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Mass Streams for Spacecraft Propulsion and Energy Generation

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A speculative propulsion concept is presented, based on accelerating a spacecraft by impact of a stream of matter in relative motion with respect to the spacecraft. To accelerate the stream to the needed velocity, the stream mass is contained in a transit craft, launched at low velocity and hence low energy cost, and then sent on a trajectory with near encounters of the planets for gravitational assist. The mass arrives at Earth or wherever the propellant is needed at much higher velocity and kinetic energy, where it is released into an extended stream suitable for propulsion. The stream, moving at a relative velocity in the range of 10 to 30 km/s, should be capable of both high thrust and high specific impulse. Means of limiting the transverse expansion of the stream during release and for the ∼1000 s duration of impact are a critical requirement for practicality of the concept. The scheme could potentially lead to a virtually unlimited energy source. One can imagine using a portion of one stream to launch another, larger payload on a similar trajectory. This creates, in effect, an energy amplifier extracting energy from the orbital motions of the planets. The gain of the energy amplifier is only limited by the capacity to prepare mass in transit craft.

Nomenclature

A	=	impact plate cross-sectional area
a	=	pressure coefficient
C_{HR}	=	radiative coupling coefficient
e_{stream}	=	stream acceleration efficiency
F	=	total force acting on the propelled spacecraft
f	=	acceleration efficiency factor
G	=	gravitational constant
g	=	acceleration
h	=	enthalpy
$h_{\max}$	=	maximum enthalpy
L_{str}	=	stream length
M_l	=	stream mass/unit length
M_S	=	solar mass
M_{str}	=	stream mass
$\dot{M}_a$	=	ablated mass rate/unit area
$\dot{M}_s$	=	total mass source rate/unit area
$\dot{m}_s$	=	cumulative mass source/unit area
P	=	pressure
$P_{\max}$	=	maximum pressure
R_E	=	Earth orbital radius
R_J	=	Jupiter orbital radius
S	=	total radiative power incident on surface
s	=	coordinate along stream direction
T	=	gas temperature
t	=	time from onset of stream impact
t_f	=	final time
v	=	fluid velocity
v_E	=	Earth orbital velocity
v_I	=	stream velocity in spacecraft reference frame
$v_{\max}$	=	maximum spacecraft velocity for finite θ
v_p	=	spacecraft velocity
v_{pf}	=	final spacecraft velocity
v_{str}	=	stream velocity
$w(s)$	=	stream particle contour for finite θ
x	=	coordinate along direction of spacecraft acceleration
z	=	fluid coordinate
ε	=	energy loss factor
$\varepsilon_{\mathrm{vaporize}}$	=	heat of vaporization
θ	=	angle between stream and direction of spacecraft acceleration
ρ	=	fluid density
$\dot{\rho}_s$	=	mass source density rate from stream particle vaporization

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I. Introduction

THIS paper considers a novel propulsion scheme especially suited to high-value missions for which the travel duration must be kept to a minimum and both thrust and specific impulse are at a premium, for example, for manned missions to the planets. The concept, sketched in Fig. 1, employs an extended mass stream moving at a velocity in the range of 10 to 30 km/s that impacts a spacecraft over a period of typically a thousand seconds. The mass stream, rendered into the form of small granules, dust or gas, can impact a plate/ablator similar to a reentry heat shield. A high-temperature gas or plasma cloud forms near the plate, aiding in vaporization of particles and creating an opaque layer that partially shields the plate from plasma radiation. When combined with gravitational assist, the scheme can also serve as an energy source of potentially unlimited magnitude, where the inertia of mass mined on the moon or asteroids could be the working material for energy-producing streams. At 50 to 500 MJ/kg the inertia of the stream contains an order of magnitude more energy than the same mass of chemical fuel.

The idea of using a mass stream for propulsion was first considered by Singer[1] in the context of interstellar propulsion. Singer's concept was later adapted by Willis[2] to the more modest, and hence more achievable, stream velocity requirements of interplanetary missions. Both Singer and Willis envisioned acceleration of the mass stream with an electromagnetic mass driver,[3] which requires a source of high electrical power (>GW) and would be from 10 km in length for an interplanetary driver to 10^5 km in length for an interstellar driver. The concept considered in this paper would replace the mass driver with conventional propulsion combined with gravitational assist, where the vast majority of the stream energy is drawn from the orbital kinetic energy of the planets, that is, from the gravitational assist, rather than from chemical, nuclear, or other power sources. By eliminating the need for a large capital investment to accelerate the stream, practical applications might be a nearer term possibility than other versions of the mass stream concept.

