CLIPPER SHIPS OF SPACE

BY RUSSELL SAUNDERS

A fascinating suggestion for sailing ships of space, a seemingly wild notion, but actually worked out mathematically, it makes sense! It would be possible to sail on "the wind that blows between the worlds"! See Willy Ley's letter in Brass Tacks.

Illustrated by Orban

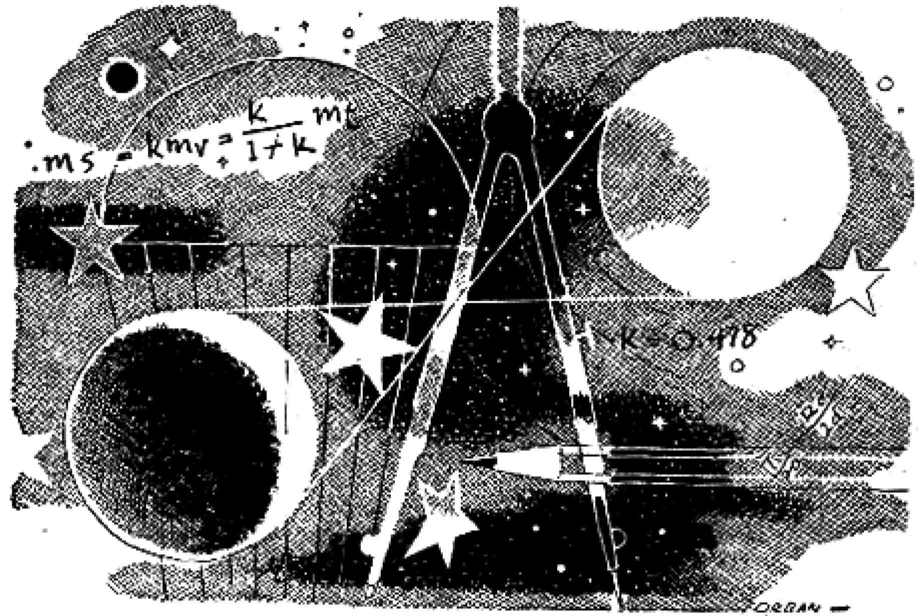
It is becoming more and more taken for granted that the only possible method of propulsion in a vacuum is the rocket. It is true that science fiction is full of various types of space-warp drives. However, even the fertile imaginations of writers in this field have not challenged the rocket as the only practical, or even possible interplanetary drive in the foreseeable future.

I intend to propose another method of propulsion in a vacuum which is based on present day physics. I will show that in many ways this drive is more practical than the rocket. In order to prove my point I will have to use a certain amount of mathematics. This will permit those who wish to, a chance to check my assertions. The rest may follow my verbal argument which I hope will be fairly coherent without the mathematics.

The proposed drive is based on a fact already widely known, the fact that light exerts pressure on material bodies. This pressure is very small except in the interiors of stars where its outward thrust prevents the stellar structure from collapsing under the pull of its own gravitational field.

Even in much less violent environments the mechanical forces exerted by light can become important if the areas of the material particles are large compared to their mass and other mechanical forces are very small. This is true of very small particles in outer space.

Whipple has pointed out that the radiation pressure by light from surrounding stars may be the agency which forms interstellar dust into sufficiently compact clouds to permit gravitational forces to take over and compress the cloud into a new star.



Long ago Arrenhius suggested that life would have voyaged through the intersellar void in the form of spores driven by radiation pressure. This idea was used in a fine science fiction story by Raymond Gallun, called "Seeds of the Dusk."

These considerations suggest the possibility of using a "sail" to obtain mechanical forces from the sun's radiation of great enough magnitude to drive a spaceship between the planets. It will be found as we proceed that the unique conditions that exist in the space between the planets actually make a drive of this sort feasible.

Except in regions very close to the planets, the gravitational forces are very small permitting the force of the sun's radiation on the sail to become a first-order effect. The sail itself must be made of lithium or some other light metal, and must be very thin. Such a sail can only exist in a vacuum since it would react with the atmosphere. In addition, it would be so fragile it would be torn apart except in free space.

In order to test the feasibility of this idea we must decide what acceleration of the ship the sail must produce. Since the acceleration is applied continuously, the amount required will be minute compared to rocket accelerations. It is important to note that both the gravitational attraction of the sun and the radiation pressure on the sail decreases inversely as the ship's distance from the sun. This means that, when the sail is erected, the ship will behave as if the mass of the sun has been suddenly reduced. If the sail produces a force equal to the attraction of the sun at any distance from the sun, the two forces will balance at any other distance and the ship will travel in a straight line through the solar system. In practice, a force sufficient to allow the ship to travel along a hyperbolic orbit is believed to be sufficient. Such an orbit will permit our ship to travel anywhere in the solar system or even leave it if desired.

