Challenge to Create the Space Drive
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To travel to our neighboring stars as practically as envisioned by science fiction, breakthroughs in science are required. One of these breakthroughs is to discover a self-contained means of propulsion that requires no propellant. To chart a path toward such a discovery, seven hypothetical space drives are presented to illustrate the specific unsolved challenges and associated research objectives toward this ambition. One research objective is to discover a means to asymmetrically interact with the electromagnetic fluctuations of the vacuum. Another is to develop a physics that describes inertia, gravity, or the properties of space-time as a function of electromagnetics that leads to using electromagnetic technology for inducing propulsive forces. Another is to determine if negative mass exists or if its properties can be synthesized. An alternative approach that covers the possibility that negative mass might not exist is to develop a formalism of Mach's principle or reformulate ether concepts to lay a foundation for addressing reaction forces and conservation of momentum with space drives.

Nomenclature

A	=	magnitude of hypothetical pitch drive effect, m/s^2
$a_{(-m)}$	=	acceleration of negative mass, m/s^2
$a_{(+m)}$	=	acceleration of positive mass, m/s^2
B	=	magnitude of hypothetical bias drive effect, $1/m$
d	=	distance, m
e^{-r^2}	=	Gaussian distribution over r, dimensionless
G	=	Newton's gravitational constant, N m^2/kg^2
m	=	normal mass, kg
$(-m)$	=	hypothetical negative mass, kg
m_i	=	inertial mass; property of mass that determines the relation between applied force and resulting acceleration exclusive of other mass properties, kg
m_R	=	reactant mass; property of mass that experiences a reaction force from a gravitational field exclusive of other mass properties, kg
m_{Ri}	=	inertial mass property of a reactant mass, kg
m_S	=	source mass; property of mass that causes a gravitational field exclusive of other mass properties, kg
m_{Si}	=	inertial mass property of a source mass, kg
r	=	distance over x-y plane $[r = (x^2 + y^2)^{1/2}]$, m
V	=	gravitational scalar potential, J/kg

Introduction

NEW theories have emerged suggesting that gravitational and inertial forces are caused by interactions with the electromagnetic fluctuations of the vacuum.[1,2] There have also been studies suggesting experimental tests for mass-altering affects,[3] and a theory suggesting a warp drive.[4] With the emergence of such new possibilities, it may be time to revisit the notion of creating the visionary space drive. Space drive, as defined here, is an idealized form of propulsion where the fundamental properties of matter and space-time are used to create propulsive forces anywhere in space without having to carry and expel a reaction mass. Such an achievement would revolutionize space travel as it would circumvent the present constraint of requiring propellant. Without such a discovery, human interstellar exploration may not be possible.[5]

One of the missing prerequisites to achieving this breakthrough is having a starting point for the research—a description of the specific problems to be solved. Without this first step of the scientific method, there is no framework against which to assess, augment, and apply emerging science to the goal of creating a space drive.

To provide such a starting point, a variety of hypothetical space drives are presented and analyzed to identify the specific problems that have to be solved to make such schemes plausible.

Problem Formulation Method

A NASA precedent for systematically seeking revolutionary capabilities is the Horizon Mission Methodology.[6] This method forces paradigm shifts beyond extrapolations of existing technologies by using impossible hypothetical mission goals to solicit new solutions. By setting impossible goals, the common practice of limiting visions to extrapolations of existing solutions is prevented. This method forces one to look beyond existing methods and specify the technologies and sciences that are genuinely needed to solve the problem, whether the solutions exist yet or not.

The theme of the Horizon Mission Methodology is followed here. The impossible goal targeted in this exercise is to create a space drive. In the spirit of the Horizon Methodology, the envisioned propulsion methods can entertain the possibility of physics yet to be discovered. However, to ensure that the envisioned methods are consistent with firmly established physics, the analysis imposes the constraints of conservation of momentum and energy, and requires that observed natural phenomena are not contradicted. From imposing these constraints, the characteristics needed to make space drives plausible can be identified.

Seven different hypothetical propulsion concepts were created for this exercise. These concepts were envisioned by considering analogies to collision forces and interactions with fields to produce net forces.

Hypothetical Collision Sails

One means to produce force is collisions. Conventional rocket propulsion is fundamentally based on the collisions between the propellant and the rocket. These collisions thrust the rocket in one direction and the propellant in the other.

