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AN INTERPLANETARY MASS TRANSIT SYSTEM BASED ON HYPERSONIC SKYHOOKS AND MAGSAIL-DRIVEN CYCLERS

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ABSTRACT

A number of innovative methods have been proposed for transporting the first human explorers to Mars. This paper takes a long-term perspective in presenting a concept for a transportation system capable of supporting the mass migration of people and goods between Earth and Mars. The proposed mass transit system integrates the magnetic sail (magsail) and hypersonic skyhook concepts proposed by Zubrin with features of Aldrin's "Mars Cycler" architecture and Forward's orbital tether concepts to define a system capable of providing regular transportation between Earth and Mars. This service would be provided by a fleet of magsail-driven "cruise ships" capable of transporting large numbers of people between Earth and Mars in relative comfort and safety. Transportation between these "MagCyclers" and planetary surfaces would use a combination of rotating hypersonic skyhooks to achieve the large velocity changes required and transatmospheric vehicles powered by local propellants for takeoffs and landings. Although the envisioned system would initially be used to establish regular Earth-Mars trade routes, its ultimate purpose is to enable a thriving system of commerce throughout the inner solar system.

A key advantage of the proposed scheme is that it provides a relatively high level of vehicle and spaceport utilization as well as the ability to repair and upgrade the ships while they are on-orbit. More efficient operation of the skyhooks is enabled by allowing the masses of incoming and outgoing cargo to be matched, thereby reducing the energy required to reboost the skyhook. The paper also discusses the anticipated evolutionary development of this space transportation infrastructure including the potential for expanding the system to provide MagCycler service to Venus.

Keywords: Mars, cycler, magsail, skyhook, tether, interplanetary, colonization, trade, emigration

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"For I dipt into the future, far as human eye could see,
Saw the Vision of the world, and all the wonder that would be;

Saw the heavens fill with commerce, argosies of magic sails,
Pilots of the purple twilight dropping down with costly bales;"

Alfred, Lord Tennyson

1. INTRODUCTION

"This is the goal….
To make available for life every place where life is possible
To make inhabitable all worlds as yet uninhabitable
And all life purposeful."

Hermann Oberth, 1923

Since the rocket-borne birth of the Space Age almost forty years ago, and most notably during the past decade, a number of visionary individuals have proposed alternative methods for reaching space and spanning the great distances between the planets. The primary goal of these methods is to reduce the cost and/or time required to safely transport passengers and cargo from Earth into space, and ultimately to the planets. In some cases the underlying technologies are also applicable to interstellar travel. The successful realization and application of these technologies, both alone and in combination, promises to dramatically increase our accessibility to space and the nearby worlds of the inner solar system, and to ultimately provide the foundation for a thriving system of commerce throughout the entire solar system.

Such advanced technologies and concepts include rotating skyhooks or tethers [1,2,3,4,9], magnetic sails [3], solar sails [4], light-craft [4], planetary "cyclers" [5], transatmospheric vehicles [4], and even more exotic and exciting fusion and anti-matter propulsion methods [4]. For obvious reasons these concepts are usually presented in papers that focus on a particular propulsion or transportation method and do not discuss how they might be synergistically combined with other technologies to create an overall transportation infrastructure. Although substantial work remains to be done on refining these ideas and the supporting technologies that will be required, it is not too early to see how several of them might be used in combination to build a safe, efficient, and cost-effective mass transportation for the inner solar system. The remainder of this paper presents just such a concept for a transportation infrastructure that incorporates rotating skyhooks, magnetic sails, transatmospheric vehicles, and planetary cycler concepts. It is primarily intended to provide inspiration and "food for thought" for the reader.

2. SYSTEM OVERVIEW

"The 21st century will see the planets drawn together and the complexion of human civilization changed. Space has already demonstrated that a bountiful future is not possible for mankind without it."

Krafft Ehricke, *Men of Space*

The basic operation of the transportation system involves transporting people and cargo from the Earth's surface in a suborbital transatmospheric vehicle (TAV) to rendezvous, at hypersonic velocities, with the lower end of an orbiting, rotating tether (skyhook) system. After linking to the TAV with a grapple device, the skyhook proceeds to throw the TAV on a trajectory to rendezvous with a large, magsail driven "cruise ship" (the "MagCycler") which is parked in a highly elliptical orbit around the Earth. Once fully loaded, the magcycler ship employs its magnetic sail supplemented, if necessary, with reaction engines, to reach escape velocity and embark on its journey to Mars.

After a six to eight month journey to Mars, the reverse sequence takes place. The MagCycler brakes into a highly elliptical orbit around Mars using its reaction engines (since Mars has no significant natural magnetic field). The TAV, which is capable of flight in Earth's or Mars' atmosphere, leaves the magcycler and flies to a rendezvous point with the upper end of a rotating Mars skyhook (equivalent to the one used at Earth). After achieving linkup, the rotation of the skyhook carries the TAV down to an altitude and velocity where the TAV is released, powers up its (Mars) airbreathing engines, and proceeds to its landing site. For the return journey to Earth, which could take from six to fourteen months depending on the launch window used, the same basic steps would take place. However, since the Earth has a substantial magnetic field, a "magneto-braking" (analogous to "aero-braking") maneuver could be used to eliminate, or significantly reduce, the need for reaction engines to enter Earth orbit.

