Final Report

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Description of the Effort

The third two months of the Phase I award, "Optimal Navigation in a Plasma Medium," involved approximately six days of research by the Principal Investigator (N. J. Fisch), as well as preparation by the Principal Investigator of the final report and a draft manuscript, "Propulsion by Asymmetric Absorption of Momentum from an Ambient medium." The main research results are given in the attached draft manuscript, which will be submitted to Physical Review E.

Overview of Research Results

Two avenues of thought were pursued. One is the highly speculative possibility of couching navigation in a plasma medium in terms of the travel of a small body through very much larger scales. The reason this might work is in a plasma the turbulent spectrum is dominated by long wavelength fluctuations. The implication might be the inapplicability of certain restrictions generally imposed by the second law of thermodynamics, which might then allow for more efficient travel. This, of course, is just an "in principle" idea. This avenue was thought about, but it was not brought up to the level that would be publishable. However, neither were any showstoppers found: in principle, it might still work, and it would be very interesting if it did from a fundamental standpoint.

The second avenue of thought pursued involves imagining methods in a plasma of creating asymmetric momentum deposition by ambient charged particles, much in the same way that a radiometer, using a painted surface, manages to absorb light from one side and reflect it from the other. Similarly, particle momentum might be absorbed or reflected asymmetrically and to advantage. This must take place in the context of heating of the medium. The efficiencies for this process were worked out quantitatively. There are both active and passive ways to accomplish this effect. The passive method involves placing a dissipative medium of one type adjacent to a dissipative medium of another type. That arrangement creates the conditions for asymmetric absorption or reflection of particles. This is the method that is like painting one side of the fins of a radiometer. In principle, this method can work, and it was developed to the point where it is publishable; the draft is attached.

Recommendations for Further Work

1. Specific scenarios need to be worked out, both for astrophysical contexts and for producing the effect in the laboratory.
2. Heat needs to be rejected for a truly equilibrium arrangement. A specific means of maintaining the plasma slabs at constant and specific temperatures needs to be investigated both in terms of efficiency and simplicity.
3. Only one passive means of inducing the asymmetry was examined. There are clearly others. One other way is to induce anisotropic distribution functions, for example, by a wedge-shaped slab. Another way is to use high atomic number plasmas for one slab. These might be more easily realized, since it might mean

that two-temperature slabs would not be required. This could be quite interesting to pursue.

4. Other effects, such as charge rejection and self-consistent electric fields need to be worked out. Also, as the craft gains speed, the effects of friction start counting. You can calculate terminal speed.
5. Finally, and most important, a specific application or missionneeds to be envisioned, which can utilize the ideas offered here.

Propulsion by Asymmetric Absorption of Momentum from an Ambient medium

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(Dated: August 1, 2004)

The propulsion of a spacecraft in an ambient medium carries the disadvantage that the spacecraft needs to overcome frictional forces in traversing the medium. On the other hand, the medium itself can be used to balance momentum, so there is no need for an on-board supply of propellant. If an asymmetry can be made with respect to absorption or reflection of ambient particles by the spacecraft, the ambient media can be used to advantage in minimizing the resistance of a body traveling through a viscous media.

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Introduction

The conventional means for propulsion of spacecraft employs onboard mass, or propellant, that is ejected in one direction to propel the spacecraft in the opposite direction. The propulsion might be necessary to achieve various missions in space travel, or simply to balance frictional losses to an ambient medium. The presence of the ambient medium, because of the frictional losses incurred, is generally considered a disadvantage. At most, there are ideas for using the mass encountered in order to scoop up more propellant, but the basic paradigm of ejecting mass to propel the spacecraft remains intact.

What this paper explores is the extent to which the ambient medium itself might be the source of momentum, rather than just a source of particles, through the asymmetric absorption or reflection of particles. This is similar to the asymmetric reflection of light in a Crookes radiometer (which was the subject of considerable debate in 1879 [1, 2]) or, even as envisioned by the painting of comets to utilize the Yarkovsky effect [3]. An analogous device in which sound waves are used, rather than light waves, is the acoustic radiometer, which operates in a high-intensity acoustic field [4]. Of course, if the ambient medium is flowing, like the solar wind, a spacecraft might set out to capture this wind [5]. There are also ideas to excite plasma waves that carry momentum to the magnetized medium [6].