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To entertain the analogy of collision forces for a space drive, consider the supposition that space contains a background of some form of isotropic medium that is constantly impinging on all sides of a vehicle. This medium could be a collection of randomly moving particles or electromagnetic waves, either of which possess momentum. If the collisions on the front of a vehicle could be lessened and/or the collisions on the back enhanced, a net propulsive force would result. Three variations of such a hypothetical collision–sail are illustrated in Figs. 1–3. In all of these illustrations, the rectangle represents a cross-sectional element of the sail, the wavy lines represent impinging waves of the isotropic radiative medium, and the large arrow indicates the direction of acceleration.

For any of these concepts to work, there must be a real background medium in space. This medium must have a sufficiently large energy or mass density, must exist equally and isotropically across all space, and there must be a controllable means to alter the collisions with this medium to propel the vehicle. A high energy or mass density is required to provide sufficient radiation pressure or reaction momentum within a reasonable sail area. The requirement that the medium exist equally and isotropically across all space is to ensure that the propulsion device will work anywhere and in any direction in space. The requirement that there must be a controllable means to alter the collisions ensures that a controllable propulsive effect can be created.
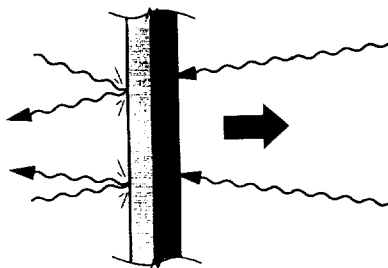

Fig. 1   Hypothetical differential sail. Analogous to the principles of an ideal radiometer vane, a net difference in radiation pressure exists across the reflecting and absorbing sides.
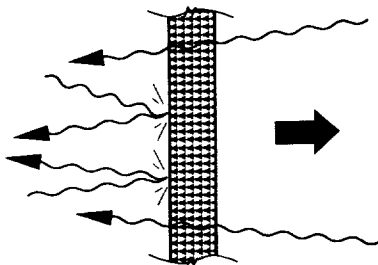

Fig. 2   Hypothetical diode sail. Analogous to a diode or one-way mirror, space radiation passes through one direction and reflects from the other creating a net difference in radiation pressure.
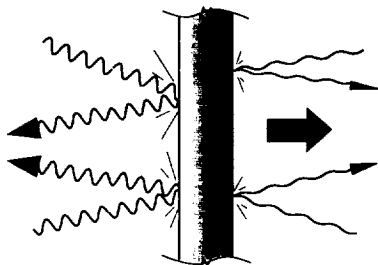

Fig. 3   Hypothetical induction sail. Analogous to creating a pressure gradient in a fluid, the energy density of the impinging radiation is raised behind the sail and lowered in front to create a net difference in radiation pressure across the sail.

The supposition that space contains an isotropic medium is reasonable. Space contains electromagnetic fluctuations of the vacuum, also called the zero point fluctuations (ZPF),[7] cosmic background radiation (CBR),[8] free hydrogen (protons),[9] the theoretically suggested virtual pairs,[10] and possibly even dark matter.[11] Whether any of these media have all of the characteristics needed to be used as a propulsive medium remains a subject for future research.

Regarding conservation of momentum, this condition can be satisfied by using the medium as the reaction mass. Any net momentum imparted to the vehicle must be equal and opposite to the momentum change imparted to the medium.

Regarding conservation of energy, this condition can be satisfied by imposing the constraint that whatever propulsive method or phenomenon is used, the total system energy before and after the propulsive effect is equal. This includes the energy state of the surrounding medium, the energy state of any energy sources on the vehicle, the kinetic energy imparted to the vehicle, and any loss mechanisms.

Hypothetical Field Drives

In addition to producing forces with collisions, forces can be produced from interactions between matter and fields. Gravitational fields accelerate masses and electric fields accelerate charges. To entertain the analogy of using field interactions to create a space drive, it is necessary to assume that there is some way for a vehicle to induce a field around itself that will, in turn, accelerate itself. Field drive concepts are more complex and speculative than collision sail drives. A description of the critical issues follows.