Although the above example refers to a single TAV, skyhook, and magcycler, there would, in fact, be a large number of TAVs used (depending on the capacity of each magcycler) and several rotating hypersonic skyhooks in equatorial orbit around each planet (depending on the transfer rate required to load and unload the MagCyclers while on orbit). As shown in Figure 1, the MagCycler ships would travel in fleets or "caravans" of three ships for safety and to allow them to perform useful maneuvers involving the coupling of their magnetic fields. Four such caravans (twelve MagCyclers total), taking advantage of available Earth-Mars opposition and conjunction launch windows and Venus flyby opportunities, and spending an average of six months on orbit for maintenance and resupply at each planet, could provide departures and arrivals at each planet at intervals averaging approximately ten months (varying from six to fourteen). With advancements in magsail technology, and experience in employing the unique orbital transfer maneuvers of which they are capable, it should be possible to make departure times more flexible.

3. MAG-CYCLER OPERATION

When ships to sail the void between the stars have been invented, there will also be men who come forward to sail those ships."

Johannes Kepler, 1600 AD

The Magsail-driven Cycler, or "MagCycler", shown in Figure 2, is a ship designed to operate in the inner solar system for the purpose of carrying passengers and cargo along the trade routes between the Earth and Mars. Each MagCycler includes a magsail for propulsion, a pair of inflatable habitation rings to accommodate passengers and cargo, and a circular array of movable solar panels to provide power. The magsail design concept presented here represents a vastly scaled up version of the magsail example presented by Robert Zubrin in [3]. Zubrin estimates that the fare for a trip to Mars on a magsail-driven cycler could be as low as $28,000 [6]. Scaling is accomplished not by increasing the overall physical dimensions, but by increasing the current carrying capacity (cable cross section), number, and arrangement of conductors in the web-like magnetic sail. This section briefly describes the MagCycler's principles of operation, living areas, and power source. Limitations of current technologies that must be addressed to realize such vehicles, primarily in the area of high temperature superconductors, are also mentioned. More detailed treatments of these topics can be found in the referenced documents.