What we have in mind here is to induce asymmetric absorption or transmission of particles in an homogeneous environment. Thus, even though a vehicle is bombarded equally from all sides by thermal particles in the ambient medium, if there is an asymmetry in the construction of the vehicle, like in a radiometer, then that vehicle might transmit or reflect particles asymmetrically. Of course, any method of using the medium is really to some extent an instance of asymmetric reflection: scooping propellant essentially takes in particles impinging on the craft, then ejects them in another direction; and generating plasma waves involves accelerating those plasma particles in proximity to the spacecraft, essentially ejecting proximate particles asymmetrically rather than captured particles. Thus, the general paradigm is the same: particles impinge on the spacecraft and are asymmetrically reflected, transmitted, or absorbed,, resulting in net acceleration to the craft. The question is how to accomplish this effect simply and with the least power expenditure.

Of particular interest here is the case when the ambient medium is plasma. We have in mind to exploit the fact that the absorption of momentum of charged particles by a plasma is highly sensitive to the velocity of the impinging particles. Charged particles in a plasma slow down very slowly when they move fast, and very quickly when they move slowly. Hence, most of their energy and momentum is absorbed in a small localized region, the so-called "Bragg peak". Consider a panel of plasma that is bombarded on all sides by an ambient medium that is also comprised of plasma, so that the bombarding particles are charged. If the width of the panel is approximately the depth of the Bragg peak, then small differences in the impinging velocities result in large differences in the ability of the panel to absorb the momentum of the impinging particles. Hence, by changing that velocity in some way asymmetrically with respect to the two sides of the panel, there may be net momentum absorbed by the panel, even though the bombardment is symmetric.

Suppose that ions and electrons at constant temperature strike the plasma slab. Now the ion speeds at the same temperature are by a factor $(m_i/m_e)^{1/2}$ slower than the electron speeds, so the momentum carried by the ions is by a factor $(m_i/m_e)^{1/2}$ greater than for electrons. However, since the electron speeds are greater by that same factor, the momentum flux to the plasma slab is only temperature dependent, and not mass dependent. The question is how much of that momentum flux is imparted to the slab.

In principle, it could be all the momentum. Suppose for example that the slowing down in the slab were by Coulomb collisions only. That would mean that the slab would be transparent to neutral atoms, but both the positive and negative charges of an ionized atom would be stopped. So, in principle, in an atomic medium, it would be possible to ionize gas on one side of the slab to make the slab feel pressure only from the side on which ionization takes place. That resulys in an imbalance of forces on the slab. Alternatively, in a plasma medium, it would be possible in principle to catalyze recombination on ine side of the slab, with the similar result of an imbalance of forces on the slab. The maximum imbalance in these cases is where half the full pressure is felt from one side, and no pressure is felt from the other. If a mechanism were found to reflect the particles from one side, but transmit from the other, then the maximum asymmetry in the force would simply be the pressure.

Of course, it would be more practical if the slowing down process were asymmetrical in some other way that did not involve ionization or recombination. Here we exploit the fact that the Coulomb slowing down can very sensitive to velocity, with nearly all the momentum dropped in a short distance. The fact that very small changes in the initial velocities can result in large changes in the momenum deposited has alrready been exploited successfully in the driving of electrical current in the plasma medium, either by waves which push electrons with specific velocities [7, 8], or ions with specific velocities [9], or other ways of inducing asymmetries in the collisionality of the plasma constituents [10]. Here the desired effect is not on the current of particles in the plasma, but on the structure that induces the currents (which could be equal currents of ions and electrons) in the plasma, and therefore experiences the recoil motion, or propulsion.