For example, a stream moving at 30 km/s with a mass flow rate of 30 kg/s, or equivalently a linear mass density of 10^{-3} kg/m, could accelerate a 100-ton spacecraft at one to two gravities and

Fig. 1 Mass stream propulsion concept viewed in the reference frame of a transit craft. In a) the transit craft (filled rectangle) carries the mass that is to released into a stream, b) the mass is released into the stream (gray dashed line) over a period of days, and c) the stream strikes an ablator on the propelled spacecraft (black rectangle). The transit craft shifts to the side to avoid a collision with the propelled craft.

final velocities of order the incident stream velocity. The enthalpy (energy per unit mass available to create thrust) of the mass streams is 3 to 30 times larger than is possible with chemical rockets. The mass stream is produced by release of a large number of low-mass objects from a transit craft that, over a period of months to years, has undergone acceleration to the required velocity. The stream must be localized transverse to its direction of flow to ~1 m, a challenging aspect discussed in Sec. II. The stream and spacecraft must also be colocated to ~1 m, normally a daunting task for objects in extreme relative motion. However, at least for the case when the stream and propelled craft are moving in nearly the same direction, the stream flows through a particular point in space for ~1000 s. If there is a positional error, the propelled spacecraft simply locates the stream flowing past and insert itself in the flow on a timescale of ~100 s or less. Ultrafast sensors or high-g maneuvering as in hypervelocity-impact missile defense systems would not be needed. Even so, it is clear that precision navigation and timing as well as planning months or years in advance will be required.

The transit craft could be launched from Earth vicinity at low velocity and accelerated to high velocity by gravitational assist from planetary encounters. The scheme becomes most attractive if the source of mass and launch of the transit craft is done extraterrestrially, for example, mined and assembled on the moon, because the cost of lifting the mass through Earth's deep gravity well is then avoided. The transit craft returns to the near vicinity of Earth moving at the speed and direction desired to accelerate the propelled craft. As an example, the Cassini mission followed a trajectory of this type, leaving Earth vicinity at a velocity of ~2 km/s and returning after two encounters with Venus, at a relative velocity of 16 km/s, for a gain of 64 in kinetic energy (see Fig. 2). Much higher velocities are also possible, for example, by employing orbits that swing by Jupiter. For a typical orbit with perihelion near Earth's orbital radius, one can choose a distance of closest approach such that the gravitational interaction with Jupiter brings the transit craft to near rest in the solar-system frame. The transit craft then follows a low angular momentum orbit with a velocity on return to Earth vicinity calculated from the difference in gravitational potential energy of the Earth and Jupiter, $v = \sqrt{[2GM_S(R_E^{-1} - R_J^{-1})]} = 37.8$ km/s. The low angular momentum means that the transit craft crosses Earth's orbit with velocity nearly normal to Earth's orbital velocity, giving a total velocity in the Earth reference frame where the stream would be employed of $v = \sqrt{[v_E^2 + (37.8\,\text{km/s})^2]} = 48.1$ km/s. Once up to speed and approaching the point of use, the mass carried in the transit craft is released in an extended stream that collides with the propelled craft to provide the acceleration. Ideally, the stream mass is much larger than the remaining mass of the transit craft after the stream is released.

A moving object colliding with a stationary one can effectively accelerate the second object, for example, if the masses are equal an elastic collision extracts 100% of the momentum from the moving mass and delivers it to the stationary mass. This is of little practical use, however, if the collision occurs between equal-mass bodies at typical orbital velocities because the bodies are reduced to high-

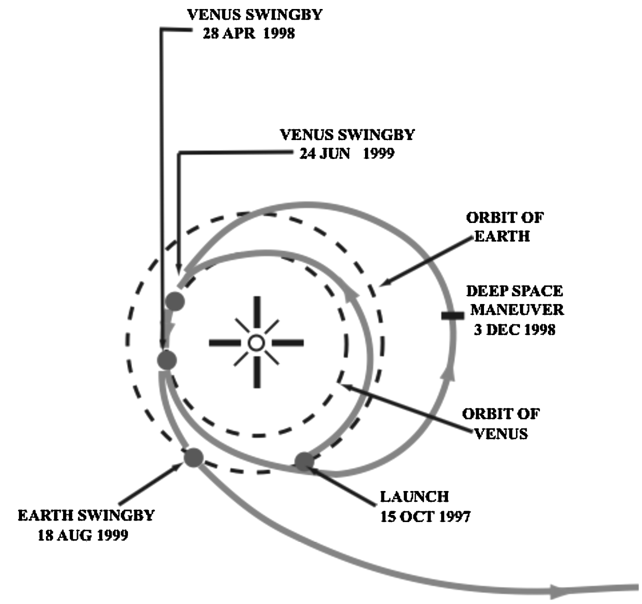

Fig. 2 Cassini gravity-assist trajectory (courtesy of NASA/Jet Propulsion Laboratory-Caltech).

temperature vapor. What is needed is a "soft," or time-extended collision where the average acceleration of the impacted body is manageable. The mass stream concept provides for just such a soft collision, although the stream and a portion of the impacted ship are still vaporized. The stream, of course, does not have to be completely steady. It could consist of mass pulses, for example, for the preceding example the average stream density of 10^{-3} kg/m could consist of pulses of 10^{-1} kg/m, 1 m in length, separated by 100 m, as long as the peak pressures generated stay below the yield stress for the impact plate. In this form, the scheme resembles Project Orion, the pulsed nuclear-explosive-driven propulsion concept.[4] However, the pulse frequency would be much higher and the impulse per pulse much lower for the mass stream than for Orion.