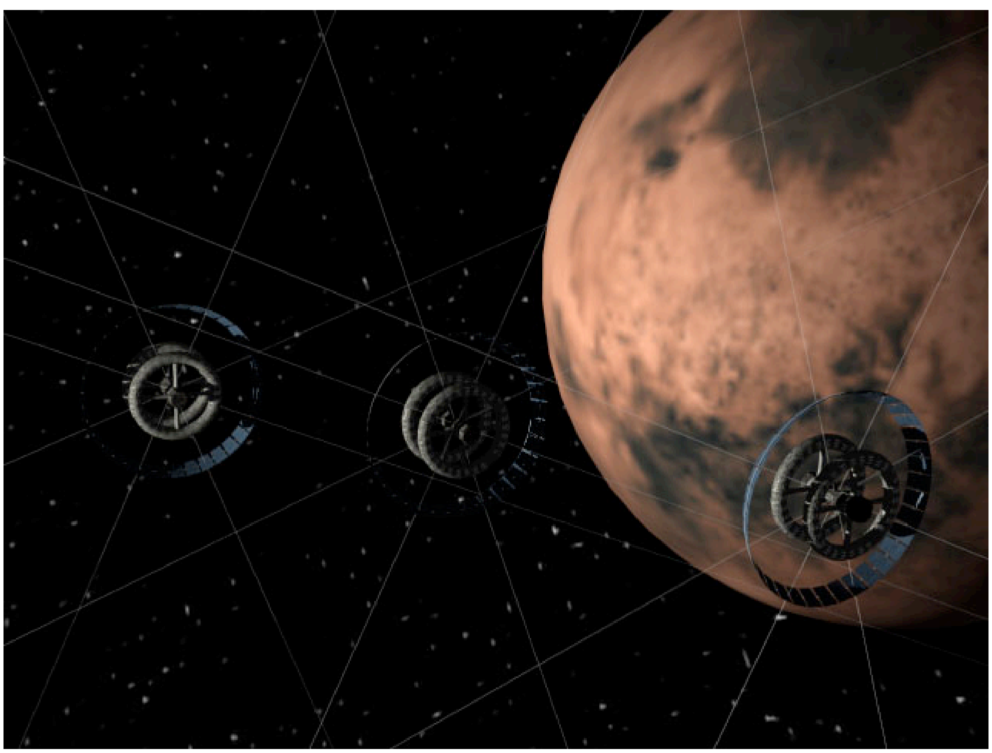

Figure 1. MagCycler Caravan Approaching Mars

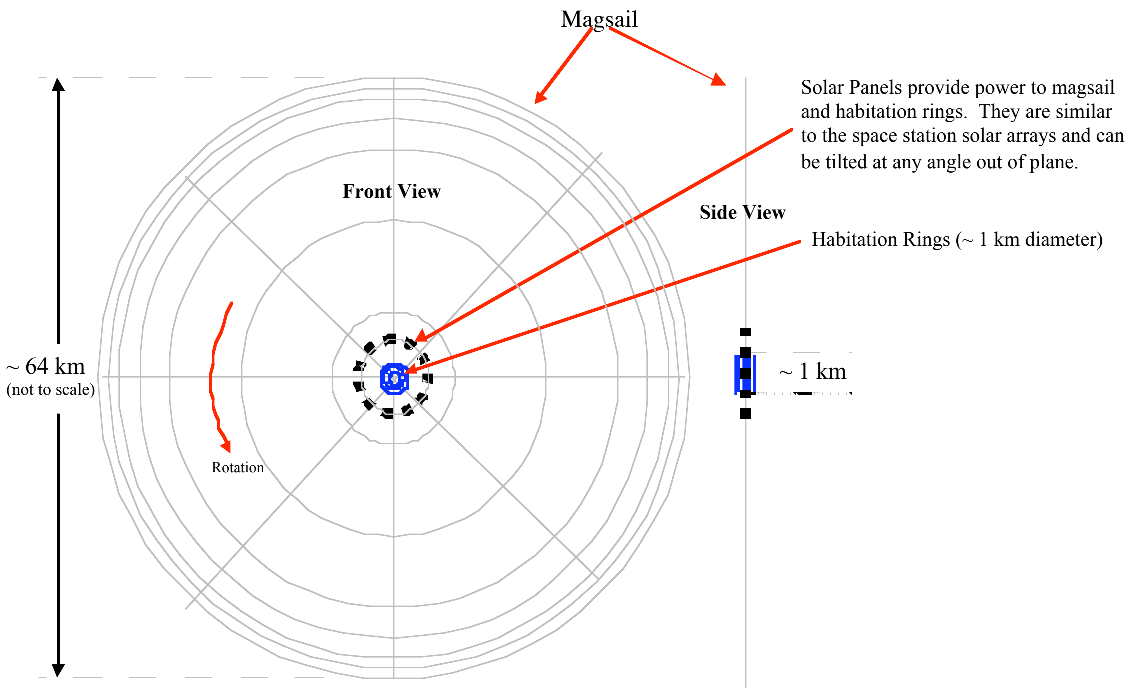

Figure 2. "MagCycler" Design Concept

3.1. Magsail Principles of Operation

A magnetic sail or "magsail" can be thought of as a magnetic "balloon" or "bubble" that is blown by the solar wind. The solar wind consists of a high velocity outflow of protons and electrons from the Sun. A magsail generates an immense magnetic field that acts as a barrier to these charged particles in the same way that the Earth's magnetic field prevents the same high energy particles from penetrating our atmosphere as illustrated in Figure 3. When the particles are blocked by it's magnetic field, they transfer a small momentum to the magsail. This small momentum, summed over the immense surface area of the magnetic field, slowly accelerates the magsail, and whatever is attached to it. The field of the magsail also acts as a shield against harmful high-energy particles that accompany solar flares and that also inhabit the Earth's radiation belts in a band from approximately 500 km to 10,000 km above the equator.

As with a hot air balloon, the magnetic field of the magsail can be "inflated" or "deflated" (increased or decreased in size). This provides the ability to control how hard the solar wind pushes against the magsail. Advanced magsail designs will also be capable of generating asymmetric magnetic fields that will turn the MagCycler without using reaction engines. As with solar sails, which are pushed by the photons in sunlight rather than the solar wind, a magsail can also "tack" against gravity, which means it can move towards as well as away from the wind (or the Sun, in this case). Furthermore, the magsail can be used to effectively counteract a small percentage of the Sun's gravity, allowing it to perform unusual orbital transfer and rendezvous maneuvers, such as arriving ahead of a planet, then continuing to travel in the same orbit but at a lower velocity, allowing the planet to "catch up" to the magsail-driven ship.

