty spacetime without inertial frames

In essence, these exercises imagine constructing a universe from first principles, starting with nothing. One by one, additional features are added and the effects between the prior and added features are specified.

The starting point is to assume a universe that does not yet have any inertial frame properties or other characteristics that would affect the motion of an object within that space. The first assumption is that this space has the familiar 3 spatial directions and time. This *null frame* is a utilitarian construct for referencing the objects placed later into this nonphysical coordinate system.

If there were a test particle within this space, it would not have inertia. Any relative motion between the non-physical frame and the particle would have no affect on the particle. This means that there would be no resulting forces if the particle were accelerated relative to that nonphysical coordinate system. Granted, this is difficult to visualize because it runs contrary to our basic founding assumptions.

8.2. Insert an imaginary inertial frame

Next, insert a spherically symmetric shell into that null space, where we define the region *inside* that shell to provide a homogeneous and isotropic inertial frame, and where the properties of that inertial frame are a function of the size and amount of matter of that shell. Regions outside that shell are of no interest at this time. Just like before, there will be no resulting forces if the shell and nonphysical coordinate system are accelerated relative one another.

At this point a provisional choice is that the *matter* of the shell that creates the inertial frame effect is *mass*. One could also posit versions based on *charge*, a combination of mass and charge, or perhaps others.

Now place a stationary test particle inside that shell. By our definition, that particle now has inertia relative to that shell, but not to the nonphysical coordinate system. If the particle is accelerated relative to the shell, it will experience inertial forces relative to that shell. Reciprocally, if the shell is accelerated relative to the particle, there will be forces between the particle and shell. Now imagine moving the nonphysical coordinate system – where its motions will have no effect on the shell or test particle. Now flip that perspective to consider what happens if the shell is moved relative to the nonphysical coordinate system. What happens to the particle in that shell? It is posited that when moving the shell relative to the null frame, the particle within that shell will move in unison with the shell.

8.3. Add a second imaginary inertial frame

Now consider the combined effect of two different, overlapping sources of inertial frames. To proceed, surround the previous spherical shell, now called A, with a larger shell, B, where that larger shell also produces an inertial frame inside. Further assume that the region inside the smaller shell, A, now has the combined contributions of both shells, A and B.

To illustrate the implications, move the shells relative to each other and consider what happens to a test particle whose initial position is at the center of each sphere (where the spheres are initially coincident). Fig. 2 presents three possible outcomes, depending on the degree to which each shell contributes to the meaning of an inertial frame.

If, for example, the outer shell, B, did not exist (or contributed nothing to the inertial frame properties), the test particle would remain fixed at the center of the inner shell, A. Reciprocally, if the inner sphere, A, did not exist (or contributed nothing to the inertial frame properties), then the test particle would remain fixed at the center of the outer shell, B. If both shells contribute to the inertial frame properties located within the inner shell, then the test particle would be somewhere in between the centers of A and B. Its relative position between the centers of shell A and B would somehow be proportional to relative strengths of each shell's inertial frame.

At this point, one could posit a mathematical model for how the two frames combine proportionally to create the inner inertial frame. The easiest to consider is that the position and strength (or amplitude) of the combined inertial frame is a linear superposition of the position and strength of both frames.

8.4. Provisional model for inertial frame strength

The perspective of an inertial frame having a certain *strength*, *intensity*, or *amplitude* is unusual, but central to these exercises. To make it easier to illustrate, consider for the moment that this inertial frame *strength* can be represented by a scalar potential.