The direction of motion of the propelled craft and the stream do not have to be exactly colinear, although the efficiency of momentum and energy coupling would decline quickly at greater than 45 deg between velocity vectors. To accomplish this, the impact plate surface is tilted with respect to the stream, and the stream is released into curved path so that the trajectory of each stream mass element intersects the impact plate. The required path is derived in the appendix. A large angle between directions of motion makes the colocation problem more difficult, however.

For a given mission, for example, sending the propelled craft from Earth to Mars using a Cassini-like gravity assist for the transit craft, the transit craft could be launched of order 20 months before the propelled craft. As found in Sec. III, the optimum energy efficiency for acceleration occurs when the propelled craft is accelerated to $\Delta v \cong 0.715 v_{\text{stream}} = 11.4$ km/s for the case when $v_{\text{stream}} = 16$ km/s, although higher velocities are possible at the cost of efficiency (even exceeding the stream velocity for non-parallel streaming and propelled craft directions as shown in the appendix) and higher stream velocities should be possible, as already noted. A typical stream duration would be 1000 s for a total stream length of 5700 km, and the stream mass would be equal to 0.83 times the propelled craft mass for the optimal case discussed in Sec. III. The final velocity for the propelled craft in this example, that is, Earth's orbital velocity plus the Δv, approaches solar escape velocity. The minimum trip time is of the order 90 days, or between $\frac{1}{2}$ to $\frac{3}{4}$ the time projected for a fast transit mission employing nuclear thermal propulsion (for instance, see the NASA web site nssdc.gsfc.nasa.gov/planetary/mars/marslaun.html) although this could be shortened further by using higher propelled craft velocities. The transit craft must be timed to not only take advantage of gravity-assist trajectories but to arrive at Earth vicinity at the appropriate time for injection of the propelled craft into a

Mars trajectory. The flexibility in direction of the stream vs direction of the propelled craft opens up a range of possible trajectories that should help make the timing problem manageable. Once at its destination, the propelled craft could decelerate by aerobraking or by impact of a counterdirected stream.

The interaction of the mass stream with the propelled spacecraft is an important problem for this concept. Direct impact of several gram or larger hypervelocity objects at normal incidence on a surface would likely cause excessive cratering and mass ejection. A grazing incidence surface, that is, a shallow angle cone, might relieve the impact issue, or alternatively the objects could be dispersed before impact to gas or micron-scale material. Micron-scale particles and smaller will be vaporized and slowed in the hot gas/plasma cloud near the impact site, and it is assumed that the mass stream is reduced to this form in the analysis in Sec. III. The impact plate/ablator on the propelled craft will necessarily be a very robust object, constituting a significant fraction of the mass of the propelled craft, and could perhaps be designed to tolerate impact by a small fraction of stream objects that do not properly disperse before impact. There are a number of ways of controlling the trajectory and dispersal of the stream that are discussed in Sec. II.

Hydrodynamic analysis of the gas/plasma cloud produced by the incident mass stream is discussed in Sec. III. The stream creates conditions similar to those found during high-speed atmospheric reentry, that is, temperatures of 9000–40,000 K depending on the stream velocity and pressure of order a few atmospheres (for a steady stream). One can make use of the extensive literature in this area to estimate the radiative loading of the surfaces and ablation of the impact region in Sec. IV. Mass ablation can contribute 10% or more to the exhausted mass from the incident stream. Section V touches briefly on the energy application.

It is assumed throughout that the mass stream and propelled spacecraft interactions take place in the vacuum of space; however, there might also be the possibility of sending a stream to a high-altitude location on the Earth's surface or to a high-flying aircraft. A scheme[5] similar to that discussed here was proposed for launching a craft from the upper atmosphere with a mass stream derived from the moon and "dropped" through the Earth's gravity well to reach 11 km/s. For any stream velocity, the leading edge of the stream would be burned away as in a meteor shower, but because the stream is thousands of kilometers in extent and aligned with precision the following particles might survive reentry in the low-density channel created by the leading edge of the stream. The stream would have to be released along a curve compensating for the substantial rotational motion of the Earth. If some of the stream survives reentry, then it might be possible to launch a craft from within the atmosphere.