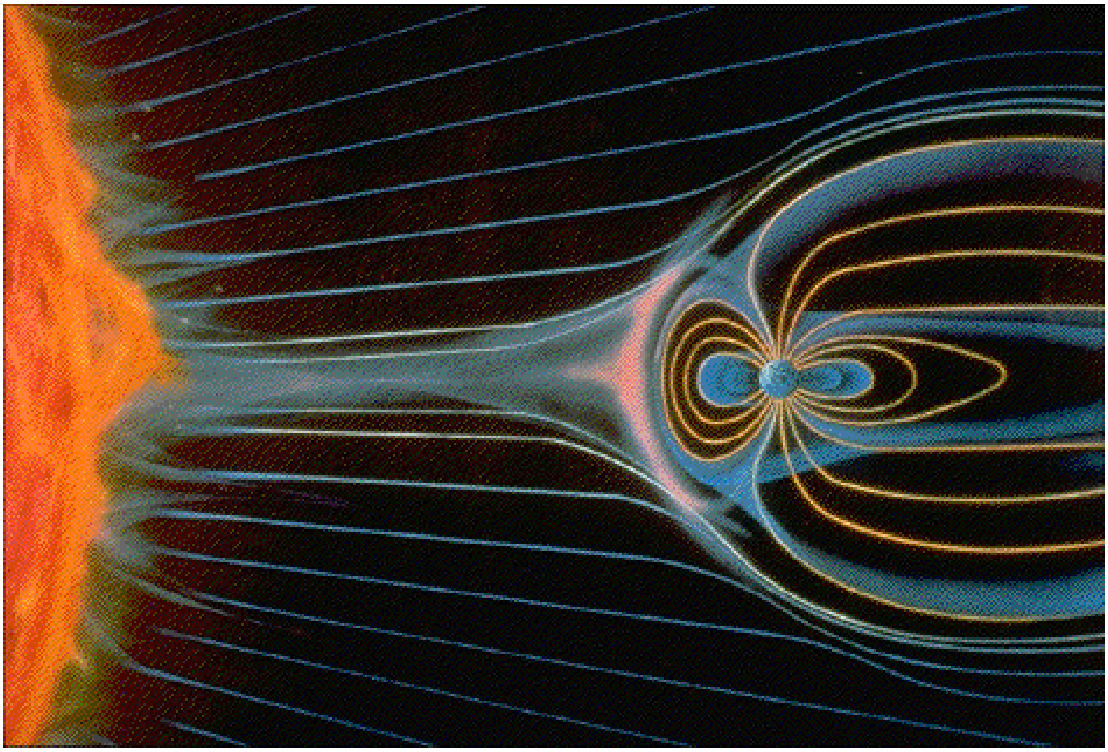

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Figure 3. Earth's Magnetic Field Deflecting the Solar Wind

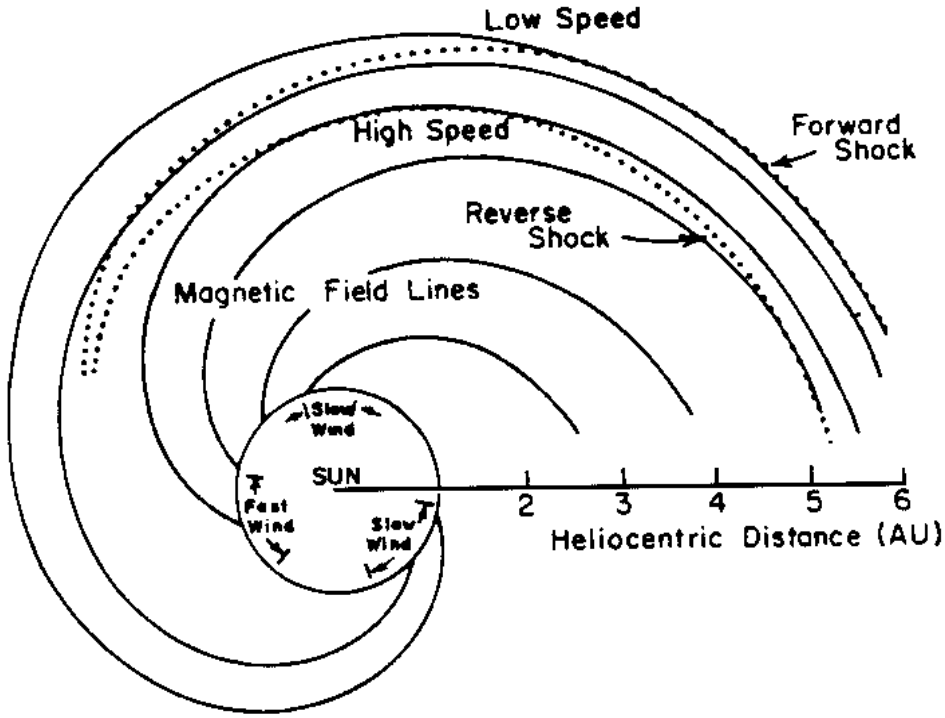


Figure 4. Example of Solar Wind Structural Details [7]

As shown in Figure 4, the solar wind is not uniform but has a large-scale structure containing regions of high and low velocity particles that are consistent over periods of several months [7]. Persistent shock waves have also been detected in the solar wind. By monitoring these variations in the solar wind a magsail-driven craft may be able to "ride the waves" more efficiently, reducing transit time between the planets.

3.2. Superconducting Magsails

A magsail capable of driving the MagCycler will require a three order of magnitude increase in field strength over the magsail example provided by Zubrin in [3]. While the payload mass assumed by Zubrin was fourteen tonnes, the mass of the habitation rings and solar panels of the MagCycler will be similar to that of a medium size cruise ship, or about 10,000 tonnes (this is roughly twenty times the mass of the International Space Station). To achieve the required increase in propulsive power while maintaining a magsail size on the order of sixty kilometers in overall diameter, the magsail consists of ten concentric conducting loops, each approximately one inch in diameter and capable of carrying 5000 kA.

Such immense, high current, magsails will only be possible if they can be constructed of superconducting (zero electrical resistance) cable. Fortunately, recent developments in high-temperature superconductors (alloys that are superconducting at readily attainable temperatures) shows promise not only in terms of significantly increased current capacity, but also in the ductility and potential availability of the massive quantities needed to fabricate the large lengths of cable required for a magsail of these dimensions.

The magsail will be deployed and stabilized both by repulsive electromagnetic forces, when powered, and by centrifugal forces provided by rotating the magsail. Due to the large diameter of the magsail its rotational rate must be independent and significantly lower than the rotational rate of the habitation rings in order to avoid developing excessive tensile forces in the magsail cables. This can be implemented through the use of superconducting magnetic slip rings and laser power transfer at the central hub.

