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EXPLORING THE NOTION OF SPACE COUPLING PROPULSION

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ABSTRACT

All existing methods of space propulsion are based on expelling a reaction mass (propellant) to induce motion. Alternatively, "space coupling propulsion" refers to speculations about reacting with space-time itself to generate propulsive forces. Conceivably, the resulting increases in payload, range, and velocity would constitute a breakthrough in space propulsion.

Such speculations are still considered science fiction for a number of reasons: (1) It appears to violate conservation of momentum. (2) No reactive media appear to exist in space. And (3) No "Grand Unification Theories" exist to link gravity, an acceleration field, to other phenomena of nature such as electrodynamics.

This paper focuses on the rationale behind these objections. Various methods to either satisfy or explore these issues are presented along with secondary considerations. It is found that it may be useful to consider alternative conventions of science to further explore speculations of space coupling propulsion.

INTRODUCTION

Space coupling propulsion is a term offered here to collectively discuss those concepts that consider interacting with the "fabric", or structure, of space-time itself to produce propulsive forces. These concepts have been grouped together because they raise similar issues and unknowns. Some of the more familiar concepts within this category include "anti-gravity", "graviton rockets", and "propellantless propulsion". "Anti-gravity" refers to the negation, control, or generation of gravitational forces, or more generally the concept where a vehicle can induce its own acceleration field (reference 1). "Graviton rocket" refers to the concept of expelling gravitons or gravitational waves to produce reaction forces. "Propellantless propulsion" is a more generic term that refers to any concept that does not need on-board reaction masses, and thus extends beyond the category of coupling to the more conventional concepts of light sails, magnetic sails, or electrodynamic tethers.

In much the same way that pioneering rocketry was inspired by the science fiction of its day (reference 2), these concepts and the awareness of their potential benefits were probably inspired by more recent science fiction. Science fiction images of vehicles that levitate off the Earth or that travel interstellar distances with ease suggest propulsion that does not require propellant, or more specifically, that can induce acceleration fields at will. Without the burden of carrying propellant, payload capacities could dramatically increase, ranges would no longer be limited by propellant supply, and there could even be higher vehicle velocities from continuous acceleration. In addition to such propulsion breakthroughs, the ability to produce acceleration fields could provide artificial gravity to enable crews to endure long voyages. Additional spin-offs could be speculated, but it is enough to say that a discovery on this frontier would constitute an enormous breakthrough.

Presently, such wishful thinking remains within the realm of science fiction for several reasons: Primarily, the notion of producing motion without a conventional reaction mass appears to violate conservation of momentum. In all known forms of propulsion, something acts as the reaction mass. Rockets expel propellant, and aircraft push against the air. Space coupling propulsion can conserve momentum by various means, but implying that some substance in space acts as the reaction mass evokes another objection: There is nothing in the vacuum of space to react against. Finally, speculations about creating a local acceleration field, similar to gravity, evokes another objection: There are no "Grand Unification Theories" (GUTs) linking the fundamental forces of nature to enable controlling gravity via intermediary phenomena, such as electrodynamics.

Because this subject is still speculation rather than engineering, space technologists are not pursuing it. Scientists are pursuing the underlying fundamentals, but that work is not targeted toward space propulsion applications. The main bodies of science that apply most closely to this subject are General Relativity, Cosmology, and Particle Physics. General Relativity deals with gravity and space-time (reference 3), including experiments aimed at detecting gravitational waves (reference 4). Cosmology, which deals with the origin of the universe and the structure of space-time, has combined with Particle Physics in pursuit of GUTs. That quest is largely based on exploring the correlations between the fundamental forces of nature at high energies, like those that existed during the "Big Bang" origin of the universe (reference 5). These approaches are making progress, but they are oriented toward general understanding rather than applications to space propulsion.

Not having any GUTs, however, should not preclude the exploration of space coupling propulsion. The lack of rigorous scientific and engineering theories should not discourage qualitative speculations about space coupling propulsion. By making "what-if" speculations (assuming that it is indeed possible to propel against space-time), while considering the science issues, various ways can be speculated for satisfying the issues, or at least identifying the unknowns within the sciences. Quantitative validation of these ideas or even a detailed identification of the unknowns are beyond the scope of a single paper. This paper is meant primarily to suggest the range of possibilities which could spur further discussion and investigation.

Motivated by the revolutionary benefits, inspired by the science fiction, and challenged by the speculative nature, this paper explores the notion of propelling a vehicle against the structure of space-time. By exploring this notion from a "what-if?" perspective, rather than "what-with?" (engineering tools/methods) we might stimulate thought-provoking explorations, might help shape the tools of science to be more applicable to the perspective of space propulsion, or might even reveal more readily obtainable solutions.

CONSERVATION OF MOMENTUM

The primary reflexive response to the notion of space coupling propulsion is concern over conservation of momentum. Newtonian mechanics requires that momentum be conserved, and propulsion without propellant appears to violate this law. In the case of conventional propulsion, conservation is satisfied because the expelled propellants possess equal and opposite momentum to the vehicle. Space coupling propulsion appears to violate this law because the reaction mass is not readily apparent. Conservation of momentum can be satisfied in various ways that do not require having an on-board supply of reaction mass. These include: conservation by using the contents of space as the reaction mass, conservation by expelling non-mass momentum, conservation by negative mass, and conservation by coupling to distant masses via the intervening space. Several of these treatments, most notably interacting with the contents of space and coupling to distant masses, evoke secondary issues.

Conservation Using the Contents of Space:

Rather than using an on-board reaction mass, momentum can be conserved by using the matter that is available in space in much the same way that aircraft propellers react against the medium of air. Space, however, is commonly thought to be empty which is another major barrier to the notion of space coupling propulsion. Space is not empty, however. Space contains interstellar matter, magnetic fields, star light, Cosmic Microwave Background radiation, and subtle substructures of space like Zero Point Energy and the virtual sea of pair creation/annihilation. And, underlying all of these media, is the "structure" of inertial frames which may also constitute a reactive medium.