Even if there was a device on a vehicle that could induce a force-producing field, there is still the question of whether such a field would accelerate the vehicle. A typical expectation is that the induced forces would just act between the vehicle's field-inducing device and the rest of the vehicle, like blowing in your own sails, or trying to move a car by pushing on it from the inside. In such cases, all of the forces act internally and there would be no net motion of the vehicle. For reference, this issue can be called the net external force requirement.

The net external force requirement is closely related to conservation of momentum. Conservation of momentum requires that the momentum imparted to the vehicle must be equal and opposite to the momentum imparted to a reaction mass. In the case of a field drive, there is no obvious reaction mass for the vehicle to push against.

Similar to conservation of momentum is the issue of conservation of energy. This issue can be satisfied by imposing the constraint that whatever propulsive method or phenomenon is used, the energy required to create the effect is equal to the kinetic energy imparted to the vehicle and to whatever constitutes its reaction mass, plus any inefficiency losses. In addition, there is also the issue of controllability, ensuring that the force-producing effect can be turned on and off at will.

A closely related aspect to controllability is sustainability. Sustainability refers to the ability to continue the propulsive effect throughout the vehicle's motion. This implies that the force-inducing effect must work in both an inertial frame and an accelerated frame. It also requires that the force-producing field is carried along with or propagated with the vehicle, or at least can be induced again after the vehicle has been set in motion.

In the spirit of the Horizon Methodology, it is assumed a priori that space drives are possible. By doing so and then addressing the critical issues, the required physical characteristics of matter and space to make such propulsion methods plausible can be identified. Future research can then determine whether these conditions can be created with the phenomena that are known to exist, or at least indicate what other phenomena to search for.

Four hypothetical field drives, diametric drive, pitch drive, bias drive, and disjunction drive, are presented next and illus-

trated in Figs. 4–7, respectively. These concepts were envisioned by examining the characteristics that describe a field or how matter reacts to a field, and then assuming it is possible to modify a given characteristic of this relation. The diametric drive works with field sources, the pitch drive with the field itself, the bias drive with the properties of the space that contain the field, and the disjunction drive with the properties of matter that create and react to a field.

A common theme to all of these drives is that an asymmetric field is induced such that a gradient is located at the center of the vehicle, or more specifically at the center of whatever part of the vehicle will experience a reaction force from the field. An asymmetric field is required so that a net force is created on the vehicle.

These concepts are presented in the context of using mass and gravitational properties. A more thorough treatise would
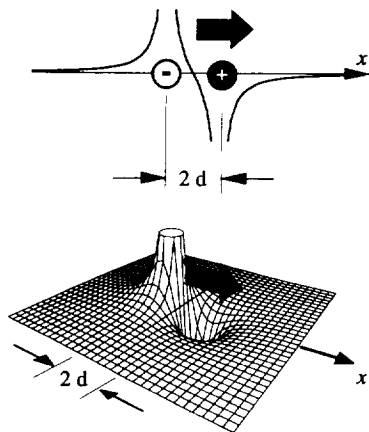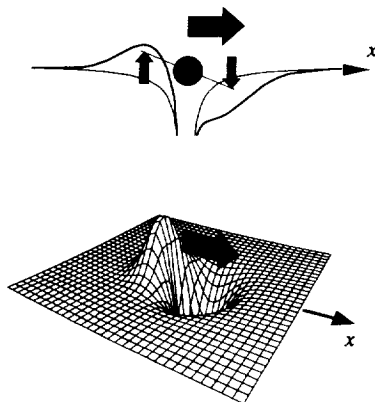
Fig. 4   Hypothetical diametric drive.
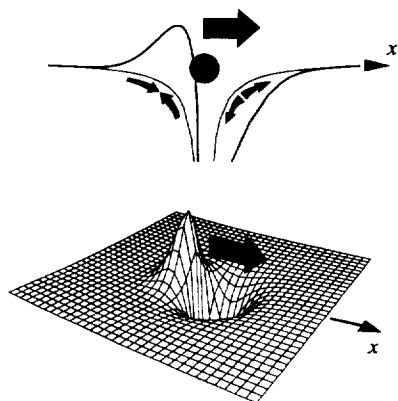
Fig. 5   Hypothetical pitch drive.