3.3. Habitation Rings

A pair of coaxial “donut shaped” rings, shown in Figure 5, provides living space on the MagCycler. Although visually reminiscent of the double-ringed station of Kubrick’s “2001 A Space Odyssey”, the MagCycler’s habitation rings differ both in scale and construction. The overall diameter of the habitation rings is one kilometer, providing sufficient living and storage volume to comfortably house several thousand passengers. To reduce weight, construction time, and cost, the habitation rings and struts are inflatable structures based on an evolved and scaled version of NASA’s TransHab design. Rigid bulkhead inserts provide separate airtight sections within the rings. Foldout floor panels built into the core of the inflatable rings are deployed to create decks. After the structure is inflated and decks deployed, walls are installed as desired using interlocking composite panels.

Figure 5. MagCycler Habitation Rings

The central hub, which acts as a hangar as well as the axis and attach point for the habitation rings and magsail, is fabricated using more conventional methods and materials, although by the time of its construction essentially all of the materials used will be lightweight composites. Due to the weight savings resulting from the use of composites and inflatable structures the overall mass of the habitation rings is expected to be equivalent to that of a medium sized cruise ship (about 10,000 tons) even though the living volume is more than five times greater.

The habitation rings are rotated to produce artificial gravity. The rotational rate is gradually changed during the course of the voyage to vary the artificial gravity from 1g (at Earth) to 0.38g (at Mars). This allows the passengers to unconsciously become acclimated to the gravitational forces at their destination.

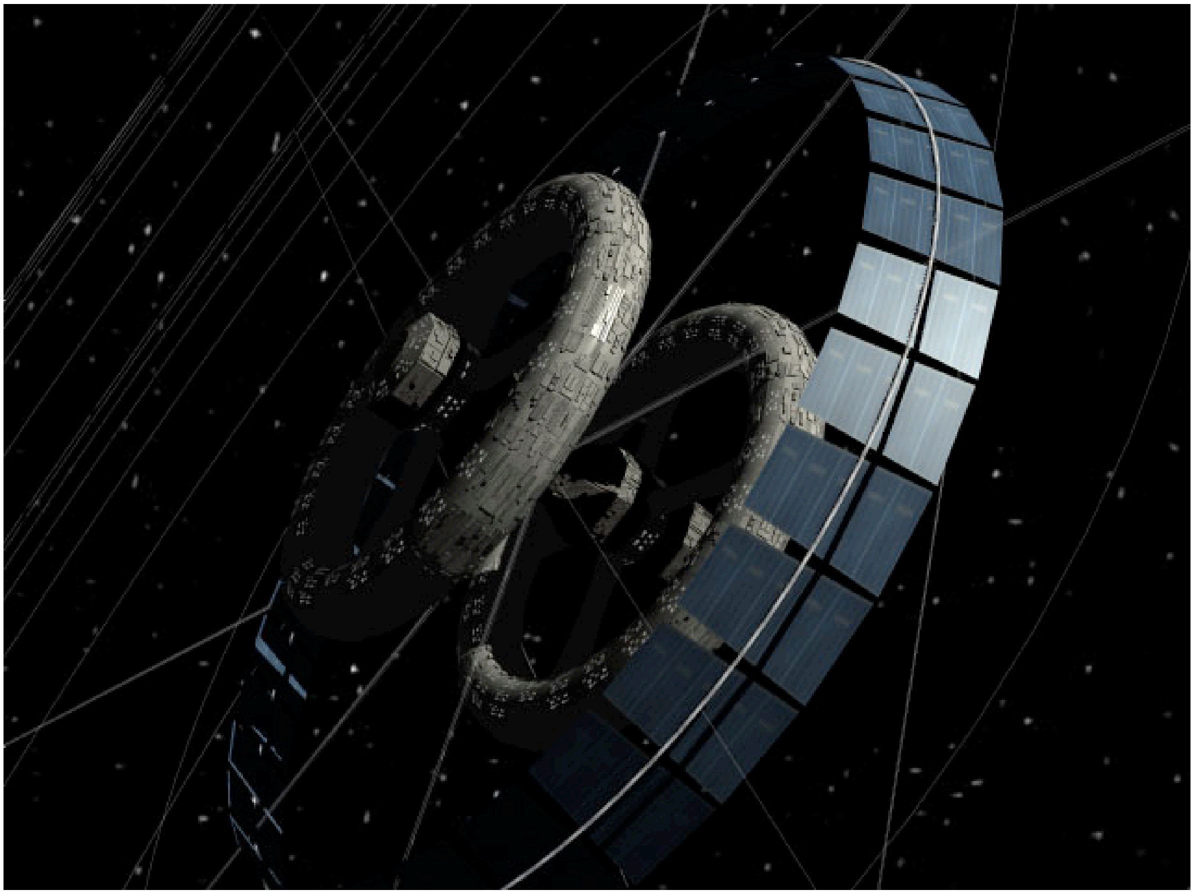


Figure 6. MagCycler Solar Panel Array

3.4. Solar Panels

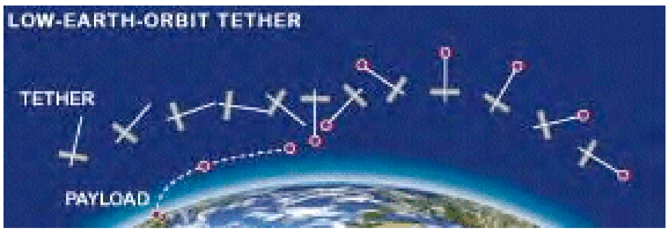
A circular array of high-efficiency solar panels, shown in Figure 6, provides the power required to "pump up" the magsail and power the environmental and control systems. The panels, which can be oriented to maximize their exposure to the Sun, are evolved versions of the solar panels used on the International Space Station. However, the surface area and power capacity of the array will be several thousand times greater, as needed to power such a massive vehicle, including rapid recharging of the magsail if necessary. Power distribution and control will be handled by a distributed system of switching nodes located at the intersections of the magsail's radial and circular current carrying cables