The more familiar contents of space, matter, light, and magnetic fields, are probably too feeble to be an adequate reactive media. Methods have been proposed that use these media for propulsion, namely solar sails (references 1,6) and an "Interstellar Ramjet" (references 1,6,7), but these methods do not constitute genuine space coupling propulsion.

A less obvious candidate for a reactive media in space, which was discovered in 1964 (reference 3) and is being studied today by the COBE space craft (reference 8), is the Cosmic Microwave Background radiation. Presumed to be a remnant from the Big Bang, this background radiation permeates all space and appears to be coincident with the mean rest frame of the galaxies surrounding earth, and provides a phenomena by which velocities relative to that frame can be measured (directional doppler shifts). Such features invite using this background as a medium to possibly react against, but, like interstellar matter, it is very feeble (4x10^-34 g/cm^3) (Reference 3). Although not promising as a direct reactive medium, it may one-day provide a useful reference for deep space navigation.

A more fundamental category space coupling media is the substructures of space. These include Zero Point Energy (also known as the vacuum fluctuations of the electromagnetic field) and the sea of virtual pair creation/ annihilation. Zero Point Energy is the absolute minimum energy of a harmonic oscillator at its ground state. This means that even in the vacuum of space, there is a non-zero energy of electromagnetic oscillations (reference 3). The sea of virtual pairs refers to the quantum mechanical possibility that particle pairs (matter-antimatter) are spontaneously produced and reconverged throughout space. Usually they are low energy photons, but could occasionally be electron/ positron pairs (reference 1). Some concepts for reacting against these medium have been speculated and may be candidates for Space Coupling Propulsion (references 1,9).

Perhaps the most likely media for genuine space coupling propulsion are inertial frames themselves. Inertial frames are the fundamental frameworks against which the laws of motion are described, and as such, have some physical significance beyond just mathematical entities. The nature of this physical significance and the correlation to other phenomena is not fully understood. Imagining inertial frames as a candidate reactive media is difficult because inertial frames are used as a reference for observing interactions, rather than as a participant of interactions. The utility of inertial frames will be discussed later in this paper under the heading; "Conservation Using Coupling to Distant Masses".

Perhaps one way to consider interacting with inertial frames is to use the previously described contents of space, in particular, the Cosmic Microwave Background radiation and Zero Point Energy. Both of these phenomena are coincident with inertial frames, and perhaps are fundamentally linked to some "structural" property that may some-day provide an indirect means to reactively couple to inertial frames themselves.

Conservation Using Non-Mass Momentum:

Another way to satisfy conservation of momentum is to consider that some non-mass momentum is expelled from the vehicle, such as photons, gravitons, or hypothetical "space waves' (figure 1). Assuming that it were possible to focus all this expelled radiation along a single direction, the general equation relating power (P), force (F), and velocity (v), P = F x v could be used to indicate the potential force per radiated power. The velocity term refers to the radiation velocity, and in the case of photons and gravitons, this is the speed of light. Entering the speed of light into this equation translates to a rather feeble force per radiated power: 3.3x10^-9 Newtons/Watt.

This force/power equation assumes, however, that the radiation has zero rest mass. Gravitons have been speculated as being a more promising candidate of energy expellant because they might not have zero rest mass and because they are related to mass/acceleration phenomena. Gravitons are quantized gravitational waves analogous to the way that photons are quantized electromagnetic waves. Unfortunately, gravitons are still just theoretical entities, and no methods have yet been proposed for using gravitons for propulsion.

Another avenue for exploring this non-mass momentum theme would be to look for alternative forms of "space waves" that either have a non-zero rest mass, or have much lower propagation velocities than light. Perhaps oscillations in the "structure" of inertial frames may constitute these hypothetical space waves.

(NOTE: The graphic device employed in figures 1-3 is space-time "fabric", where the height of the "fabric" is proportional to gravitational potential. Gradients or "hills" in this graphic fabric represent acceleration fields and, analogous to real hills, induce motion in the "down hill" direction.)

$$E/c = (mv)_{vehicle}$$

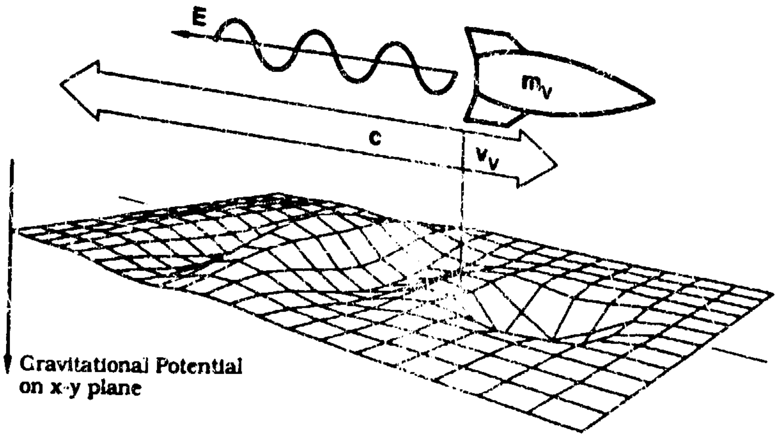

Fig. 1. Conservation of momentum by expelling non-mass momentum such as hypothetical "space waves".

$$(-m)(-v) = (+m)(+v)$$

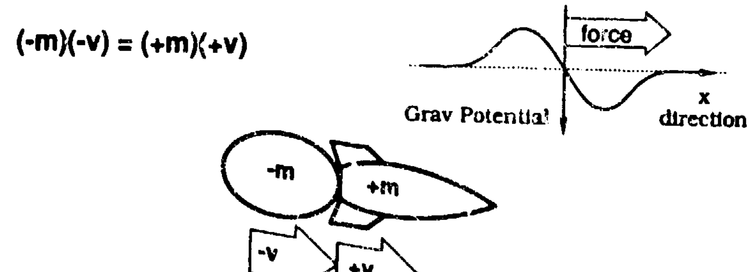

Fig. 2. Conservation of momentum by using negative mass.