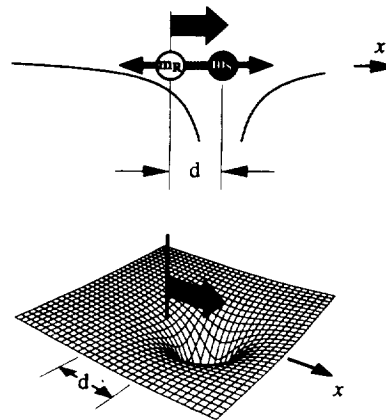**Fig. 6   Hypothetical bias drive.**

Fig. 7   Hypothetical disjunction drive.

also have to address using space media and electromagnetic phenomena.

Diametric Drive

The diametric drive (Fig. 4) considers the possibility of creating a local gradient by the juxtaposition of diametrically opposed field sources across the vehicle. This is directly analogous to the negative mass propulsion.[12–14] The diametric drive can also be considered analogous to creating a pressure source and sink in a space medium as suggested previously with the induction sail.

Negative mass propulsion is not a new concept. It has already been shown that it is theoretically possible to create a continuously propulsive effect by the juxtaposition of negative and positive mass,[12] and that such a scheme does not violate conservation of momentum or energy.[14] A crucial assumption to the success of this concept is that negative mass has negative inertia.

Qualitatively, this concept can be illustrated by the following equation:

$$V = (-m) \left[\frac{-G}{\sqrt{(x+d)^2 + y^2}} \right] + (+m) \left[\frac{-G}{\sqrt{(x-d)^2 + y^2}} \right]$$

$$(1)$$

This gravitational scalar potential is shown as a surface plot over an x-y plane in Fig. 4 (singularities have been truncated for clarity). The first term is the gravitational potential for the negative mass, and the second term is for the positive mass. The negative mass is located a distance d, along the x axis behind the origin, and the positive mass is located a distance d, in front of the origin. The origin is taken to be the midpoint between the two masses along the x axis.

By taking the gradient of the scalar potential caused by the negative mass at the location of the positive mass, and of the positive mass at the location of the negative mass, the accelerations for each mass can be calculated

$$a_{-m} = [-G(-m)]/(2d)^2 \qquad (2a)$$

for the negative mass that is in the positive x direction, and

$$a_{+m} = [G(+m)]/(2d)^2 \qquad (2b)$$

for the positive mass that is also in the positive x direction. Their combined interactions result in a sustained acceleration of both masses in the same direction. This result is also obtained by Forward using an alternative analysis.[14]

Pitch Drive

The pitch drive (Fig. 5) entertains the possibility that somehow a localized slope in scalar potential is induced across the

vehicle that causes forces on the vehicle. In contrast to the diametric drive presented earlier, it is assumed that such a slope can be created without the presence of a pair of point sources. It is not yet known if and how such an effect can be created.

Qualitatively, this can be illustrated by the following equation:

$$V = [(-Gm)/r] + (-xAe^{-r^2})$$ (3)

This scalar potential is shown as a surface plot over an x-y plane in Fig. 5, which is equal to the superposition of the potentials from the vehicle and the induced pitch effect. The term on the left is for the vehicle's gravitational potential. The term on the right represents the hypothetical pitch drive effect where a localized gradient in the scalar gravitational potential is induced across the vehicle. This induced pitch effect is represented by a magnitude A, with a negative slope in the positive x direction, and is localized by a Gaussian distribution centered at the origin. This localizing equation was arbitrarily chosen for illustration purposes only.

By taking the gradient of the scalar potential at the location of the vehicle, specifically the derivative of V with respect to r of the induced pitch effect at $r = 0$, the acceleration for the vehicle is determined to be equal to A, and acts in the positive x direction.

Bias Drive

The bias drive (Fig. 6) entertains the possibility that the vehicle alters the properties of space itself, such as the gravitational constant G, to create a local propulsive gradient. By modifying Newton's constant to have a localized asymmetric bias, a local gradient similar to the pitch drive mechanism results.

Qualitatively, this concept can be illustrated by the following equation:

$$V = (xBe^{-r^2} + 1)[-G(m/r)]$$ (4)

This scalar potential is shown as a surface plot over an x-y plane in Fig. 6. This scalar potential includes the familiar Newton's gravitational potential on the right that is multiplied by a spatially asymmetric modifier on the left. The spatially asymmetric modifier includes a term for B, multiplied by x to give a positive slope in the positive x direction, and is localized by a Gaussian distribution as with the pitch drive. The $+ 1$ identity term is necessary to return the Newtonian gravitational potential to its original form at large distances ($r \gg 0$). Unfortunately, it is not possible to present a qualitative representation for the resulting acceleration for this hypothetical example since the gradient of this scalar potential produces a singularity at the origin.