II. Stream Control

For the example given in the Introduction, a mass stream of 10^{-3} kg/m with a total mass of 10^5 kg would have length 10^8 m. If this stream were released from the transit craft at a relative velocity of 10^2 m/s, the release time is of order 10^6 s, or about 11 days. The objects in the mass stream must have a transverse deviation from the mean trajectory by no more than the radius of the impact zone on the propelled craft, say, of order 1 m. For free-flying objects, this implies initial transverse velocities (random deviations caused by imperfect mass ejection) of 10^{-6} m/s or less, which would be difficult. If the mass stream is released directly in the form of dust or fine granules for such an extended period other effects, such as space charge induced by photoelectric emission in the presence of the solar ultraviolet flux, become a problem. A charged stream would have a tendency to push itself apart. It seems likely that the mass must be released in the form of larger objects, which in turn release or are reduced to gas or dust shortly before impact. One can imagine using a small explosive charge embedded in several-gram to ~100-gram objects as a possible method of dispersal. Release of granular material from the propelled craft, upstream of the impact point, could be a means for dispersing larger particles. In the extreme limit of the mass-pulsing, Orion-like version of the concept, one could consider not dispersing the incoming objects but ejecting comparable mass objects from the propelled craft that collide with the incoming objects and vaporize in the near vicinity.

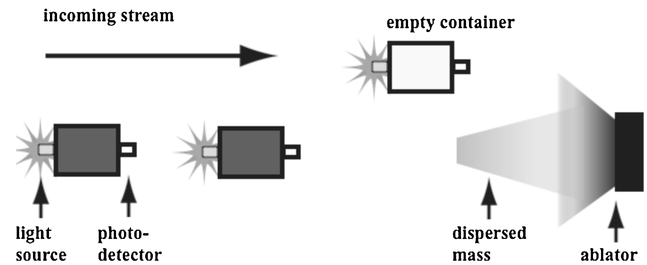

Fig. 3 One version of the mass stream consists of microspacecraft that maintain alignment with a light source and photodetector on each object. The microspacecraft release their mass before encountering the ablator on the propelled craft.

Perhaps the most straightforward possibility is to use ~1-kg objects containing micron-scale dust, which is released seconds before impact in a miniature version of the large-scale stream release pictured in Fig. 1. For this case, a simple method of effecting the release is to employ a small thruster to accelerate backward along the stream contour, allowing the dust to drain from its container, for example, one gravity acceleration for 10 s could disperse a dust stream 500 m in length. The propellant energy needed to accelerate the objects in this manner is 10^{-3}–10^{-4} times the kinetic energy stored in the stream.

At least two methods come to mind for maintaining alignment of the larger objects that constitute the stream. The first, and most promising, borrows from recent developments in microspacecraft technology.[6] If the objects released are microspacecraft weighing a few grams or more and having a very modest maneuvering capability, for example, delta-v of order the velocity errors introduced by mass ejection, $\sim 10^{-2}$ m/s or less, then they can correct their trajectory as required. The microspacecraft must be able to sense their location, say, with a photo detector viewing a light source on the microspacecraft some meters ahead (see Fig. 3) or collimating laser beams emitted by the transit craft. Because the relative velocities of the microspacecraft are nearly zero, the detection and information processing requirements should be very achievable. The relative ease of collocating the stream with the propelled craft and the modest requirements for adjusting the elements of the stream were first noted by Singer.[1] Interestingly, the costs per kilogram of mass-produced microspacecraft are plausibly similar to those of consumer electronics because the basic ingredients (structural materials, integrated circuits, a small power source) are similar and hence small compared to the typical several thousand dollars per kilogram in launch costs. The economics improve further if one invokes the mass pulsing, nonsteady stream concept mentioned in the Introduction and/or the dust-release concept just mentioned. A ~ few gram microspacecraft could be attached to an essentially inert (and hence inexpensive) 100 g or larger payload. Instead of being attached to the larger mass, the microspacecraft could also act as "shepherds" for the inert masses. An alternative method for keeping the particles in line is a low-mass, low-tension tether, or possibly a series of short tethers combined with microspacecraft.

III. Mass Stream Impact Hydrodynamics

One can idealize the incoming stream as a collection of solid particles that are annihilated in the stagnating gas cloud. The results are similar to results for a pure hydrodynamic interaction with the incoming mass, that is, if the particles are reduced to gas before impact, one does not expect a qualitative change in the conclusions with regard to momentum input or stagnation temperatures although the detailed flow profiles will differ. The one-dimensional hydrodynamic equations for steady flow, including sources of mass momentum and energy from the annihilating particles, are given by

$$\frac{d\rho v}{dz} = \dot{\rho}_s, \qquad \frac{d}{dz}(\rho v^2 + P) = -\dot{\rho}_s v_I$$
$$\frac{d}{dz}\left[\rho v\left(h + \frac{v^2}{2}\right)\right] = \varepsilon\frac{\dot{\rho}_s v_I^2}{2} \tag{1}$$