Thus, consider that a superthermal particle slowing down in a plasma by Coulomb scattering obeys

$$\frac{dv}{dt} = -\nu(v)v = -\frac{\alpha}{v^2}, \tag{1}$$

where we defined the collision frequency $\nu(v) \equiv \alpha/v^3$, where α is a constant. At present, for simplicity, we consider one-dimensional motion only, and consider the particle to be an ion or an electron in the appropriate velocity regime. This slowing down law is readily integrated, with solution

$$v(t) = \left(v_0^3 - 3\alpha t\right)^{1/3} = v_0\left(1 - t/\tau\right)^{1/3}, \tag{2}$$

whe v_0 is the initial velocity and τ is the characteristic time scale $v_0^3/3\alpha$. The distance traveled across the slab can then be found to be

$$x(t) = \frac{3}{4}v_0\tau\left[1 - \left(1 - t/\tau\right)^{1/3}\right], \tag{3}$$

so that we can also write v in terms of x as

$$v(x) = v_0\left(1 - x/x_{\max}\right)^{1/4}, \tag{4}$$

where $x_{\max} = v_0^4/3\alpha$. For $x > x_{\max}$, we have $v = 0$. Thus if $x > x_{\max}$, all the momentum of an impinging particle is absorbed by the slowing-down medium.

Now consider the momentum absorbed by the medium of length L if it does not completely slow down. Then we have

$$P_{\text{absorbed}}(x) = mv_0\left(1 - L/x_{\max}\right)^{1/4}, \tag{5}$$

Define $P_{\text{abs}}(v, L)$ as the momentum absorbed by a particle with velocity v impinging perpendicularly upon a slab of thickness L. Note that we can write

$$\frac{P_{\text{absorbed}}(x)}{mv_0} = \left(1 - 3\alpha L/v_0^4\right)^{1/4} \equiv \left(1 - v_c^4/v_0^4\right)^{1/4}, \tag{6}$$

where in writing the second equality we defined the critical velocity $v_c = (3\alpha L)^{1/4}$. Note that as a function of v_0, we $P_{\text{absorbed}}(v_0) = mv_0$ for $v_0 < v_c$. In this regime, the slab acts as a normal medium in the sense that $dP_{\text{absorbed}}/dE > 0$, or the faster the impinging particle, the more thrust it transmits to the medium. However, for $v_0 > v_c$, the medium is *anomalous* in the sense that $dP_{\text{absorbed}}/dE < 0$, or the faster the impinging particle, the less thrust it transmits to the medium.

Moreover, not only is the slope dP_{absorbed}/dE discontinuous at $v_0 = v_c$, but as $v_0 \to v_c^+$, $dP_{\text{absorbed}}/dE \to -\infty$, meaning that the efficiency of pushing just the right particle is infinite. Thus, if a particle were going to just make being slowed down within the medium, giving that particle a very small kick, so that it avoids slowing down in the medium, makes a very large change in the momentum transferred to the medium.

Thus, one paradigm for efficient acceleration would be an active means, namely to select just those particles near the Bragg peak, specifically just those particles that would just manage to slow down in the plasma slab – and to accelerate those particles slightly before they enter the plasma slab. In principle, the selection of the particles with just the right speed could be made precisely on the basis of their velocity, like in the current drive effects [10], where a wave-partcle resonance condition can be exploited. Only a small amount of energy and momentum would be transferred to these particles, but then these particles impart essentially no momentum to the slab. Suppose that the particles are impinging from the left: then to accelerate slightly these particles, momentum $m\Delta v$ is expended, meaning that the craft feels an impulse to the left of $m\Delta v$; but then since all the momentum is now avoided, whereas the symmetric particle coming from the right deposits all its momentum, the craft feels a net impulse to the left of $mv + m\Delta v$.

Note, however, that the number of particles which behave in this anomalous fashion with very small energy transfer is limited. It would essentially only be those particles essentially at $v_0 = v_c$. Thus, while the energy input is limited, the total thrust that can be imparted is not only finite, but also only a very small fraction of the total thrust that might be transmitted.