4. HYPERSONIC SKYHOOKS

"Rockets are the ferry boats of orbital travel,
[but] bridges to orbit may also be possible…"

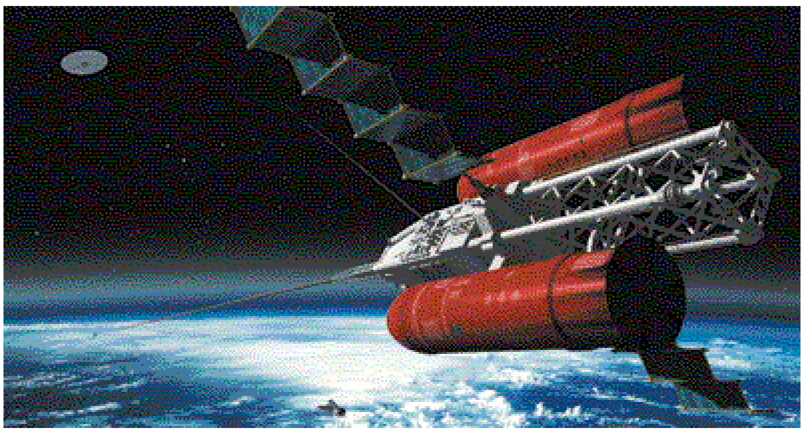
Hans Moravec, 1977 [9]

Skyhooks are bridges to orbit. In physical terms they are "momentum exchange" devices, or "orbital slings", that can catch a payload traveling at one velocity and release it at a higher or lower velocity later in its rotation. As shown in Figures 7 and 8, a skyhook consists of a long cable or "orbital tether", a grapple device and control module, and ballast that accounts for the bulk of the skyhook's momentum [1,2,3]. The ability to exchange some of the skyhook's momentum for a corresponding change in the payload's momentum (i.e. velocity) enables the inexpensive and efficient transfer of payloads to and from orbit. After catching or releasing a payload the skyhook ends up in a slightly higher or lower orbit. The skyhook's orbit can then be returned to its initial state using thrusters or electrodynamic forces acting on an electrically conducting portion of the skyhook. Alternatively, if the skyhook alternates between catching and tossing payloads of equal mass, or is designed and operated in a "double ended" fashion, simultaneously catching and releasing equal incoming and outgoing payloads on opposite ends of the skyhook, its net momentum is maintained and little or no reboost is required.



Tethers Unlimited

Figure 7. Orbital Skyhook/Tether Operation
(Produced by Johann Rosario for Tethers Unlimited)



SLIM FILMS

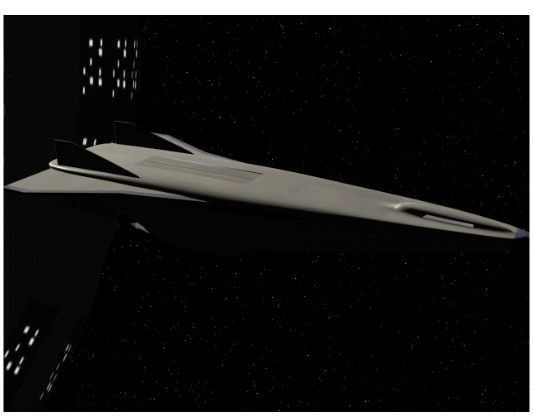
Figure 8. Orbital Skyhook Concept
(Produced by SLIM FILMS for Scientific American)

The "rotating hypersonic skyhook" design envisioned for use in the mass transit system is a scaled-up, two-ended variant of the "MarsWhip" and EarthWhip" orbital tether designs developed by Dr. Robert Forward and others [1,2]. One of the most significant advantages of these designs is that they can be constructed using existing materials, such as Spectra™ 2000, that is already available in large quantities. The skyhook is "hypersonic" because the lower end is traveling at a velocity of about Mach 5 when it approaches the top of the sensible atmosphere where it rendezvous' with a suborbital payload carrier. In the system presented here the entire payload carrier, a transatmospheric vehicle (TAV) is carried to orbit by the skyhook and released on a trajectory to rendezvous with the MagCycler in a higher elliptical orbit.

An interesting option presented by the rotating hypersonic skyhook is the ability to directly throw payloads between Earth and Mars. The payload is caught on the receiving end by an equivalent skyhook. Although this option will almost certainly be used to transport some cargo directly between the planets, the transport of passengers, and certain personal cargo, will take place in the spacious accommodations of the MagCycler. This is primarily due to the large masses of the habitation and power modules and the corresponding accelerations required to complete a direct transfer between skyhooks at the two planets. The reader is referred to the "Tethers Unlimited" papers [1,2] for a detailed analysis of the design and operation of these orbital tethers/skyhooks, including the direct "throw and catch" technique.