Conservation Using Negative Mass:

An imaginative means of conserving momentum is to create a condition where the total mass, and hence momentum, is always zero. This treatment uses hypothetical "negative mass". If equal amounts of positive and negative mass were placed side by side, they would both accelerate along the vector pointing from negative toward positive matter because of the interactive properties of negative and positive mass (figure 2). This negative matter propulsion concept does indeed satisfy the laws of motion (reference 10). The weakness of this negative matter scheme, aside from the problem of obtaining and handling negative matter, is whether or not the laws of motion would still be satisfied if unequal proportions of negative and normal mass were used. Conservation may still hold with unequal masses if the concept of coupling to distant masses is considered. This concept is discussed next.

Conservation Using Coupling To Distant Masses:

Perhaps the most fundamental and broad-sweeping concept for space coupling propulsion is the concept where a vehicle produces its own acceleration field to push against some "structure" of space. To satisfy conservation of momentum with this concept, it is necessary to speculate that the reaction force is imparted onto distant masses via this space structure in much the same way that gravity attracts distant masses. Momentum is conserved by the equal and opposite momentum imparted to the space/matter system (Figure 3). This requires the perspective that matter is somehow connected to space, and that space has a degree of "stiffness" to transmit force to distant matter. This perspective is difficult to conceptualize, and evokes secondary issues that are discussed next.

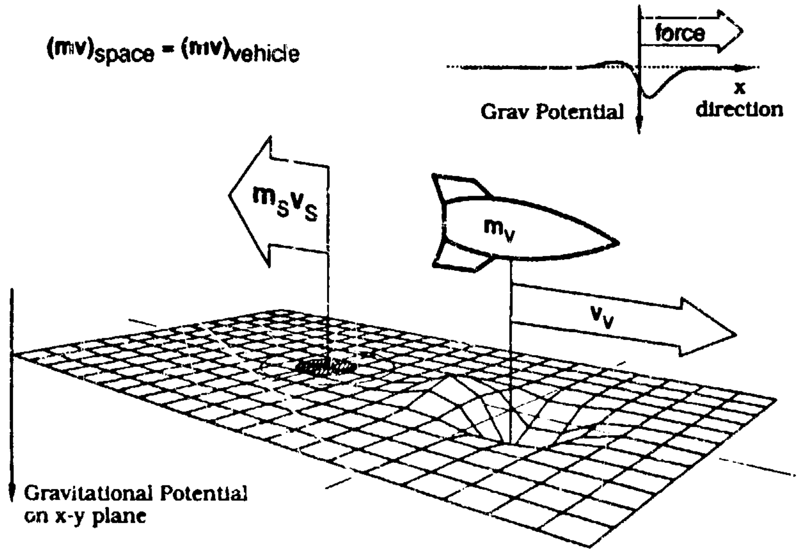

Fig. 3. Conservation of momentum by coupling to distant masses via coupling to the structure of space.

Mass is known to "connect" to space in two ways; gravity and Mach's Principle. Gravity is the field phenomena related to the presence of mass, where this field causes an attraction with other distant masses. Mach's Principle relates the presence of matter to the definition of inertial frames. Mach theorized that inertial frames exist only because of the presence of matter (reference 3). Additionally, as indicated by inertial drag, a given point in space may actually be a composite of inertial frames, each of which is somehow "connected" to its source mass. Another interesting point is that gravity and inertial frames are related. Gravitational fields are, in essence, accelerated inertial frames, and alternatively, unaccelerated inertial frames are gravitationally flat (the gravitational potential across the space is constant).

To further consider reacting against distant masses, it is useful to indulge in some alternative perspectives of these known phenomena. For example, it is useful to consider that inertial frames and their "connection" to their source masses provide *the* structures for reactive coupling. This implies that inertial frames would have a property for referencing position, in addition to referencing acceleration, to allow position relative to the frame's source mass to be uniquely defined. This is unconventional because inertial frames are thought to provide only a reference for measuring accelerations, not velocity or position. Additionally, it is useful to assume that this position property has some characteristic "stiffness" that allows forces to be imparted across space to the source masses. Such considerations evoke the notions of the proverbial "aether" and the theoretically defunct "absolute reference frame". The similarity between these views and those unpopular notions is not exact, and hence, should not prejudice indulgence in these perspectives.

Continuing with these speculative perspectives, forces could be induced relative to inertial frames if it were possible for a vehicle to alter its gravitational field distribution or its connectivity to its own inertial frame. By redistributing its own gravitational field, it could, in effect, create a local asymmetric acceleration field. The reaction forces would be imparted to the "stiff" inertial frames and subsequently to their source matter (figure 3). This is similar to the special case in the concept of negative mass propulsion where there is more normal mass than negative mass. In this case the non-zero momentum of the vehicle would be balanced by the equal and opposite momentum of the inertial space and its associated matter.

An issue related to these speculations, whose investigation may provide clues to the "structure" of inertial frames, is the proportionality of the imparted forces. If inertial spaces are pushed against, do the frames' source matter move in unison (Case A, figure 4), or do they move proportionally (Case B, figure 4)? What is this proportionality based on; the distance from that point and/or the magnitude of the source mass? One speculation to quantitatively explore this proportionality is to assume that the proportionality coefficient at a given point in space is simply the gravitational potential of the source mass at that point in space. These speculations and questions have yet to be fully explored.

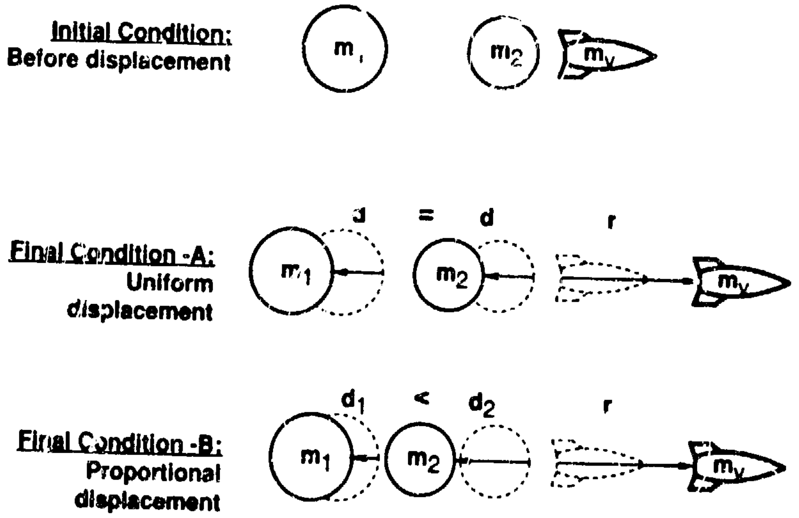

Fig. 4. Questioning the proportionality of coupling to distant masses.