We may find the acceleration on the ship which the sail must produce to establish a hyperbolic orbit by remembering that a body in a stable circular orbit must double its kinetic energy, if it is to go into a hyperbolic orbit and escape the attracting center. Suddenly halving the mass of the attracting center would have the same effect. The repulsive force on the sail will halve the apparent mass of the sun, if it produces an acceleration outward which is half the gravitational acceleration of the sun at the same distance.

The gravitational acceleration of the sun in the orbit of Earth is -0.529 cm/sec². Therefore, the sail must produce an outward acceleration of half this amount or -0.265 cm/sec².

We must now find the total force acting on the ship and sail in order to find the acceleration produced by a given ship and sail design. This force will be the difference between the gravitational and radiation forces being exerted.

Let

m_v = mass of the vessel

m_s = mass of the sail = $km_v = \frac{k}{1+k} m_t$

m_t = total mass = $m_s + m_v$

P = area density of sail in grams/cm²

σ = radiation pressure on sail in dynes/cm²

A— = area of sail in cm² = $\frac{m_s}{P}$

α_s = gravitational acceleration of the sun

α = acceleration of ship

F = total force exerted on the ship

When we consider the problem of attaching the ship to the sail we will see that the sail must be a hemisphere. The effective area over which the radiation pressure is exerted is the projection of the sail on a plane normal to the sun's rays. This projected area is the base of the hemisphere, which has half the area of the hemispherical sail.

The total force exerted on the ship is given by

$$F = (\sigma \frac{A}{2} + \alpha_s m_t)$$

$$= m_t \left(\frac{\sigma}{2_p} \frac{k}{(1+k)} + \alpha_s \right)$$

$$\frac{F}{m_t} = \alpha = \frac{\sigma}{2_p} \frac{k}{(1+k)} + \alpha_s$$

Now α must be half of α_s in order to establish a hyperbolic orbit. Putting in this value of α we may solve for k, the ratio between the mass of the vessel and the mass of the sail.

$$k = \frac{-\alpha_s}{\frac{\sigma}{p} + \alpha_s}$$

We will find k assuming the ship is in Earth's orbit. This value of k will give a hyperbolic orbit starting at any point in the solar system as explained before. We will choose magnesium for our sail material since it has a fair strength mass ratio and is opaque for sheets 0.15 microns thick which is the thickness we will assume. This makes P equal to 26×10^{-6} grams/cm².

We will use the pressure exerted by the radiation of the sun at the surface of Earth on a surface reflecting ninety-four percent of the incident energy. This is 85×10^{-6} dynes/cm². This figure is pessimistic since Earth's atmosphere scatters about thirty percent of the sun's radiation back into space. The ratio k is now found to be equal to 0.193. If we had desired to travel in straight lines, we would have found k = 0.478.

We have proved that the sun's radiation can produce adequate ship accelerations for sails which have between nineteen percent and forty-eight percent of the mass of the vessel. This shows that radiation pressure may be used as a practical drive for interplanetary ships.

The mass of the sail compares very favorably with mass of the fuel which must be carried by a rocket. The rocket requires fuel masses of over three times the mass of the rocket structure while the sail of our "light-jammer" is less than half the mass of the ship. Furthermore, the rocket is good for one trip, then its fuel is exhausted and more must be ferried up from the surface of a planet. The sailing ship can operate for an indefinite number of voyages once it is constructed. An error in navigation may be corrected by maneuvering under sail. The rocket is helpless once its fuel is expended.

A hidden bonus is provided by the fact that the accelerations experienced by the ship are always minute. This means that the ship structure need only withstand internal air pressure. It may be a thin metal skin inflated to spherical form by the air within. This results in a ship which is mostly payload and very little structure. A rocket must be stressed to withstand the high accelerations which occur during operation of the motors. This results in a heavy structure and small payload.

Before going further we must examine the problem of attaching the ship to the sail. As mentioned before, the sail will be a hemisphere open toward the sun. The rim of the sail will contain a stress distributing wire and a series of rigging wires will go from the rim back to the ship. The sail will then look like a parachute with the ship suspended from it. Since the sail can withstand no shearing stress it will find a shape for which it is in pure tension. This shape will be close to hemispherical.