Z is the spatial coordinate, $z = 0$ at the ablator surface, ρ is the gas density, v is the velocity, $\dot{\rho}_s$ is the mass source density rate as a result of particle annihilation, v_I is the incident velocity, and $\varepsilon < 1.0$ is an energy loss factor to account for radiative losses. Velocities are in the frame of the spacecraft, that is, v_I will decrease as the craft accelerates. Taking $z > 0$ away from the ablator surface, the incident stream has velocity $v_z = -v_I$ in the spacecraft frame. A realistic treatment of radiation would alter density and enthalpy profiles near the stagnation surface, but for this simple model the losses are lumped in the factor ε estimated from detailed models of radiative transfer referenced next. The equations assume one-dimensional axial flow, that is, a cylindrical "bucket" of fixed cross section collects the incident matter or that the scale height in the z direction is small compared to the ablator diameter. Integrating Eqs. (1) in z gives

$$\rho v = \dot{m}_s, \qquad \rho v^2 + P = P_{\max} - \dot{m}_s v_1$$
$$\rho v\left(h + \frac{v^2}{2}\right) = \varepsilon\frac{\dot{m}_s v_I^2}{2}, \qquad \dot{m}_s = \int_0^z \dot{\rho}_s\,dz \tag{2}$$

The mass source/unit area $\dot{m}_s$ becomes the independent variable in these equations, and the mapping from $\dot{m}_s$ to z can be determined *a posteriori* from the solution and a model for ablation of the particles, for example, if the particles are uniformly ablated then $\dot{m}_s$ is just proportional to z. To close the set of equations, one needs an equation of state relating pressure to enthalpy and density, and hence must choose constituents for the mass stream. Silicon carbide is chosen arbitrarily, although similar results are found for other low-to-moderate atomic number materials in the expected density and temperature range. From the Livermore equation-of-state tables[7] produced at Lawrence Livermore National Laboratory, one finds an approximate relationship

$$P = a\rho h \tag{3}$$

with $a = 0.21$ for pressures of 1–10 atm and temperatures 9000–40000 K. An approximate fit to the tables gives a relationship for the enthalpy in the same parameter regime,

$$h = 15\,T^{1.6}\ \text{J/kg} \tag{4}$$

with T in degrees Kelvin. Combining the first and third of Eqs. (2) gives

$$h = \varepsilon\left(v_I^2/2\right) - v^2/2 \tag{5}$$

Note that the maximum enthalpy, occurring near the impact surface, is

$$h_{\max} = \varepsilon\left(v_I^2/2\right) = 5 \times 10^7 \varepsilon(v_I/10\,\text{km/s})^2\ \text{J/kg} \tag{6}$$

as compared with 1.3×10^7 J/kg for hydrogen + oxygen, giving an improvement of between 3 and 30 for the mass stream over chemical rockets for the parameter range of interest. There is a factor as a result of the direct momentum deposition, as seen in the following, that gives an additional factor of 2 or more advantage to the mass stream.

Combining Eqs. (4) and (5) gives us the temperature near the material surface, $v = 0$ (neglecting ablation)

$$T = 11900\varepsilon^{0.63}(v_I/10\ \text{km/s})^{1.25}\ \text{K} \tag{7}$$

For example, for typical radiation losses of 30% (see next) then $\varepsilon = 0.7$, and the temperatures are given in Table 1.

Substituting $\rho = \dot{m}_s/v$ from the first of Eqs. (2) into second of Eqs. (2) and making use of Eqs. (3) and (5) yield a quadratic equation

Table 1 Temperature vs stream velocity

v_I, km/s	T, K
10	9,530
20	22,700
30	37,600

for the velocity. The solutions are

$$v = (P_{\max}/\dot{m}_s - v_I) \pm \sqrt{(P_{\max}/\dot{m}_s - v_I)^2 - a\varepsilon v_I^2(2-a)}\Big/(2-a) \tag{8}$$

These represent subsonic and supersonic roots to the steady flow equations. Because $v = 0$ at the surface, the subsonic root (−sign) is required. It is easy to verify that v vanishes as $\dot{m}_s$ and z go to zero for this root.

In a realistic system, the thruster geometry must flare into a cone and/or allow a free expansion at some point beyond which the flow becomes supersonic. At the flare point the roots must coalesce, that is, the flow reach Mach 1 as in a Laval nozzle. A well-designed thruster will have $\dot{m}_s = \dot{M}_s$, the total incident mass flux near this point because the density and particle ablation drop rapidly in the expansion region. If one demands $\dot{m}_s = \dot{M}_s$ where the roots coalesce, then

$$P_{\max} = \dot{M}_s v_I[1 + \sqrt{a\varepsilon(2-a)}] \tag{9}$$

From Eq. (9) one sees that if $\varepsilon = 0$, the pressure and hence momentum input rate at the surface are consistent with the incident momentum flux, that is, the incident mass has an "inelastic collision" with the surface (the total force $F = P_{\max}A = \dot{M}_s v_I A$, where A is the cross-sectional area). For ε nonzero, one has a pressure enhancement, for example, for $\varepsilon = 0.7$ and $a = 0.21$ as in the preceding example, the term in parentheses is 1.51, still short of the factor 2.0 expected for an "elastic collision" of the mass stream with the surface. For the example with $\dot{M}_s = 30$ kg/s and $v_I = 30$ km/s and taking $\varepsilon = 0.7$ and $a = 0.21$, the total force would be 1.36×10^6 Nt or 139 metric tons of thrust. If the thruster radius is 1 m, then the pressure is 4.3 atm. If the thruster has a flared nozzle, the total momentum input to the spacecraft can come closer to the elastic collision limit. With mass ablation (see the next section) the momentum input could exceed the elastic collision limit.