5. TRANS-ATMOSPHERIC VEHICLE OPERATION

The Trans-Atmospheric Vehicle (TAV) concept shown in Figure 9 is an adaptation of current hypersonic waverider designs to hybrid rocket and "airbreathing" operation in both Earth's and Mars' atmospheres. A basic ground-rule in the design of the TAV would be that all fuels used in the engines must be available in quantity at both planets, even if this means accepting somewhat suboptimal performance in the Earth's atmosphere. A likely candidate fuel for the rocket engines would be a combination of liquid oxygen (LOX) and methane, which can be manufactured using in-situ propellant production methods at Mars. Two of the relatively few materials that burn in the presence of carbon dioxide and which can be found or produced in quantity on Mars are magnesium and silane (SiH_4). The airbreathing component of the propulsion system may therefore extract carbon dioxide from the atmospheres (at either planet) and use it to burn magnesium or silane. The chemistry involved in producing LOX-methane and silane-carbon dioxide fuels using in-situ resources is described in [6].



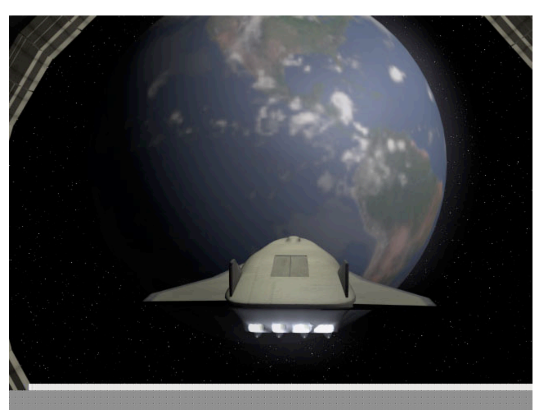


Figure 9. Suborbital Trans-Atmospheric Vehicle (TAV)

Due to the low density of the Martian atmosphere it is likely that the engines will not be true "air breathers" in the sense that they won't use the gases directly from the atmosphere in flight, but will instead be fed from tanks of carbon dioxide which are replenished during the TAV's stay on Mars or Earth. The differences in atmospheric density of the two planets could also result in the engines being divided into two "clusters", one at the rear of the vehicle and the other at the bottom. In the Earth's atmosphere the vehicle would obtain significant lift from the thicker atmosphere and could fly to a horizontal landing using only the rear engines. On Mars the bottom engines would compensate for the lack of aerodynamic lift and would be used to execute a vertical landing.

Either a built-in payload bay or a piggyback detachable canister arrangement can be used to carry cargo and/or passengers to the skyhook. If the TAV is carrying passengers bound for another planet the entire vehicle would be captured by the skyhook and released into a transfer orbit to rendezvous with the MagCycler. If only cargo is being transported a small guidance and reaction control system integrated with the payload canister will be necessary to guide it to the vicinity of the MagCycler for pickup or for interplanetary course corrections if the payload is being thrown directly to another planet.

6. TRANSPORTATION SYSTEM EVOLUTION

"Destiny is not a matter of chance, it is a matter of choice;
it is not a thing to be awaited, it is a thing to be achieved."

William Jennings Bryan, 1899

Once a thriving system of commerce has been established between Earth and Mars, people will begin to turn their eyes and energies outward to the asteroid belt and inward to Venus and Mercury. Due to their positions and composition, it is likely that Mercury and the asteroids will be used principally for their mineral resources. It is also conceivable that by this time terraforming activities will have begun on Mars and that the incredibly challenging task of taming Venus's acidic atmosphere will appear less daunting. If so, Venus will become the next target for colonization. With one of the MagCycler trade routes already passing Venus on the way from Mars to the Earth, a key enabling component for the next phase in the history of the inner solar system will already be in place.

To extrapolate beyond this time frame into the more distant future it may be helpful to take a look at the history of transportation over the past 150 years. In his seminal paper, "Dynamics of Transportation Infrastructures [8]", Nakicenovic uncovers the amazing pattern evident in Figure 10. This historical data, depicting the relative percentages of the total transportation route distances for various transportation modes from the mid nineteenth century to recent times, reveals a regular pattern of transition between dominant transportation infrastructures. These transitions have always been accompanied by the ability to travel farther, faster, and through a wider range of environments (water, land, and air…). If one assumes that this pattern will continue and extrapolates the starting points and slopes of future cycles, the result is the plot shown in Figure 11. Note that the starting years derived for the next two cycles are 2010 and 2175. It is interesting to speculate that the upcoming cycle, which should begin around 2010, may represent the beginning of travel to near-Earth space by multitudes of people. The next cycle, starting around 2175, may see the birth and growth of manned interplanetary space travel. And perhaps the following cycle, beginning about 2350, will herald the development of interstellar travel. Peering even further into the future, one can only wonder what the cycle beginning around 2720 might bring!