We must now make sure that the tension on the sail can be safely withstood by the metal. The radiation force on the sail is $\pi R^2 \sigma$ where R is the radius of the hemisphere. This force must be transmitted to the wire rim through the sail area immediately adjacent to the rim. The area of the metal through which the stress is transmitted is $2\pi Rd$ where d is the sail thickness. The stress on the metal is then

$$\frac{R\sigma}{2d}$$

Allowing a twenty-to-one safety factor, we will equate this stress to one twentieth the tensile strength of the metal. Or

$$\frac{T}{20} = \frac{R\sigma}{2d}$$

where T is the tensile strength of the metal in dynes/cm^2. We may now solve for R to find the largest sail radius which will not overstress the sail.

$$R = \frac{Td}{10\sigma}$$

If the ship is to approach the orbit of Mercury, σ the radiation pressure may be ten times its value in the Earth's orbit or 8.50×10^{-4} dynes/cm^2. The thickness d was taken as 1.5×10^{-6} cm in computing the value of k. T for magnesium is about 2.3×10^6 g/cm^2. Then R will equal forty kilometers. This is surely as large a sail as we would care to build for a long time to come.

We can now examine the design of a particular ship in order to make the design more concrete. Let the total mass be 100,000 kilograms or a little over 100 tons. Then the sail's mass is 16,100 Kg and the vessel's mass is 83,900 Kg. The sail's area is 61 square kilometers and its radius is 4.4 kilometers. This radius is well within the maximum permissible radius of 40 kilometers. The force transmitted to the ship through the rigging will be the mass of the ship times the acceleration due to the sail or 2.26×10^4 grams. If the ship is three times the sail diameter behind the sail and the rigging is also magnesium, then it will have a mass of 1,960 kilograms, if a two-to-one safety factor is assumed. This figure includes the wire in the sail rim which is assumed to be the same strength as all the rigging wires.

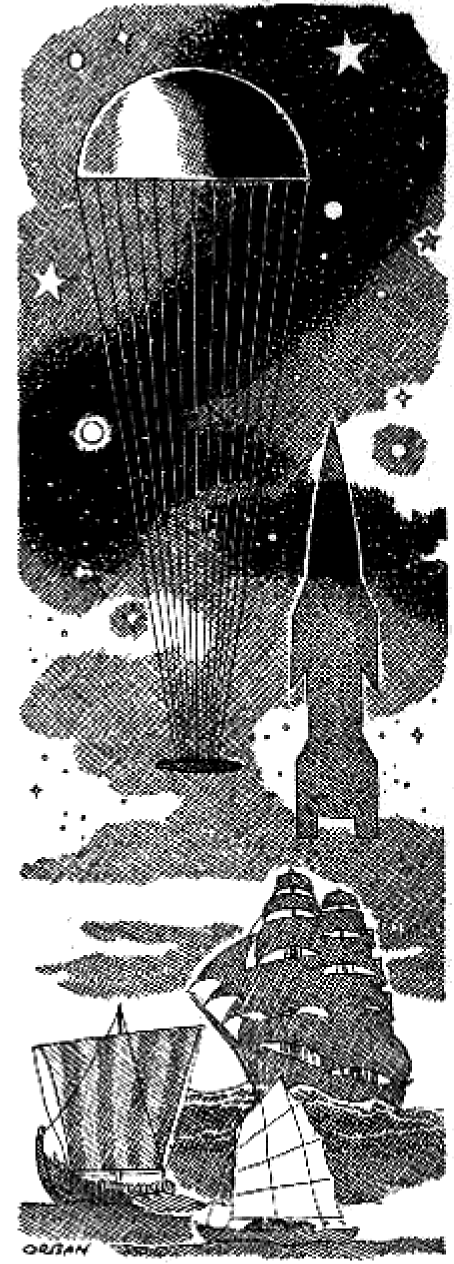
Having satisfied ourselves as to the basic feasibility of the system we can now examine the method of operating our ship. The objection will be made that such a ship could never land on a planet. This is true but not a fatal objection. The ship must be docked at an artificial satellite circling the planet and passengers and freight ferried to and from the planet by rocket.

The ship itself must be built at the artificial satellite. The sail can be constructed by vacuum evaporation methods. A thin plastic sheet may be electrically charged. This will cause it to become rigid. Then lithium can be sprayed onto the sheet by heating the metal in a boiler and directing the resulting metal vapor at the plastic sheet with a nozzle. When the metal sheet is completed, the plastic may be coated with lampblack so it will absorb heat and then turned toward the sun. The plastic will melt and may be stripped off by charging the boiler with respect to the sail. The resulting electrostatic attraction will cause the plastic to return to the boiler. It may then be formed into a new sheet.

The metal skin, which will become the ship, can also be constructed at the satellite and then inflated.

Let's now consider the problems of navigating the vessel. Many of its characteristics are similar to a normal sailing ship. Like its Earth-bound cousin, it carries no fuel and an error in navigation does not leave it stranded in space like a rocket would be in similar circumstances. Once constructed, our ship is good for an indefinite number of trips. This makes it appear that interplanatory travel could be accomplished on an economical basis. Most of the cost would be involved in the ferrying trips to and from the artificial satellites which act as docks for our deep-space vessel.