It is straightforward to calculate the acceleration history of the spacecraft if it is assumed that the factor in parentheses in Eq. (9), $f \equiv 1 + \sqrt{[a\varepsilon(2-a)]}$, remains constant as the relative velocity between the stream and spacecraft changes. Defining v_P as the velocity of the propelled spacecraft ($v_P = 0$ at onset of stream impact), then both the stream velocity in the spacecraft frame, $v_I = v_{\text{str}} - v_p$, and the mass flux in the spacecraft frame, $\dot{M}_S = M_l(v_{\text{str}} - v_p)$, decline as the spacecraft accelerates. M_l is the mass per unit length of the stream with area $A = 1$, for simplicity. The equation of motion for a spacecraft of mass M_p, neglecting ablation, is then

$$M_p\ddot{x} = fM_l(v_{\text{str}} - v_p)^2, \qquad \dot{x} = v_p \tag{10}$$

where x is the coordinate along the direction of spacecraft acceleration. The stream and spacecraft are assumed to be moving in the same direction (see the appendix for a discussion of the case of a stream at an angle). Equations (10) can be solved for the time-dependent position and velocity of the spacecraft:

$$x = v_{\text{str}}t - \frac{M_p}{fM_l}\log\left(1 + \frac{fM_l v_{\text{str}}t}{M_P}\right)$$
$$v_p = v_{\text{str}} - v_{\text{str}}\Big/\left(1 + \frac{fM_l v_{\text{str}}t}{M_P}\right) \tag{11}$$

If the stream is of length L_{str}, then the acceleration is completed at a time $t_f = (L_{str} + x_f)/v_{str}$. The final spacecraft velocity v_{pf} is then

$$v_{pf} = v_{str}(1 - e^{-fM_s/M_p}), \qquad M_s = M_l L_{str} \tag{12}$$

where M_s is the total stream mass. From Eq. (12) one can calculate the efficiency of stream acceleration e_{stream}, defined as the ratio of spacecraft kinetic energy to stream kinetic energy. The optimum e_{stream} occurs for $M_s/M_p = 1.2564/f$ with $e_{stream} = 0.4073f$ and $v_{pf} = 0.7153v_{str}$. For the optimum case $L_{str} = x_F = v_{str}t_F/2$. For $f = 1.51$ as in the preceding example, the maximum efficiency is $e_{stream} = 0.615$. The efficiency can obviously never exceed 1, which is confirmed by these results because $f < 2$ (the elastic collision limit).

IV. Thermal Loading and Ablation

To estimate the thermal loading and mass ablation of the stagnation surface, one can rely on the extensive body of work[8] modeling heat-shield ablation for high-speed atmospheric reentry, where densities, pressure, and temperatures are in a similar regime. At reentry velocities (or mass stream velocities in this case) of 10 km/s or greater, radiation emission and absorption become dominant processes. The emission and absorption properties of the material are dependent on the atomic, ionic, and molecular species present in the gas, which can of course differ from atmospheric air in the case of the mass stream. For purposes of this estimate, it is assumed that the constituents can be chosen so that the radiative properties are the same as atmospheric air. It might be possible to choose materials that reduce the radiative coupling, but defer that issue to a more detailed study of the concept.

Reference 8 shows that the radiative coupling to the surface is a weak function of the assumed flowfield properties. It is assumed that this remains the case for the hydrodynamic solution found in Sec. III. If the incident stream is completely reduced to gas, then the flowfield, that is, a shock standing off the surface, reduces to the case considered in Ref. 8. The total radiative power incident on the surface can be expressed as

$$S = C_{HR}\left(\dot{M}_s v_I^2/2\right) \tag{13}$$

Reference 8 shows that the dimensionless coefficient typically varies from $C_{HR} = 0.01$ at $v_I = 10$ km/s to a saturation value of $C_{HR} \sim 0.1$ for $v_I > 15$ km/s. C_{HR} is a weakly increasing function of pressure and an increasing function of the scale height of the gas layer. Values larger than $C_{HR} \sim 0.1$ were not found for velocities less than 20 km/s, pressures less than an atmosphere or scale heights less than 30 cm. As an estimate, it is assumed $C_{HR} = 0.1$ represents a bounding value over the whole range of parameters. The physical reason for the heat-flux limit is the presence of a comparatively cool layer of gas near the surface that strongly absorbs in the UV, shielding the surface from the intense radiation of the hot gas. Reference 8 shows that the total radiative loss (into and away from the surface) is about 3S, or 30% of the incident power if $C_{HR} = 0.1$. This is the rationale for choosing $\varepsilon = 0.7$ in Sec. II.