For a more familiar example, recall the instructional physics problem of calculating the gravitational field inside of a spherical mass shell (or electric field from a charged spherical shell). Inside that sphere the *field* is zero, but there is a constant, non-zero scalar potential (homogeneous and isotropic) that is proportional to the mass of the sphere, divided by its radius. If we echo those examples, then one way to represent the functional dependence of the inertial frame properties inside the shell could be:

$$\Phi_F = \frac{S_F}{4\pi}\frac{M_F}{R} \tag{6}$$

where:

Φ_F = Scalar potential of inertial frame strength
S_F = Scaling factor
M_F = Source matter of inertial frame effect
R = Radius of spherical shell

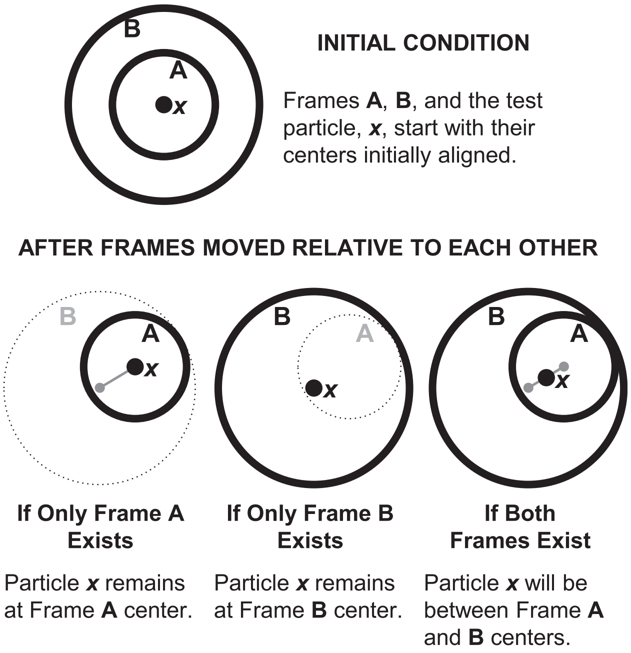

Fig. 2. Thought experiment on the superposition of different inertial frame sources of varying strengths.

The presence of the 4π copies the prior mathematics of both gravitational and electrostatic forces, where those fields fall off as $1/r^2$. In the case of the gravitational scaling factor, also called "Newton's constant," G, the 4π is implicit within that constant. In the case of electrostatics, the 4π is separated from the scaling factor of the permittivity of free space, ε, and so the 4π shows up in the electrostatic equations.

The scaling factor, S_F, will depend on both the units chosen to represent the variables and the natural properties of the space.

For now it is sufficient to notice the functional relationship for this provisional example of a mathematical representation. Specifically, the strength of an inertial frame, Φ_F, increases with more source matter, M_F, and decreases as that matter is spread farther apart over a radius, R.

When combining more than one overlapping inertial frame, the composite frame's strength inside the smallest shell can be taken as the linear sum of all the frames' scalar potentials, Φ_F. The position of the center of the composite frame can be taken as the center of mass of all overlapping frames, whose positions can be referenced to the null space coordinates. Other options for mathematical relationships and summing rules exist.

For comparison, the Riemannian geometry description for the inside of a spherical shell is similar, but not identical to the Euclidean version. In the case of a *non-rotating* sphere, both the Riemannian and Euclidean formalisms yield the same result of the absence of a gravitational *field* (or "flat Minkowski space") inside the shell [49,50]. Unlike the Euclidean version, the Riemannian version does not describe a scalar potential value. Another difference is that the Riemannian version indicates that there will be a frame-dragging effect inside a *rotating* shell.

8.5. Inertial frame affecting inertia

The next step is to specify how an inertial frame affects inertia. To illustrate, consider two different inertial frames, one weaker and the other stronger. Provisionally, it is posited that the *effective inertia* of an identical test mass in each frame would be less in the weaker frame and greater in the stronger frame. For example, if the same force is applied between the frame and test particle in each frame, the resulting acceleration would be greater in the weaker frame, as illustrated in Fig. 3. Similarly, if a test particle has the same momentum in each frame, then the velocity of the particle would be greater in the weaker frame.

To represent this mathematically, one could hypothesize that the frame's inertial strength affects the test particles *mass*, its *motion* (acceleration and velocity), or some combination of *both*. In the case of hypothesizing that the inertial frame affects *motion*, then that could be represented by how the frame's strength affects the rate of *time*.