A similar concept by Alcubierre[4] suggests creating a propulsive effect by asymmetrically altering space-time itself. Alcubierre[4] theorized that by using large quantities of negative energy density with an equally large positive energy density, faster-than-light travel would be possible without violating general relativity. The negative energy density expands space-time behind the vehicle, and the positive energy density contracts space-time in front of the vehicle. The net effect is that this warped space and the region within it would propel itself with an arbitrarily large speed. Observers outside this warp would see it move faster than the speed of light. Observers inside this warp would feel no acceleration as they moved at warp speed. Although a sub-light-speed space drive would constitute a sufficiently important breakthrough, the possibility that a space drive may also enable faster-than-light transport is intriguing. The feasibility of this warp drive theory is an open issue.

Disjunction Drive

The disjunction drive (Fig. 7) entertains the possibility that the source of a field and that which reacts to a field can be separated. By displacing them in space, the reactant is shifted to a point where the field has a slope; thus producing reaction forces between the source and the reactant. It is assumed that the source and reactant are held apart by some sort of rigid device.

Obviously, a critical issue of this scheme is whether the field's source is a separate entity from that which reacts to a field. This perspective is similar to that used in the analysis of the properties of negative mass.[12] In the course of examining the nature of hypothesized negative mass, three different masses can be distinguished: the source mass, reactant mass, and inertial mass. Although these distinctions were made to classically analyze the behavior of negative mass, they do invite speculation. Could either a source or reactant mass be mimicked through some coupling between gravity, electromagnetism, and space-time? If so, the propulsive effect may be possible. This is unknown at this time.

Qualitatively, this concept can be illustrated by the following equations:

$$V = \frac{-Gm_S}{\sqrt{(x - d)^2 + y^2}}$$ (5)

This scalar potential is shown as a surface plot in Fig. 7. It is simply the familiar Newton's gravitational potential of the source mass located a distance d, along the x axis, from the reactant mass. The source mass is defined to have the property that it only causes a field, but does not react to one. The reactant mass is defined to react to the presence of a field, but not to cause one. Thus, there is no force on the source mass from the reactant mass.

To illustrate how this concept works, examine the sum of the resulting forces:

$$\sum \text{forces} = \frac{Gm_S m_R}{d^2} + m_{Si}a + m_{Ri}a$$ (6)

The first term of the sum is the gravitational force from the source mass acting on the reactant mass. By definition, there is no force created on the source mass from the reactant mass, and hence, no term for that force in this equation. However, to entertain the possibility that the source and the reactant mass have inertial mass, terms are included for the reaction forces resulting from these inertiae. These reaction forces are the second and third terms in the summation. Because it is assumed that the masses are rigidly connected by whatever device has pulled them apart, the acceleration a is the same for both masses. Solving for the acceleration gives

$$a = \left(\frac{G}{d^2}\right)\left(\frac{m_S m_R}{m_{Si} + m_{Ri}}\right)$$ (7)

which acts in the positive x direction.

Although existing evidence strongly suggests that the source, reactant, and inertial mass properties are inseparable, any future evidence to the contrary would have revolutionary implications to this propulsion application.

Remaining Research

There are a variety of unexplored paths toward discovering the physics for a space drive. To explore the collision sail concepts, it would be useful to seek any means to interact asymmetrically with the media that are known to exist in space. In particular, the medium of the electromagnetic fluctuations of the vacuum, also called the ZPF, is a promising candidate because of its high-energy density, estimated to be

as high as 10^{114} J/m³. A recent experiment to re-examine the Casimir force, which is an empirical artifact of this energy density, found agreement with the theory at the level of 5%.[15]

Multiple research paths exist to further explore field drive concepts. First, the concept of negative mass, with its inherent negative inertia, could be further explored. Another research path that covers the possibility that negative mass cannot exist, is to develop a formalism of Mach's principle or reformulate ether concepts to provide an alternative means to satisfy momentum conservation for field drives. Such formulations would also have to address how to impart reaction forces against space itself. A more general approach that may encompass these other two approaches is to develop a physics that describes inertia, gravity, or the properties of space-time as a function of electromagnetics that leads to using electromagnetic technology for inducing propulsive forces.