It has not been shown how our ship can go inward toward the sun, but this will be discussed very shortly. The fact that it is possible means that after the first sailing ships have been constructed of materials ferried up from Earth, all future ships should be constructed from material available in the asteroid belt. No fuel is required to get this



material into free space and once a ship is constructed it can be sailed anywhere throughout the system. Iron and nickle are available in the asteroid belt and the existence of stonelike meteors indicates that the same asteroids will contain light metal oxides. These oxides may be reduced to obtain light metals for sails and oxygen.

The book "The Atmospheres of the Earth and the Planets," edited by Dr. Kuiper, contains data which supports the belief that the inner moons of Saturn are composed of ice. These moons could be mined to furnish water, hydrogen, and oxygen. This material can be carried to free space without undue expenditure of energy since these satellites are small. The presence of methane and ammonia in the atmosphere of Titan furnishes a source for these gases for further synthesis and provides the elements nitrogen and carbon. Thus, the basic elements for construction and the support of life are probably available without the expenditure of large amounts of chemical energy needed to carry them into free space from the surfaces of the planets. Their location in the solar system does not matter since sailing ships can carry the material to the orbit desired without expenditure of chemical energy.

Returning to the navigation problem, we find that our ship must be sailed in the true sense of the word. Like an ocean-going sailing ship, we need a keel otherwise we can only "run before the wind." Fortunately, the equivalent is available. It is the gravitational field of the sun or any of the planets. To make this statement more concrete, let us consider the problem of leaving a stable orbit about a planet. The accelerations provided by the sail are not great enough to blow the ship out of the potential well surrounding the planet which is of great depth and very steep. However, the ship can escape by what amounts to tacking.

After erecting the sail, the ship must turn itself so that the sail is edge on to the sun while in the portion of its orbit during which it is approaching the sun and then turn the sail normal to the sun's rays while receding from the sun. The system will gain energy during each revolution and eventually will accumulate sufficient kinetic energy to leave the potential well.

If the ship and sail rotate about their common center of gravity at half the rate at which they revolve about Earth, then the sail will be edge on to the sun on one side of its orbit and normal to the sun on the other side. The fact that the ship is first on the sunward side and then away from the sun on alternate revolutions makes no difference since centrifugal force will keep the rigging and sail in tension in both positions.

As the ship spirals outward it will revolve more and more slowly. The rate of rotation may be decreased to keep step with this change by gradually lengthening the rigging wires. The time required to escape from Earth's field is in the order of several months.

Since the forces acting on the sail are so minute, the orbit of the artificial satellite from which the ship starts its journey must be at a great enough altitude to reduce drag due to the residual atmosphere of Earth to a value low compared to the radiation forces on the sail. Using present estimates for the density of the upper atmosphere, the minimum orbit is found to be at an altitude of two thousand kilometers. By the time the ship reaches interplanetary space the drag due to gas will drop to about 10^{-5} the radiation forces.

Once the ship has escaped from Earth's field it can be maneuvered to any point in the solar system by opening and closing the sail at the proper times thus changing from one conic section to another. It is to be noted that on elliptical orbits where the ship is approaching the sun, the sail is actually doing work on the sun's radiation and the ship is losing energy.

However, in order to arrive at any given planetary destination with the same velocity as the planet, the ship must be able to change its angular momentum. This it cannot do as long as it experiences only central forces. Fortunately, the sail can produce a component of force normal to the direction of arrival of the sun's radiation. This may be done by turning the sail so that it does not make a right angle with the incident energy. The reflected light will then leave the sail at an angle with respect to the radial line from the sun to the ship and a portion of the recoil will be a tangential force on the sail. If the sail were flat plate, the maximum tangential force is obtained when the sail is turned thirty degrees to the normal. The tangential force for this position is three fourths the force the radiation exerts on the sail in its normal position. Calculations show that if the ship possesses the same angular momentum per unit mass as Earth then by "tacking" with the sail cocked, the angular momentum of the ship may be adjusted to the correct value for making a landing on any of the inner planets in about a month.

The other method of changing the angular momentum of the ship is to guide the ship to an intermediate planet and make a hyperbolic passage near the planet. If this is done correctly, the ship can transfer the correct amount of angular momentum to the planet to make its angular momentum equal to the value required if it is to reach its destination planet at zero velocity with respect to the planet.

Since the ship can continually alter its course by sail trimming as it nears the intermediate planet, it is felt that the approach may be controlled accurately enough to make possible a precise control over the change in angular momentum caused by the passage by the intermediate planet.

THE END