However, there are passive means of arranging an asymmetry that similarly exploits the velocity sensitive slowing down in a plasma. Suppose that there are two plasma slabs placed close to one another, but the slowing down of charged particles in each of the slabs is different. This can be arranged, in principle, by maintaining the plasma slabs at different temperatures, so that particles impinging are superthermal in one slab, but subthermal in the other slab. So consider now the passive case with two slabs: slab B involves inverse cubed slowing down (particles are superthermal in this slab) and slab A involves exponential slowing down (particles are subthermal in this slab). The point is that it then makes a big difference which slab is encountered first.

In slab A, suppose that charged partices are slowed down in a slab in which the slowing down obeys

$$\frac{dv}{dt} = -\nu_0(v)v, \tag{7}$$

where we assume the collision frequency $\nu_0(v) = \nu_0$ is a constant of v. This slowing down law is also readily integrated, with solution

$$v(t) = v_0 \exp^{-\nu_0 t}, \tag{8}$$

and the distance traveled in the slab can be put as

$$x(t) = \frac{v_0}{\nu_0}\left(1 - \exp^{-\nu_0 t}\right), \tag{9}$$

or as a function of distance traveled, we have

$$v(x) = v_0 - \nu_0 x, \tag{10}$$

so long as $x < L$. For a slab of length L all particles impinging with any velocity sufficient to traverse the slab lose a constant velocity decrement $\Delta v = \nu_o L$.

Assume a thin slab A, so that a constant velocity decrement Δv is lost in slab A no matter where we put slab A relative to slab B. But if we put slab A first, then there is a very large differential effect in slab B for those particles near the critical velocity for slab B. The equations developed can be used to write a precise answer, but to see the approximate effect, suppose that only particles with velocity $v_0 < v_c$ transmit momentum to slab B, and that slab B is transparent to all other particles. This is a crude approximation of the slowing down result derived, which should be useful so long as we integrate over smooth velocity distributions. Then the approximate effect of slowing down by Δv first is that those particles within Δv of the critical velocity v_c now give up theit momentum, instead of being transpaent. The number of particles involved for a Maxwellian distribution $f_M(v)$ is about $\Delta v f_M(v_c)$ The difference for each of these particles is about their momentum,or about mv_c, and that rate of this happening is proportional to their velocity which is about v_c. So the pressure difference is about

$$\Delta P = m v_c^2 \Delta v f_M(v_c). \tag{11}$$

This can be put more precisely, but it is clear that by choosing $v_c \sim v_T \sim \Delta$, where v_T is the thermal velocity, a sizable fraction of the maximum pressure difference might be possible. Since the maximum is about $2nmv_c^2$, the ratio is about $2/\Delta v f_M(v_c)$.

It remains of course to choose the plasma slab parameters, and to keep these slabs in equilibrium. If the craft gathers relative speed to the medium, it encounters friction, and a terminal speed will be achieved. The craft also needs to reject heat to be in full equilibrium with its environment. Finally, to the extent that the effect works better on ions or electrons, the discharging of the craft needs to be investigated. Nonetheless, as a paradigm for propulsion, such an arrangement of slabs, connected to a spacecraft, offers the opportunity for forces to be exerted on the craft that rae of the order of the ambient pressure. It may be worthwhile to steer a apacecraft into high pressure environments just to capture this effect.

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[1] J. C. Maxwell, Royal Soc. Phil. Trans. **170**, 231 (1879).
[2] O. Reynolds, Royal Soc. Phil. Trans., Part 2 (1879).
[3] J. N. Spitale, Science, **296**, 77 (2002).
[4] B. Denardo and T. G. Simmons, Am. J. Phys., **72**, 843 (2004).
[5] R. M. Winglee, J. Slough, T. Ziemba, and A. Goodson, J. Geophysical Res. Space Phys., **105**, 21067 (2000).
[6] S. D. Drell, H. M. Foley, and M. A. Ruderman, J. Geophysical Res., **70**, 3131 (1965).
[7] N. J. Fisch, Phys. Rev. Lett. **41**, 873 (1978).
[8] N. J. Fisch and A. H. Boozer, Phys. Rev. Lett. **45**, 720 (1980).
[9] N. J. Fisch, Nuclear Fusion **21**, 15 (1981).
[10] N. J. Fisch, Rev. Mod. Phys. **59**, 175 (1987).