The concept of coupling to distant masses requires some unconventional perspectives on the structure of space, particularly with respect to the definition of inertial frames and their relation to matter. Further investigations of this coupling possibility would likely require further indulgence and refinement of these unconventional perspectives, including exploration of the proportionality issue and the relation to Mach's Principle.

SEARCHING FOR A FORCE INDUCING TOOL PHENOMENA

Having addressed the issues of conserving momentum and the contents of space, and having identified the desirability of inducing a localized acceleration field onto an inertial frame, the next issue is to identify candidate mechanisms to create this acceleration effect. Acceleration fields imply gravity, and hence, the target mechanism is to discover some means to alter gravity. This evokes the last major reflexive response to the notion of space coupling propulsion: There are no known ways to practically manipulate the phenomena of gravity. There are two avenues to respond to this issue. The first avenue is direct manipulation of gravity by the motion of masses. The second avenue is to induce gravitational forces via an intermediary phenomena, such as electrodynamics, which evokes the need for a "Grand Unification Theory". Although science has not yet provided such a theoretical mechanism, there are several different approaches toward discovering a useful connection between gravity and other phenomena. All these approaches offer different applicability or viability for space coupling propulsion and are described next.

Inducing Accelerations by Motion of Masses:

Several concepts exist that consider inducing force or local accelerations by the motion of nearby masses. In general, these concepts are either impractical because of the enormous mass densities and speeds required, or are of doubtful viability because of uncertain physics.

1. **General Relativity Based Gravity Devices:** An impractical, but theoretically sound method to create acceleration forces is based on "magnetic gravity". General relativity provides the possibility of an analogous phenomena to gravity that magnetism is to electricity. Unfortunately, in order to produce appreciable forces with these conceptual devices, ultra-dense masses (densities approximately that of a white dwarf) must be moved at relativistic speeds along strictly defined paths (reference 1).

2. **Gyroscopic Antigravity Machines:** On a more speculative side, devices have been designed and patented (reference 11), that claim to produce gravity negating forces by gyroscopic motion. These devices are variations on a theme of converting angular momentum into linear force; a scheme which violates conservation of linear momentum. One example of this is a "Laithwaite Engine" (reference 12) which gives the appearance of providing upward forces by the upward swing of its gyroscopes once the device begins to rotate. This motion, however, is not a propulsive force, but rather a torque that makes the gyros change orientation in order to conserve angular momentum. This device and others like it do not hold much promise as propulsion devices, but are excellent instructional tools for understanding conservation of angular momentum.

3. **Anomalous Gyroscopic Measurements:** Recently, another gyroscopic device has been reported to produce reductions in weight proportional to rotational motion (reference 13). This report is not a proposed antigravity device, but rather an observation of an unexplained result. A gyroscope weighing on the order of 150 grams and with a vertical spin axis, was found to have weight reductions on the order of milligrams when rotated in the right-hand direction, and no weight change when rotated in the left hand direction. This is probably just an experiential error, but being such a peculiar observation, it is worthy of note.

Inducing Acceleration Effects via Intermediary Phenomena:

In addition to the perspective of inducing forces from the simple motion of matter, there is the perspective of using some intermediary phenomena to induce effects. This means finding some controllable phenomena that is related with the phenomena of gravity, and using this control phenomena to indirectly induce gravitational effects. An example of this intermediary principle is the way that microwaves (electrodynamics) are used to induce molecular vibrations (heat). With respect to space coupling propulsion, the prime intermediary phenomena is electrodynamics. Various approaches to correlate gravity to other phenomena are briefly reviewed below and include: (1) General Relativity's connection between inertial frames and gravity as referenced by electrodynamics, (2) Gravity as an index of refraction for electrodynamics, (3) Gravity as a Zero Point Energy effect, and (4) The hypercharge force.

1. **General Relativity, Conventional Correlations:** Although gravity is known to effect electrodynamics (gravitational fields bend the path of light), General Relativity has not provided a gravity/electrodynamic tool applicable for space coupling propulsion. Instead, General Relativity uses electrodynamics (specifically the speed of light) as the reference for describing how gravity relates to inertial frames. For example, in the basic equation governing the relation between distance (d), time (t), and the phenomena of light, $d = t \times c$, the speed of light (c) is the reference constant, and space and time are the variables that "warp" relative to gravity (reference 3). Although this perspective has proven its usefulness, it may not be optimum for the perspective of space coupling propulsion.

2. **Index of Refraction and Gravity:** An alternative approach to describe the same natural observations is to treat the speed of light as the variable that gets "warped" in the presence of gravity. Basically, this perspective takes the form of relating the index of refraction of light to gravitational potential (references 14, 15). In the case of space coupling propulsion, it may be more useful to consider distance as "stiff" and the speed of light as the variable with respect to gravity. This approach allows considering electrodynamics as the intermediary mechanism rather than as the reference. To date, no proposed mechanism based on such perspectives have been reported, but this may be an interesting avenue for further exploration.

3. **Gravity and Zero Point Energy:** An interesting alternative approach to relating gravity and electrodynamics is the theory that gravity is an induced effect associated with Zero Point Energy fluctuations of space (reference 16). Various methods that use Zero Point Energy for propulsion have been proposed (references 1, 9), but no concept has been proposed that takes advantage of these correlations to induce asymmetric gravity fields. This approach also merits additional consideration.