Regarding the physics of negative mass, it is not known whether negative mass exists or if it is even theoretically allowed, but methods have been suggested to search for evidence of negative mass in the context of searching for astronomical evidence of wormholes.[16] If negative mass is found to exist and if methods can be eventually engineered to collect and handle negative mass, it seems reasonable that a propulsive effect could be engineered as previously discussed with the diametric drive. If negative mass does not exist naturally, it is still possible, in the spirit of the Horizon Methodology, to consider the alternative of artificially synthesizing negative mass effects using some as-yet-undiscovered physics, perhaps using a form of gravity–electromagnetic coupling.

The idea of discovering some gravity–electromagnetic coupling goes beyond the idea of mimicking negative mass. If there is any way to modify gravity, inertia, or the properties of space-time using electromagnetics, it may be possible to mimic negative mass to create a gravitational dipole, induce gravitational or electromagnetic fields to create a pitch drive, or modify other properties of space to create a bias drive.

The idea of using one phenomenon to control another is not new. Electric fields are used to create magnetic fields. By knowing the specifics of how these phenomena are coupled, it is possible to engineer such effects. In the case of a space drive, it is hoped to create an acceleration-inducing field using some phenomenon like electromagnetics that can be readily controlled.

Electromagnetism is suggested as the control phenomenon for two reasons: electromagnetism is a phenomenon for which we are technologically proficient, and it is known that gravity, space-time, and electromagnetism are coupled phenomena. In the formalism of general relativity, this coupling is described in terms of how mass warps the space-time against which electromagnetism is measured. In simple terms, this has the consequence that gravity appears to bend light, red-shift light, and slow time. These observations and the general relativistic formalism that describes them are experimentally supported.[9] Although gravity's effects on electromagnetism and space-time have been observed, the reverse possibility, of using electromagnetism to affect gravity, inertia, or space-time, is unknown. To explore this possibility, it would be advantageous to have a formulation that describes these observed couplings as a function of electromagnetics.

Electromagnetism is also suggested as a target phenomenon for space drive research because of the ZPF. The ZPF is an electromagnetic phenomenon. Discovering any way to react asymmetrically with the ZPF would likely create a space drive. ZPF has also been theorized to be an underlying phenomenon to inertia and gravity,[1,2] and experiments have been suggested to test these theories and other related speculations on the relation between the ZPF and mass properties.[3] Note that these theories were not written in the context of propulsion and do not provide direct clues for how to electromagnetically manipulate inertia or gravity. Also, these theories are still too new to have either been confirmed or discounted. Despite such un-

certainties, these theories provide new, alternative approaches to search for breakthrough propulsion physics.

Inherent to all of the propulsive mechanisms discussed in the preceding text is the need to generate an asymmetric field, one that results in a net acceleration of the vehicle. One way to search for such asymmetric effects is to search for nonlinear or nonconserved effects. If, for example, there exists some characteristic coupling between electromagnetism, space-time, inertia, or gravity that behaves nonlinearly, has some hysteresis, or is nonconserved (analogous to friction), it may be possible to create net forces from imbalanced, cyclic perturbations of this effect.

To illustrate this possibility, consider the analogy of an irregularly oscillating mass affixed to a cart that is initially at rest on the floor. When the mass moves slowly in one direction, its reaction forces are not sufficient to overcome the static coefficient of friction between the cart and the floor, and the cart remains still. When the mass moves quickly in the other direction its reaction forces are sufficient to overcome the static coefficient of friction, and the cart rolls. Repeating this cycle results in a net motion of the cart. If there are any field properties of space that have such a characteristic nonconserved interaction analogous to friction, then it may be possible to create an analogous propulsive effect in space.

A more conventional example, which better illustrates the possibilities of nonlinear propulsion, is a method suggested by Landis.[17] This concept outlines a technique for changing the orbits of satellites without using propellant, and does so using conventional physics. It uses tethers on a satellite to take advantage of the nonlinear nature of a gravitational well. If the orbiting satellite extends a tether toward Earth and another tether away from Earth, the imbalanced reactions will create a net force toward the Earth. This is because the downward force on the near-Earth tether increases more than the outward force on the outer tether as the tethers are deployed. By alternately deploying and retracting long tethers at different points during the orbit (apogee and perigee), an orbiting satellite can change its orbital altitude or eccentricity.