Again, these thought experiments are a work in progress. With each added step there is more than one way to mathematical represent that step. So far the steps include; (1) establishing a relation between an inertial frame's strength and the surrounding matter (using the simple case of a spherical shell), and then (2) how the strength of that frame affects the motion of a mass inside that frame.

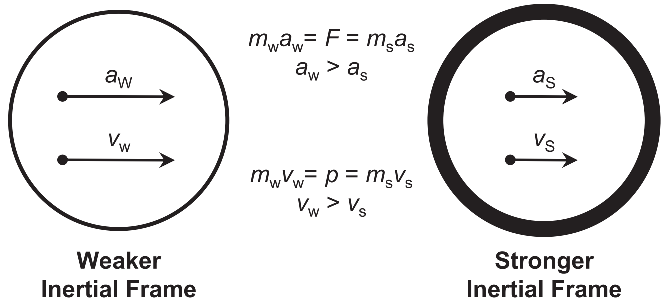

Fig. 3. Thought experiment about changing inertial frame strength and its effect on the motion of mass.

8.6. Inertial frame affecting lightspeed

The prior step considered how an inertial frame's strength affects the motion of mass. This step considers how an inertial frame's strength affects the motion of light.

For comparison, the Riemannian formulism for the inside a spherical mass shell shows that the speed of light inside the shell would appear slower to an external observer – that the clocks run slower inside a spherical mass shell [50]. Similarly, the optical-mechanical analogy states that the speed of light is slower near a gravitating body – described as a function of the gravitational scalar potential. It follows then that the speed of light would be slower in a spherical shell having more mass or a smaller radius. In other words, the greater the absolute value of that scalar potential, the slower the lightspeed.

Following those lines of thought, it is posited that the strength of an inertial frame will affect the speed of light inside that frame, where a stronger frame yields a reduced speed of light, as illustrated in Fig. 4. We can define this relationship in terms of how the frame's strength affects *lightspeed*, the rate of *time*, or some combination of *both*.

8.7. Propagation delay for changes in inertial frames

Another situation to ponder is if there is a lag time for a test particle to react to the motion of a frame. So far the implicit assumption is *instantaneous* tracking, where the test particle and frame move simultaneously in unison. One can also consider a time delay, where the test particle does not immediately react to the motions of the frame (or to changes in the frame's properties). This situation allows consideration that there is a finite propagation speed for inertial frame effects.

In general relativity it is hypothesized that the propagation speed for gravitational effects is identical to lightspeed and there is no experimental evidence to suggest otherwise (the speed of quadrupole gravitational waves is a separate phenomenon) [24]. For this exercise of exploring new laws of motion, it would be more illuminating to leave this question open. Consider that lightspeed in these exercises (and in the optical-mechanical analogy) is variable. To encompass more possibilities, this exercise considers that the propagation speed of inertial frame effects might be different than lightspeed, different than the speed of gravity, or perhaps even variable.

To convert these hypotheses into mathematical representations, different possibilities again arise. The propagation speed of the inertial frame effects can be considered a constant related to the non-inertial null space, or as a variable depending on the characteristics of the frame (where changes to the distribution or amount of the frame's matter might alter that speed), or some combination thereof.

8.8. Compilation of different step hypotheses

With each step in this exercise, it has been shown that there is more than one way hypothesize its constructs. With each additional step, the

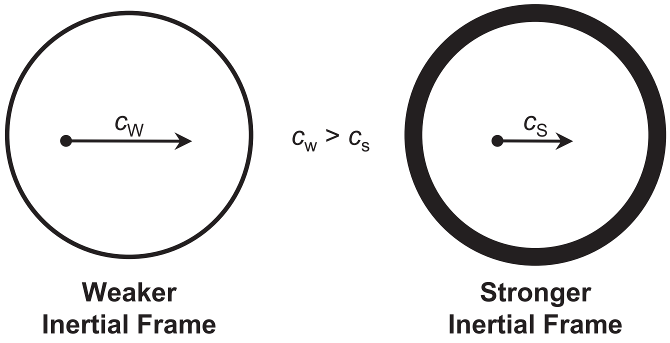

Fig. 4. Thought experiment about changing inertial frame strength and its effect on lightspeed.