4. **Fifth Force, Hypercharge Force:** Another interesting perspective linking gravity to some other more manageable phenomena, is the "hypercharge force" concept. In a reanalysis of the experiment that demonstrated that all masses, independent of composition, accelerate uniformly in a gravitational field, it was found that there may be a correlation between gravitational acceleration and a sub-atomic characteristic called hypercharge or baryon number (reference 17). This correlation has yet to be fully proven or disproven, but either way, it does not hold much promise as a candidate mechanism for space coupling propulsion. The differences in gravitational attraction by hypercharge are negligible (delta-g/g approximately 10^-7) (reference 17).

CONCLUDING SUMMARY

"Space coupling propulsion" refers to the category of propulsion concepts that involve some means of coupling to the structure of space-time itself to produce propulsive forces. Such speculations are enticing because of the enormous benefits that could result. Unfortunately, such concepts are also considered science fiction. Even though these notions are still fiction, avenues for advancement exist. This paper examined the reasons behind the "science fiction" conclusion, and, based on the unknowns within those reasons, identified a variety of avenues for making progress on this potentially breakthrough subject.

The primary reasons that space coupling propulsion is considered science fiction are: (1) It appears to violate conservation of momentum, (2) There appears to be nothing in space to act as a reactive medium, and (3) There are no "Grand Unification Theories" which link the phenomena of gravity, an acceleration field, to manageable phenomena of nature, such as electrodynamics.

Conservation of momentum can be satisfied by using the media in space as the reaction mass, expelling non-mass momentum, using negative mass, or by coupling to distant masses via the structure of inertial frames. None of these methods are readily available, but the most promising pursuit may be to fundamentally explore coupling to distant masses via the structure of inertial frames, perhaps by some interaction with Zero Point Energy or the Cosmic Microwave Background radiation.

The contents of space that are candidates for reactive media include: interstellar matter, magnetic fields, starlight, Cosmic Microwave Background radiation, and the substructures of space such as Zero Point Energy, virtual pair creation/annihilation, or inertial frames themselves. None of these contents appear to be substantial enough to constitute an adequate reactive medium, but may be useful tools in the search for more fundamental structures of space. Perhaps the most promising direct medium for space coupling propulsion is Zero Point Energy, and the most promising indirect candidates are to use Zero Point Energy or the Cosmic Microwave Background radiation as intermediary phenomena to explore the structures of inertial frames.

With respect to searching for theories that link the phenomena of gravity to some intermediary phenomena, the possible avenues include: conventional General Relativity, exploring the notion of the speed of light as a variable relative to gravity, exploring the notion of gravity as a Zero Point Energy force, and exploring the use of the hypercharge force. None of these avenues presently provide a mechanism to alter gravity by practical means, but all are worthy of further investigation. Promising avenues could be the notion of the speed of light as a variable relative to gravitational potential, and the notion of gravity as a Zero Point Energy effect.

Although no methods yet exist to enable genuine space coupling propulsion, there are many unknowns and unexplored avenues that may one day lead to a breakthrough discovery on this frontier. These avenues are not always obvious nor do they promise high chances of success, but the potential benefits are enormous. So long as speculations can be offered, the opportunity to translate them into testable concepts exists, and within such activities may spring new awareness and closer avenues toward discovering the breakthrough potential of space coupling propulsion.

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Tethers and Asteroids for Artificial Gravity Assist in the Solar System

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Planetary missions have benefited greatly from the gravity assist mechanism where a planetary flyby can boost or otherwise modify a spacecraft trajectory to accomplish specific goals. The multiplanet encounters of Voyager 2, for example, were accomplished using this process. The Galileo mission will utilize over a dozen flybys of the Galilean moons to perform a complete scientific investigation of the Jupiter system. Can asteroids be used in a manner similar to gravity assist? Their gravitational pull is too weak to provide the required bending of the trajectory, but this turning can be done by means of a tether. For example, the spacecraft may release a 100-km tether that will attach itself to an asteroid as it approaches. The spacecraft then will be forced to turn in a long arc, which can be terminated upon release of the tether when the proper vector is obtained. The primary limitation of using this process will be tether strength which, with today's technology, will not allow relative velocities to exceed 1-3 km/s. This and other limits are investigated, as well as some mission possibilities using this method. Methods of tether/asteroid attachment and release will be discussed as well.

Introduction

"GRAVITY assist" is the term given to the effective use of the gravitational field of a massive body to deliberately modify the trajectory of a flyby spacecraft. For example, the two Voyagers[1] utilized the gravity assist of Jupiter to give them additional energy to continue their flight to Saturn. Jupiter not only provided a needed velocity boost so that it could reach the orbit of Saturn, but also turned the trajectories through just the angles needed so that the spacecraft would intercept the planet. Voyager 1 is headed out of the solar system, but Voyager 2, with a gravity assist by Saturn, will encounter Uranus in 1986, and then, again via gravity assist, will encounter Neptune in 1989. Similar gravity assist missions were Mariner 10, which flew by Venus before going to Mercury,[2] and Pioneer 11, which used a Jupiter gravity assist to lob it out of the ecliptic plane and across the solar system to Saturn.[3]

It is the ability of a massive body to bend a spacecraft trajectory in a near collision approach that is essential to the gravity assist process. Jupiter is very massive, and will bend the spacecraft trajectory through a large angle of the order of 180 deg. In contrast, the asteroids have such low surface gravity that flybys of them are nearly rectilinear. If, however, in the course of a flyby, a spacecraft can be attached to an asteroid with a tether, then the spacecraft can swing around the asteroid through a large angle to accomplish the same type of trajectory change as gravity assist from a massive planet. Here, more about benefits than about means will be discussed, hoping to stimulate the process leading to the utilization of asteroids in a mode similar to gravity assist.