Another approach is to revisit the field properties of space itself in search of evidence of imbalanced forces. One experiment to explore this possibility is where a homopolar motor is used to illustrate a paradox of apparently imbalanced magnetic reaction forces.[18] Another is from experimental observations of unipolar induction that explores the relation between magnetic fields and the surrounding space.[19]

To further explore the propulsive implications of any of these imbalanced force concepts, it is necessary to fully address the law of conservation of momentum. In the case of the tether example discussed in the preceding text, the Earth acts as the reaction mass to conserve momentum. In the case of negative mass propulsion, conservation of momentum is satisfied by taking advantage of the negative inertia of negative mass.[14] With the remaining field drives, however, research will be required to determine how the surrounding space can be used to satisfy conservation of momentum.

One approach to conserve momentum is to consider space itself as the reaction mass. This approach evokes the old idea of an ether. To be strictly consistent with empirical evidence, such as the Michelson–Morely experiment, any further research to revisit the idea of an ether would have to impose the condition that an ether is electromagnetically Lorentz invariant. Note that this condition is a characteristic of the ZPF.[7]

An alternative to considering space as the reaction mass is to further develop Mach's principle. Mach's principle asserts that surrounding matter gives rise to inertial frames, and that the inertial frames are somehow connected to the surrounding matter.[9] Mach wrote that although he felt that a connection to the surrounding matter was required for the property of inertia to be detectable, he also admitted that such a treatment was not necessary to satisfactorily describe the laws of motion.[20] To search for new, additional laws of motion to explore the

goal of field drives, it may be useful to revisit Mach's principle more literally. Specifically, to be useful for propulsion physics, a formalism of Mach's principle is required that provides a means to transmit reaction forces to surrounding matter. This implies developing a quantitative description for how the surrounding matter creates an inertial frame, and how pushing against that frame with a space drive is actually pushing against the distant surrounding matter.

It is also possible to consider the very structure of space-time itself as a candidate for propulsive interactions. If it were possible, for example, to create asymmetries in the very properties of space-time that give rise to inertial frames, it may be possible to create net inertial forces. This is similar to the warp drive suggested by Alcubierre.[4]

It is also conceivable that other research approaches exist. To further explore any of these possibilities, it would be useful to have a succinct problem statement to guide the evaluation and application of emerging science toward the goal of creating a space drive. Such a problem statement is offered next.

Problem Statement

The critical issues for both the sail and field drives have been compiled into the problem statement offered next. Simply put, a space drive requires some controllable and sustainable means to create asymmetric forces on the vehicle without expelling a reaction mass, and some means to satisfy conservation laws in the process. Regardless of which concept is explored, the following criteria must be satisfied.

1) A mechanism must exist to interact with a property of space, matter, or energy that satisfies these conditions: it must be able to induce an unidirectional acceleration of the vehicle, be controllable, be sustainable as the vehicle moves, be effective enough to propel the vehicle, satisfy conservation of momentum, and it must satisfy conservation of energy.

2) If properties of matter or energy are used for the propulsive effect, this matter or energy must have properties that enable conservation of momentum in the propulsive process; exist in a form that can be controllably collected, carried, and positioned on the vehicle, or be controllably created on the vehicle; and must exist in sufficiently high quantities to create a sufficient propulsive effect.

3) If properties of space are used for the propulsive effect, these properties must provide an equivalent reaction mass to conserve momentum, be tangible and be able to be detected and interacted with, exist across all space and in all directions, have a sufficiently high equivalent mass density within the span of the vehicle to be used as a propulsive reaction mass, and have characteristics that enable the propulsive effect to be sustained once the vehicle is in motion.

4) The physics proposed for the propulsive mechanism and for the properties of space, matter, or energy used for the propulsive effect must be completely consistent with empirical observations.

Conclusions

Prior to the emergence of new theories suggesting connections between gravity, inertia, and the electromagnetic fluctuations of the vacuum and the recent warp drive theory, the prospects for creating a space drive have seemed too far in the future to provide near-term research opportunities. Now with these emerging theories, new research approaches exist.