options permutate into a wide range of possible concatenated derivations. At this time, such thought experiments are a work in progress and offered more to illustrate the process than to assert a specific derivation. To cover all the possibilities, it would be necessary to advance each of these permutations into testable mathematical representations, and then see if any of these accurately match physical observables. To that end, a span of possible hypotheses for each step are compiled below:

- How does the distribution of matter define the strength of an inertial frame? (The introductory example modeled a spherical shell of matter).
  - Is the basis of assuming a 3-dimensional space with one time dimension adequate?
  - What kind of “matter” contributes to the inertial frame's strength?
    - Gravitational mass
    - Electrical charge
    - In terms of an energy density
    - Another hypothesized phenomenon
    - Some combination of these
  - How does that inertial frame effect spread over space?
    - Following an inverse square law like mass and charge
    - Wave phenomena
    - Some combination of these
    - Other
  - How do the effects of multiple sources of inertial frames combine, both in the case of uniform overlapping frames and individual points of matter?
    - Linear superposition of a scalar value
    - Linear superposition of other field or vector values
    - Nonlinear summations
- What is the delay rate for how long a change in the frame's position will reach and affect a test particle?
  - Instantaneous
  - A constant propagation speed, attributable to a property of the null space
  - A variable depending on the inertial frame's strength
  - Some combination of these
- How does the strength of an inertial frame affect acceleration for objects in the frame?
  - The frame affects the perceived inertial mass of the particle
  - The frame affects the resulting acceleration, with the particle's inertial mass unaffected
  - The frame affects the rate of time
  - Some combination of these
- How does the strength of an inertial frame affect momentum for objects in the frame?
  - The frame affects the perceived inertial mass of the particle
  - The frame affects the resulting velocity, with the particle's inertial mass unaffected
  - The frame affects the rate of time
  - Some combination of these

Again, these are only beginning steps to develop a new formalism. It is hoped that, by sharing these exercises, more complete attempts will follow.

9. Conclusions

At this stage, the physics from which to engineer a space drive does not exist, but the subject has advanced to at least the first stage of the scientific method – defining the problem. Though there are a number of space drive concepts, few have advanced to having testable hypotheses. Most can be considered provisional concepts.

A common issue with space drive concepts is ensuring that they satisfy conservation of momentum, which then leads to open physics questions about the inertial frame properties of space. Inertial frames are the reference frames for Newton's and the relativistic laws of motion, but it is still unknown what causes inertial frames to exist and if they have any deeper properties that might prove useful.

To further explore the possibilities of space drives, various approaches regarding the origins of inertial frames were examined to identify which are more advantageous to space drive contemplations. Of these, a variation of Mach's principle is considered – where inertial *frames* are considered to be created by surrounding matter, and then as a separate step, how the properties of that frame affect the motion of mass and light within that frame. This is more applicable than the alternate assumption that inertia is a fixed, intrinsic property of space. Further, since such an interpretation of Mach's principle leads to a unique reference frame for the universe, Euclidean geometry, instead of Riemannian geometry, is selected. The choice of Euclidean geometry then necessitates using the “optical–mechanical analogy” to model the relationship between gravitation and light.

A short series of thought experiments were offered to begin the development of a new formalism based on these assumptions. In the course of these initial exercises, numerous different hypotheses are possible, hence a large number of resulting formalisms to develop and test.

Physics is ever evolving. Amid the unknowns there is room for more discoveries. It is hoped that, by viewing the unsolved physics from a propulsion point of view, this additional line of inquiry might lead to new discoveries.

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