Dynamics and Limitations of Gravity Assist

A gravity assist is kinematically equivalent to an elastic collision of two bodies, which produces a momentum exchange between them. It is an example of a "soft" collision, as compared to a hard collision involving actual surface impact. In the case of Voyager 2, in a gravitational encounter with Jupiter, an observer on Jupiter will see the spacecraft travel a hyperbolic path, and the spacecraft's outgoing speed will equal its incoming speed. However, a momentum increase (or decrease) will be seen by a heliocentric observer. Thus in a direct flyby of Jupiter, Voyager 2 experienced a velocity increase of several kilometers per second, permitting it to fly out to Saturn. On the other hand, a retrograde flyby of Jupiter will be needed for the Starprobe spacecraft to lower its sun relative velocity and cause it to fall to within 4 solar radii of the sun.[4]

Although gravity assist by the planets and the large planetary moons (such as the moons of Jupiter for the Galileo mission)[5] is a useful technique for expanding our capability to explore the solar system, the assisting planet or moon must be at the right place at the right time. Therefore, launch opportunities are restricted; favorable dates may be years apart. In an extreme case, the Voyager 2-type mission to the four giant planets will not be available again for 175 years.[6]

Knowing the mechanism, value, and limitations of planetary gravity assist, is there an alternate means of producing the same effect with the smaller but more numerous asteroids or comets? At the current level of space operations the answer is no, but with the development of tethers, which is now in the infant stage, it may be possible in the future. Since tethers are so new in space applications, some examples that are being seriously considered will be given. The realization that some applications have already been assigned Shuttle flight target dates may remove a somewhat science fiction aura that has surrounded the tether concepts.

Considering that there are thousands of asteroids greater than 1 km in diameter, the opportunities for utilizing gravity assist through soft collisions will expand by orders of magnitude. More asteroids will be discovered and smaller ones will be even more numerous. Those as small as 10 m in diameter will weigh over 1000 metric tons and could also be effectively used.

Some Proposed Tether Applications

In 1988, it is planned to conduct some Shuttle-based tether experiments from orbit at a 200-km altitude in space.[7] In the first experiment, a 200-kg satellite made by an Italian team will be deployed 30 km above the Orbiter, connected to the Shuttle by an electrodynamic tether. Measurements will be made of the electric power generated as the tether moves through the geomagnetic field, and reciprocally of the thrust developed as a current is passed through the tether.

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On a second Shuttle launch, the same Italian spacecraft with different instruments will be suspended on a tether 100 km below the Orbiter to measure the atmospheric properties in a region where the Orbiter itself cannot fly. This experiment will analyze the aerodynamic and aerothermal interactions in a density regime where there will be some departure from free molecule flow. This tether has a circular cross section 2 mm in diameter with an inner core of Kevlar 49 and an overcoating of Teflon to protect the Kevlar from interaction with atomic oxygen and from solar uv exposure. In both flights, the tether dynamics will be studied and controlled as the tether and satellite are deployed into their gravity-gradient-stabilized position, and again as the satellite is reeled back into the Orbiter cargo bay.

In another proposed application,[6] tethers are used to assist in the transfer of payloads from low-Earth orbit (LEO) to geosychronous orbit (GEO). A Shuttle payload in LEO is deployed upward on a long tether. By taking advantage of the deployment dynamics, one can arrange that at the minimum altitude, the payload, swinging in an arc about the Shuttle payload center of mass, is moving so that the swinging velocity is in the direction of the orbital motion. At that point the payload is released. It moves in a new orbit with a higher perigee than the Shuttle, and a much higher apogee due to the velocity from both the swinging motion and the Shuttle angular velocity. At apogee it is caught by a tether lowered from a station in circular orbit. Since the payload usually will have a lowered velocity than the station, it will revolve in a circle about the station while constrained by the tether. The two masses can remain in this rotating configuration until the payload is released at its highest point to attain a yet higher orbit. Another station at a still higher altitude can repeat the catch-and-release process so that the payload eventually reaches GEO. We have computed that two or three stations would be needed if the tethers are to be made of an existing material such as Kevlar.

Upon closer examination, it can be seen that this method of momentum transfer, where the station loses the momentum that the payload gains, is a soft collision similar to a gravity assist. In this case, the station takes the place of the planet.

Tether Strength Requirements

Assuming, at present, that some means have been developed for attaching a tether to an asteroid during a flyby, it is possible to determine the tether strength requirements as a simple function of the relative velocity (V_i) and the payload-to-tether-mass ratio. In these calculations, the asteroid is considered as an anchor point only, and its gravity gradient effect on the tension in the tether is neglected.

The spacecraft, of mass M and velocity of approach V_i, is swung in a circular arc of length L about the asteroid. At the spacecraft end, the tension is $T_L = M\omega^2 L$, where $\omega = V_i/L$ is the angular velocity of revolution. This represents a boundary condition on the system. If the tether has a constant cross-sectional area A and mass density ρ, the differential equation for the tension T as a function of radius r is

$$\frac{\mathrm{d}T}{\mathrm{d}r} = -A\rho\omega^2 r \tag{1}$$

and the stress in the tether is $S = T/A$. The solution to this equation with the boundary condition above is

$$SA = T = M\omega^2 L + \frac{\rho A\omega^2}{2}(L^2 - r^2) \tag{2}$$

We will choose the cross-sectional area A to make the stress at the origin (where the stress is greatest) to be the safe working stress S_0 of the tether material. We can then obtain the tether mass $m = \rho AL$. After some algebraic manipulation, we can find the spacecraft-to-tether mass ratio as

$$\frac{M}{m} = \left(\frac{V_c}{V_i}\right)^2 - \frac{1}{2} \tag{3a}$$

$$= \delta\left(\frac{C_L}{V_i}\right)^2 - \frac{1}{2} \tag{3b}$$

where the characteristic velocity is calculated as $V_c = \sqrt{S_0/\rho}$. In the second equality, the stress S_0 has been replaced by $S_0 = \delta E$, where E is Young's modulus and δ is the safe working strain, and the fact that the longitudinal sound velocity is $C_L = \sqrt{E/\rho}$ has been used.

This equation shows that as the spacecraft mass approaches zero, there is an upper limit to the velocity that can be constrained by the tether, namely, $V_{i\max} = \sqrt{2\delta}C_L$. This result is remarkable in that this limit does not depend upon the spacecraft mass or tether length. It is an intrinsic property of the tether material. For Kevlar 49, $C_L = 10$ km/s, and a good value for the working strain is $\delta = 0.01$. (Actually, the breaking strain is $\delta_B = 0.02$, therefore, we have an adequate, but not generous, safety factor of 2 in the working strain.) Then, the characteristic velocity is $V_c = \sqrt{\delta}C_L = 1$ km/s, and the maximum spacecraft velocity is $V_{i\max} = 1.4$ km/s.