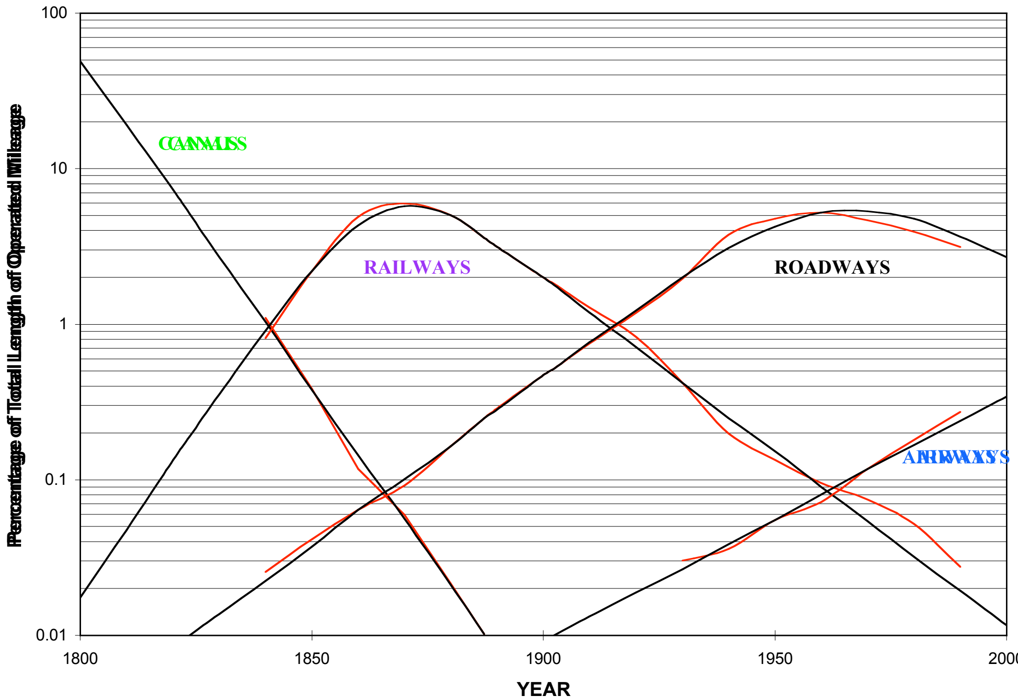


Figure 10. Evolution of Transportation Infrastructure in the U.S. (1800 – present)
(Red Lines - Actual Data; Black Lines - Curve Fit)

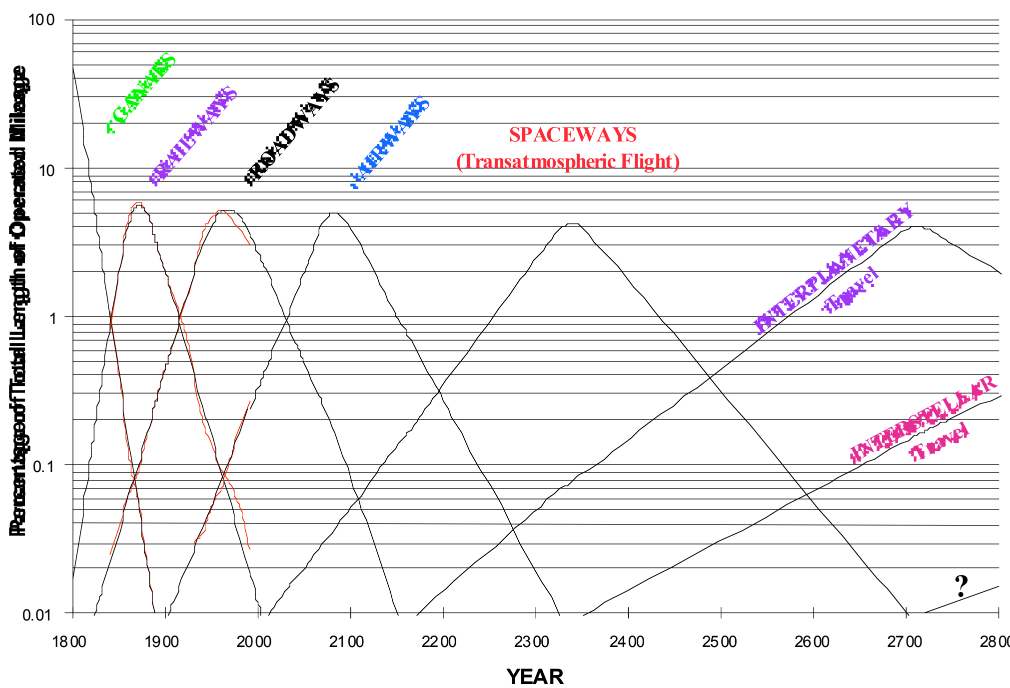


Figure 11. Projected Evolution of Transportation Infrastructure (1800-2800)

7. EPILOGUE

Will this vision or something like it, really come to pass? In the words of Arthur C. Clarke: "The challenge of the great spaces between the worlds is a stupendous one; but, if we fail to meet it, the story of our race will be drawing to its close. Humanity will have turned its back upon the still untrodden heights and will be descending the long slope that stretches across a thousand million years of time, down to the shores of the primeval sea…"

Three decades ago we took the first small step in answering the challenge of the great spaces between the worlds. Now the capability to travel to worlds beyond the Earth, won by our intellect, sweat, and blood, presents us with a choice; the most profound choice ever faced by mankind and perhaps by life itself…. As H.G. Wells once said: "It is the UNIVERSE or NOTHING…"

Which shall it be?

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