If one neglects conduction, which can reduce ablation at low heat flux, then the ablation rate can be found from the heat of vaporization:

$$\dot{M}_a \varepsilon_{vaporize} = S \tag{14}$$

Combining Eqs. (13) and (14) and using $\varepsilon_{vaporize} = 60$ MJ/kg for carbon and $C_{HR} = 0.1$ gives the estimate

$$\dot{M}_a = 0.083\dot{M}_s(v_I/10\,\text{km/s})^2 \tag{15}$$

Equation (15) shows that one expects mass ablation to be less than 10% of the mass in the incident stream at stream velocities of 10 km/s or less. Ablation would climb to an amount of order the incident stream mass at 30 km/s.

Equation (15) can also be used to estimate ablation of particles in the mass stream. The result is that roughly micron-sized objects should be vaporized for the typical parameters discussed. Equation (15) somewhat underestimates the ablation of small particles because the particles are likely to be smaller than the physical scale of an opaque shielding layer.

V. Energy Source

Also in a speculative vein, if the scheme is practical for propulsion it could potentially serve as an energy amplifier by using a small stream, or portion of a stream, to accelerate a larger mass to velocities sufficient for a gravity-assist trajectory. The large mass then returns as an energetic stream capable of accelerating an even larger mass, etc. In this case, it is more efficient to use a small mass to couple to a greater mass of ablator, that is, intentionally increase, rather than minimize, ablation. The greater ablated mass, with lower specific impulse than the stream, is then better matched to launching a spacecraft at low (~2 km/s) velocity. One can consider launching a transit craft directly from the lunar surface in this way, avoiding any need for chemical propellant, with the stream coming in from deep space tangent to the moon's surface. Some chemical propellant might still be necessary for adjusting the trajectory so that it passes through the desired point and in the correct direction.

The location of the energy source is also obviously of importance. Availability on the moon is perhaps of limited interest, although the moon becomes an attractive place for industrial activity if lunar mass is worth 10 times or more its own weight in chemical fuel. As mentioned in the Introduction, there is also some possibility the scheme could be used to launch vehicles directly from the Earth's surface and thereby locate both the mass launch and energy generation on the Earth's surface.

For the energy source to be viable, the economics of preparing, launching, and steering the mass stream are important. For an order-of-magnitude sense of what is needed, consider that a kilowatt-hour (kWh) of electricity for a terrestrial source is worth approximately \$0.05. A mass stream impacting at 16 km/s has an energy of 128 MJ/kg or 10.7 kWh/kg if one assumes 30% conversion to electricity, as is typical of a thermal cycle, and imagining efficient conversion of the incoming kinetic energy to heat. The conversion from kinetic energy to heat could take place in a cavity with an entrance hole that captures most of the debris of impact and plasma radiation, and hence most of the incoming kinetic energy in the mass stream. If the cost of producing the stream were ~\$0.5/kg or less, then an economical energy source might be possible. At 32 km/s the energy content would be four times as great, hence, the costs of producing the stream could be larger by a similar factor. Detailed estimates of the costs of producing the stream are beyond the scope of this paper.

VI. Conclusions

This paper has explored a novel, if speculative, method for achieving high-thrust and high-specific-impulse spacecraft propulsion employing mass streams. The scheme can also be useful for energy generation in space or otherwise. The analysis shows that an interesting regime lies in the range of 10 to 30 km/s. Below 5 km/s, the enthalpy of the mass stream approaches the values for chemical rocket fuel and hence offers little advantage for propulsion. Above 30 km/s, it appears that ablation of the impact surface becomes large. In the range of 10 to 30 km/s, the mass stream potentially offers an advantage of 3 to 30 in propellant enthalpy over chemical rockets while providing comparable thrust. The direct momentum deposition of the stream, an effect absent in a normal rocket, is typically comparable to the thrust produced by expulsion of the hot gas. A propulsion mode at higher stream velocities is also possible using low incident mass and momentum fluxes and relying on ablation for most of the impulse. In that case, the exhaust velocity and specific impulse depend on details of the ablation process and will be less than the stream velocity. The net result is that there is a fairly wide parameter regime where a mass stream could rapidly accelerate a massive payload to much higher velocity than is possible with a chemical rocket, leading to short travel times to the planets.

At the low end of the stream velocity range, performance would be comparable to a nuclear thermal propulsion system,[9] which is capable of ~ one gravity acceleration at an exhaust velocity of

~9 km/s. The predicted performance at higher stream velocities is more like an Orion-type propulsion system. An advantage of the mass stream over both of these is that the cost, complexity, environmental and political issues associated with nuclear propulsion are avoided. Ion thrusters are capable of the high (or higher) specific impulse provided by the mass stream, but cannot provide the high thrust needed for rapid interplanetary transport.