Equation (3b) places limitations on the achievable relative velocities for a given material and a given spacecraft-to-tether mass ratio M/m. A plot of this relation for Kevlar and stronger materials is given in Fig. 1.

This velocity limitation may be circumvented in two ways. First, from Eq. (1), since the tension decreases as the distance from the center of rotation increases, it is possible to decrease the cross-sectional area accordingly. The solution is an exponentially tapered tether (see Ref. 9, for example). Unfortunately, the tether mass required increases rapidly with velocities larger than V_c. For example, for $V_0 = 2V_c$, the tether-to-spacecraft mass ratio is 17.7. Thus, flyby velocities should be restricted to the characteristic velocity or less, except for situations where the tether is reused extensively.

A higher velocity may be achieved, however, through control of tether tension by paying out or reeling in the tether. It has been assumed that the spacecraft-asteroid tether attachment will occur when the velocity vector is exactly perpendicular to the radius vector between the two. Normally, however, there will be a radial component of velocity that the tether system must handle. If this component is outward, then the tether must be payed out to avoid the tether tension exceeding some maximum. If the component is inward, then the tether should be reeled in to ensure rotation of the spacecraft. Higher velocity than the limit may be handled by paying out the tether when the maximum tension would otherwise be exceeded. This cannot go on indefinitely, therefore, at some point the tether must be detached. Higher velocities, then, will limit the turning angle available for artificial gravity assist.

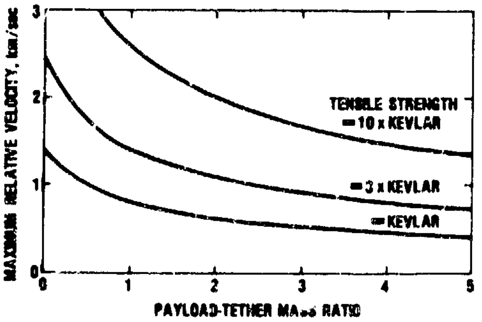

Fig. 1 Velocity limitations for various payload-tether mass ratios and tether strength.

Methods of Tether Attachment to Asteroids

The material strength of the asteroid surfaces will not be known in detail when a tether assist mission is designed, therefore, the methods by which tethers are attached should be largely independent of surface characteristics. For small bodies, say 10 min in diameter, the entire asteroid could be surrounded by a fishnet-type structure made of flat Kevlar tape which when drawn tight does not place a concentrated load on any surface portion. As a single numerical example for orientation purposes, consider a Kevlar net engaging the 10-m-diam asteroid with tapes 0.01-g/cm^2 thick that cover 3% of the asteroid surface. This net will have a mass of 1 kg only, yet will be able to sustain a force of 10^5 N applied to its drawstring. A spacecraft of 1000 kg traveling at 1 km/s past the asteroid, and held by a 100-km tether will generate a centrifugal force of only 10^4 N, which could be held safely by the net.

For large bodies with strong surface structures, the tether end could be fastened to a ground penetrator that would anchor into the asteroid. The penetrator would be left behind when the tether is released to let the spacecraft fly off.

For large bodies of about 1 km in diameter with a highly brecciated surface that would have little mechanical strength, there may be nothing worthwhile for the tether to hold onto, and the fishnet required to englobe the asteroid would be too massive. It is suggested that the tether end have a plow-shaped device which the spacecraft drags along the asteroid surface. The plow exerts a force on the tether, due not to the strength of the surface it breaks up, but to the inertia of the material it displaces. Preliminary calculations show that appropriate tensions can be sustained with plow masses substantially smaller than the spacecraft mass. However, some active control system is necessary to cushion the shock if the plow hits a strong surface feature.

Mission Capabilities for Artificial Gravity Assist

The velocity limitations just derived place some restrictions on the general use of artificial gravity assist. For example, none of the Jupiter flyby missions mentioned earlier could have been accomplished by this alternate method, since the relative velocity (V infinity) exceeded 6 km/s in all cases. Because of this velocity limitation, each application must be examined carefully. For example, in an asteroid belt tour it is quite likely that a series of hops could be made with less than 1 km/s velocity difference in each. Furthermore, the tether method might well be aided by some rocket propulsion to reduce the velocity difference, since in any event propulsion would be necessary to achieve a close enough approach to use a tether.

Given the velocity limitations for soft collisions imposed by tether strength, it is possible to compute the orbit change available using this technique. Assuming a circular orbit for the asteroid (eccentric orbits with the same major axis give similar results), a soft collision with it, using a tether, will allow departure in any direction from the asteroid. The most favorable departure direction, to enlarge the orbit, is in the direction of the asteroid's orbital motion about the sun. The aphelion increase in terms of the radius of the initial orbit and the relative velocity is given in Fig. 2.

For an asteroid in the Earth's orbit, for example, having an orbit radius of 1 a.u., about 3 km/s are required to reach out to Mars orbit which is at about 1.5 a.u. A velocity of 1 km/s will only extend about 0.15 a.u. from the Earth's circular orbit.

Applying Fig. 2 to larger orbits, this technique is more effective. A tethered swing around an asteroid in Mars' orbit will extend the spacecraft aphelion out to 2.5 a.u., assuming a relative velocity of 3 km/s. This is still not as effective as a gravitational assist by Mars itself. At one phase in the Galileo mission design, for example, a close flyby of Mars was proposed to boost the spacecraft out to Jupiter, which is at 5.2 a.u.[10]

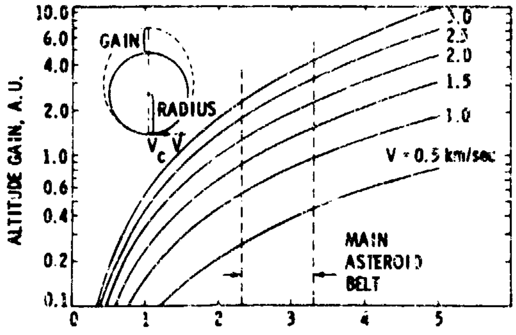

Fig. 2 Aphelion altitude gain for velocity applied to circular orbits.