To provide a framework for taking advantage of these emerging theories and progressing science toward the goal of a space drive, a problem statement was needed and is now offered in this paper.

Regarding the prospects for breakthroughs, consider the following quotes from past experts:

"Heavier than air flying machines are impossible," "Radio has no future," and "X-rays are a hoax." [William Thomson (Lord Kelvin), President of London's Royal Society (1895–1904)].

"There is no likelihood man can ever tap the power of the atom." [Robert Millikan, Nobel Prize in Physics (1923)].

"The secrets of flight will not be mastered within our lifetime . . not within a thousand years." [Wilbur Wright (1901)].

Acknowledgments

References

[1]Haisch, B., Rueda, A., and Puthoff, H. E., "Inertia as a Zero-Point Field Lorentz Force," Physical Review A, General Physics, Vol. 49, No. 2, 1994, pp. 678–694.

[2]Puthoff, H. E., "Gravity as a Zero-Point-Fluctuation Force," Physical Review A, General Physics, Vol. 39, No. 5, 1989, pp. 2333–2342.

[3]Forward, R. L., "Mass Modification Experiment Definition Study," Phillips Lab, TR-96-3004, Edwards AFB, CA, Feb. 1996.

[4]Alcubierre, M., "The Warp Drive: Hyper-Fast Travel Within General Relativity," Classical and Quantum Gravity, Vol. 11, May 1994, pp. L73–L77.

[5]Millis, M. G., "Breaking Through to the Stars," Ad Astra; the Magazine of the National Space Society, Vol. 9, No. 1, 1997, pp. 36–40.

[6]Anderson, J. L., "Leaps of the Imagination: Interstellar Flight and the Horizon Mission Methodology," Journal of the British Interplanetary Society, Vol. 49, No. 1, 1996, pp. 15–20.

[7]Boyer, T. H., "The Classical Vacuum," Scientific American, Aug. 1985, pp. 70–78.

[8]Muller, R. A., "The Cosmic Background Radiation and the New Aether Drift," Scientific American, Vol. 238, No. 5, 1978, pp. 64–74.

[9]Misner, C. W., Thorne, K. S., and Wheeler, J. A., Gravitation, W. H. Freeman & Co., New York, 1973.

[10]Kaufmann, W. J., III, Black Holes and Warped Spacetime, W. H. Freeman & Co., San Francisco, CA, 1979, pp. 206–208.

[11]Krauss, L. M., "Dark Matter in the Universe," Scientific American, Dec. 1986, pp. 58–68.

[12]Bondi, H., Negative Mass in General Relativity, Reviews of Modern Physics, Vol. 29, No. 3, 1957, pp. 423–428.

[13]Winterberg, F., "On Negative Mass Propulsion," International Astronautical Federation, Paper 89-668, 40th Congress of the International Astronautical Federation, Malaga, Spain, Oct. 1989.

[14]Forward, R. L., "Negative Matter Propulsion," Journal of Propulsion and Power, Vol. 6, No. 1, 1990, pp. 28–37.

[15]Lamoreaux, S. K., "Demonstration of the Casimir Force in the 0.6 to 6 μm Range," Physical Review Letters, Vol. 78, No. 1, 1997, pp. 5–8.

[16]Cramer, J., Forward, R. L., Morris, M., Visser, M., Benford, G., and Landis, G., "Natural Wormholes as Gravitational Lenses," Physical Review D, Particles and Fields, Vol. 51, No. 6, 1995, pp. 3124–3127.

[17]Landis, G. A., "Reactionless Orbital Propulsion Using a Tether," Acta Astronautica, Vol. 26, No. 5, 1992, pp. 307–312; also NASA, TM-101992, April 1989.

[18]Eagleton, R. D., and Kaplan, M. N., "The Radial Magnetic Field Homopolar Motor," American Journal of Physics, Vol. 56, No. 9, 1988, pp. 858, 859.

[19]Kennard, E. H., "On Unipolar Induction: Another Experiment and Its Significance as Evidence for the Existence of the Aether," Philosophical Magazine, Vol. 33, No. 2, 1917, pp. 179–190.

[20]Mach, E., The Science of Mechanics, 5th ed., Open Court Publishing Co., London, 1942.