The concept depends on creating a very extended stream of mass-containing objects (10^5 or more) that will require a modest sensing and maneuvering capability of at least some of the objects constituting or accompanying the stream. These could be several gram-scale or larger microspacecraft. To avoid cratering the impact surface on the propelled craft, some means of mass release from the objects or reducing the objects to microscopic particles is likely to be needed. Several techniques for controlling and dispersing the stream were discussed in Sec. II.

A first test of mass stream acceleration could be done in a fairly straightforward manner. Spacecraft launched in counter-rotating low Earth orbits would have a closing velocity of 16 km/s, in the middle of the desirable mass stream velocity range. One of the spacecraft would release a modest number of mass-containing microspacecraft of the type discussed in Sec. II, which could be deployed into a short stream capable of testing the issues of navigation, stream interaction and momentum deposition on impact with the counter-rotating spacecraft.

If the energy amplification aspect were to prove viable, one can envisage a time when large amounts of mass would be continuously mined, prepared, and placed in transit around the solar system, providing both rapid transportation between the planets and a source of unlimited energy.

Appendix: Stream Path for Impact at an Angle

In general the direction of motion of the incident stream (the "streaming" direction) and the propelled spacecraft do not have to be colinear. In the process, momentum must of course be conserved, notably the component perpendicular to the direction of spacecraft motion. The perpendicular component of residual momentum of the postimpact stream plus that of any ablated mass must equal the same component of momentum of the incident stream. As a simple example, consider the idealized case of an elastic, glancing angle collision of a stream particle with a perfectly reflecting plate. The particle would depart its collision with the plate with no change of the component of momentum parallel to the surface of the plate, which is accelerated in a direction normal to the surface by the collision. Ablation and inelastic collision effects could affect the direction of acceleration in a more realistic case.

For a stream, the particles must be positioned so as to "lead" the propelled spacecraft because its acceleration causes it to move with some component perpendicular to the streaming direction (see Fig. A1). Note that, although the stream particles are laid out or released into a curve, they are all moving in the same direction to very good approximation, that is, the velocity differences between particles might be a few meters/second vs the overall stream velocity of 10 km/s or greater. It is straightforward to calculate the curve of stream particles $w(s)$, where s is a coordinate antiparallel to the streaming direction with $s = 0$ at the leading edge of the stream and $w(s)$ the distance transverse to the streaming direction ($w = 0$ at $s = 0$).

If the spacecraft is undergoing uniform acceleration g in the x direction, then its displacement is simply $x = gt^2/2$, where t is time elapsed because the onset of acceleration. Uniform acceleration implies a nonuniform mass distribution in the stream to compensate for the change in relative velocity between spacecraft and stream. The streaming direction is at angle θ with respect to the x direction. Time can be related to the initial coordinate s of a stream particle

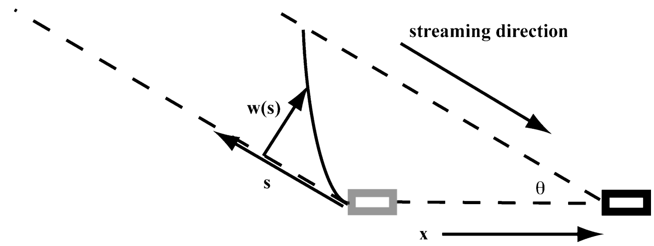

Fig. A1 Stream particles are distributed along an initial curve $w(s)$ at the onset of impact with the spacecraft (rectangle). The streaming direction and spacecraft direction of motion are at an angle θ.

because the particle must arrive at the spacecraft location at a time t. In this case $t = L/v_{\mathrm{str}}$, where $L =$ distance traveled $= s + x\cos(\theta)$ and v_{str} is the stream velocity. The transverse distance of the stream particle must project to the spacecraft position, that is, $w = x\sin(\theta)$. Combining relations gives

$$w(s) = 2s_{\max}\tan(\theta)\left(1 - \frac{s}{2s_{\max}} - \sqrt{1 - \frac{s}{s_{\max}}}\right)$$

$$s_{\max} = \frac{v_{\mathrm{str}}^2}{2g\cos(\theta)}$$

where $s_{\max}$ is the maximum value for which a curve $w(s)$ can be found, $\mathrm{d}w/\mathrm{d}s \to \infty$ as $s \to s_{\max}$.

These relationships also reveal the maximum velocity that can be reached by the spacecraft. Because the velocity is simply given by $v = gt$, with $t = [s + w/\tan(\theta)]/v_{\mathrm{str}}$, the maximum velocity is found for $s = s_{\max}$. Plugging in the expression for w gives a maximum spacecraft velocity, $v_{\max} = v_{\mathrm{str}}/\cos(\theta)$. Interestingly, at finite angle of incidence the spacecraft can be accelerated to velocities higher than the stream velocity. Similar analysis could be done for nonuniform acceleration.

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