The effectiveness of tether-asteroid assist improves considerably at the main asteroid belt and beyond. At Jupiter's orbit, for example, a tethered spin around with a relative velocity of 2 km/s will extend a spacecraft orbit to 10 a.u., or out to Saturn. Near Jupiter thre are many small bodies, which are possibly available for a tethered artificial gravity assist. Attending the planet itself, in addition to the four large Galilean moons, there are eight other smaller satellites orbiting at large distances. Their sizes are estimated to range from 1 to 50 km in diameter. Furthermore, as a result of Jupiter's influence, over a dozen known asteroids cluster about the two Trojan points located in Jupiter's orbit 60 deg ahead and behind Jupiter itself. Very likely there are many much smaller undiscovered trojans oscillating about these two stable points. In the future, when missions are flown to these asteroid groups, perhaps the soft collision techniques presented here may be of some benefit.

Mission Applications

No specific missions using this technique have been calculated in detail, but some mission applications will be described to illustrate its potential. Some applications show how this tether assist method may ease the propulsion requirements of previously considered missions, and some show how the method may open up new mission possibilities.

Mars Missions

A Hohmann transfer from Earth orbit to Mars orbit requires velocities of about 3-4 km/s. Using an intermediate tether-asteroid assist between Earth and Mars can reduce the propulsion requirements by about 50 %. The relative velocity requirements at the asteroid would be about 1.3 km/s, requiring a spacecraft-to-tether mass ratio of 0.1 for Kevlar (Fig. 1) or 1.2 for a tether three times stronger. An Aten-type asteroid, which has an aphelion less than that of Mars, and whose orbit is nearly in the ecliptic, would be a suitable intermediary. It is estimated that about 2500 asteroids with diameters greater than 1 km are in suitable near-Earth orbits. Probably, there are enough of these bodies so that the Earth-asteroid-Mars phasing problem would disappear, since at any launch time one of them would be in a proper position to accommodate a tethered assist.

Outer Planet Missions

Transfer velocities from Earth to Jupiter orbits and beyond are much greater: 9 km/s compared with 3 km/s to reach Mars. A Mars true gravity assist to Jupiter can reduce this transfer requirement to about 6 km/s. Instead of Mars, a suitable asteroid in the main belt could be used with the tether artificial gravity assist method. Phasing would not be a problem, as it would be for Mars itself, since many of these asteroids are fairly evenly distributed in near-circular orbits, and are close to the ecliptic.

An even more advantageous method would be to transfer to Mars' orbit with about 4 km/s, and perform a Mars gravity assist into the asteroid belt. Next, use tether assists with several main belt asteroids in succession to gain the velocity required to reach out to Jupiter. By using Mars, lower relative velocities of the spacecraft with each asteroid will be needed, and hence a lighter tether may be used than with a single intermediary asteroid. We believe that in most of these applications all or a major part of the tether is reuseable. This is one advantage of using a tether compared with using rocket propulsion and expending fuel.

Similar scenarios for tether assist missions may be developed for the other outer planets. It should be remembered, however, that Jupiter remains the most powerful source for gravity assist in the solar system.

Main Belt Asteroid Missions

The asteroid belt itself is the natural place for tether assist missions. As mentioned for the Jupiter mission, the spacecraft may utilize a Mars gravity assist to get from Earth into the asteroid belt. One can then imagine a spacecraft collecting samples of asteroid material at the same time it is performing a tether assist to fly on to another asteroid. After a tour of a number of asteroids, the process could be reversed by performing a gravity assist at Mars to return to Earth with the asteroid samples collected.

Main belt asteroid tours have been seriously considered using low-thrust rocket propulsion.[11] Successive rendezvous with from 4 to 8 asteroids would take up to 10 years. Although penetrators were suggested for in situ measurements, sample returns were not considered. Perhaps the ideal spacecraft to explore the asteroids in the main belt would use both low thrust and tether assist. With thrust, midcourse corrections could be made and the relative velocities at the asteroids could also be reduced to values where conventional materials would be adequate for a tether assist.

It is not known how many small asteroids (but still large enough for a tether assist) there may be in the main belt, since Earth-based telescopes cannot detect bodies smaller than about 1 km in diameter at that distance. There are probably more than a billion greater than 10 m in diameter with a mass greater than 1000 tons each, adequate for our method. In that case, the complete mission need not be preplanned based on knowledge of the position and orbits of selected asteroids that it should encounter. Instead, a spacecraft, thrust into the asteroid belt, could be capable of detecting 10-m asteroids at an adequate distance; for example, with passive optical sensors, backed up by ranging lasers once an object is detected. Then it would be determined whether the spacecraft can maneuver into position for a close flyby and perhaps a tether assist. In this manner, successive hops could be made with relatively little propulsion yet adding up to a considerable total velocity increment. No detailed analysis has been done on this unique mission as yet.

Finally, tethered assists may be valuable in the far future for possible economic utilization of asteroidal materials in space. It may, for example, be necessary to return asteroidal mass to the vicinity of the Earth or Moon on a continuing basis. Rather than expendable propellants, a set of permanent reuseable tether stations on a string of asteroids could provide the means to transport the mined material back to Earth.

Conclusions

An alternate method of producing gravity assist using asteroids has been presented. Successful development of this technique will depend on many factors, some of the more important being: higher-strength tether material, a method of attaching and releasing a tether with an asteroid, tether dynamics control, and development of a navigation system to achieve the required accuracies for tether attachment and release.

Even when these problems have been solved, actual use of the system will be heavily mission-dependent. Tradeoff studies will be required to decide whether the tether system or conventional rocket propulsion or some combination of both is optimum for the mission goals. Tethers appear to have significant merit in missions where they can be reused several times. For highly repetitive use they may be the only practical devices.

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