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Magnetobraking:
Use of Tether Electrodynamic Drag for Earth Return From Mars

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EXTENDED ABSTRACT

It has often been proposed that a vehicle returning from Mars will use aerobraking in the Earth's atmosphere to dissipate hyperbolic excess velocity to capture into Earth orbit. Here a different system for dissipating excess velocity without expenditure of reaction mass, magnetobraking, is proposed [1].

Magnetobraking uses the force on an electrodynamic tether in the Earth's magnetic field to produce thrust. An electrodynamic tether is deployed from the spacecraft as it approaches the Earth. The Earth's magnetic field produces a force on electrical current in the tether. If the tether is oriented perpendicularly to the Earth's magnetic field and to the direction of motion of the spacecraft, force produced by the Earth's magnetic field can be used to either brake or accelerate the spacecraft without expenditure of reaction mass. The peak acceleration on the Mars return is 0.007 m/sec^2, and the amount of braking possible is dependent on the density and current-carrying capacity of the tether, but is independent of length. A superconducting tether is required. The required critical current is shown to be within the range of superconducting technology now available in the laboratory.

Since energy is produced as the spacecraft velocity decreases, no on-board power source is required. A difficulty in magnetobraking is dissipating the energy produced. As the spacecraft approaches the Earth, the magnetic field increases and the power produced by the tether increases, reaching a maximum of about 800 W per kilogram of spacecraft mass at closest approach. If the tether current is decreased during closest approach, this peak can be reduced, at the cost of reducing the braking effectiveness.

The energy produced as the spacecraft crosses the Earth's magnetic field can be used, for example, to drive an electric-propulsion engine such as an ion engine or a pulsed-inductive thruster. The power densities produced by an electrodynamic tether in the Earth's magnetic field can be orders of magnitude higher than power densities produced by other means, and hence extremely effective electric propulsion is possible. Used together, an electrodynamic tether and electric propulsion could be the most effective solution for braking a returning Mars vehicle.

General principles of electrodynamic tethers are discussed in many references [2-5], and will not be reviewed here. There have been several demonstrations of tether operation in space. The experiment TSS-1 ("Tethered Satellite System-1), although it did not deploy to the full length, demonstrated controllability of a tether in space in the most critical regime of short tether lengths as well as verifying the VxB voltage expected by the conducting tether perpendicular to the Earth's magnetic field. The Delta-launched SEDS-1 ("Small Expendable Deployer-1") demonstrated full deployment using a simple friction-braked reel. The follow-on experiment demonstrated the plasma-contactor and the principle operational features of electrodynamic tether. Thus, all the required principles of tether technology have been demonstrated in orbit.

The calculation of the force on the magnetobraking tether is straightforward. (A more complete analysis can be found in the complete paper [1]. The force produced on a tether by the Earth's magnetic field is:

$$F = IL \times B \tag{1}$$

where L is the length of the tether, I the current, and B the magnetic field. The Earth's magnetic field at a distance r from the surface can be expressed as:

$$B = B_0 (R_e/r)^3 \tag{2}$$

R_e, the radius of the earth, is $6.4 \cdot 10^6$ m. The surface field B_0 is:

$$B_0 = 35\ \mu\text{Tesla}\cos(\lambda) \tag{3}$$

where λ = latitude from magnetic equator. Here we will assume that the spacecraft comes in along the magnetic equator, and hence $\lambda = 0$.

The values of current density and density will depend on the material used. The new "high temperature" (HT) superconductor materials are less well developed technically, but can be operated at temperatures of 77°K and higher, allowing the possibility of cooling by passive means in space. Superconductors are characterized by a maximum current density, known as the critical current. This is a function of the applied magnetic field and the temperature.

The most important value is the current density which has been obtained from material in the form of wires. $YBa_2Cu_3O_{7-x}$ (referred to as YBCO) is the most well-developed of the HT superconductor materials. In wire form, YBCO can be purchased with a critical current density (at 73°K) of 1000 A/cm^2. The density ρ of YBCO is 6.3 gr/cm^3. A somewhat less developed HT superconductor, Bi 2223 ($Bi_2Sr_2Ca_2Cu_3O$), can be purchased in strip form with a critical current density of 3500 A/cm^2 ($J=3.5 \cdot 10^7$ amps/m^2) at 77°K. For currently available Bi 2223 superconductor strip, the specific current density LI/m ($=J/\rho$) is $5.5 \cdot 10^3$ amps-meters/kg. This is below the minimum specific current density needed for magnetobraking. Thus, high temperature superconducting materials now available in wire or strip form will not suffice for magnetobraking

However, both the achievable current densities and the technology for making HT superconductors in wire form is advancing rapidly. It is plausible that current densities now achieved in bulk material may in the near future be achievable in material manufactured into wires. At 77 °K, bulk YBCO has achieved currents over 10^8 amps/m^2. Other superconductor materials have even higher critical currents. Critical current (at 77K) for HoBaCuO is $3 \cdot 10^{10}$ amps/m^2. If the HoBaCuO material could be made into wire form, it would have a specific current density of $4 \cdot 10^5$ amp-meter/kg, which is quite sufficient to achieve magnetobraking. To this mass, of course, would have to be added other elements of the system, including a method of handling the power produced, plasma contactors, cooling systems, and structural elements.

In summary, the current densities required for magnetobraking are higher than those achieved in wire form today, but within levels which are technologically achievable.

Other Applications

The concept of magnetobraking is not limited to Mars return applications. It can also be used during a gravity assist in the Earth's magnetic field, either to produce thrust, to change the orbital plane, or to add magnetic force to the gravity force in a magnetically-enhanced gravity assist..

Jupiter is a much better planet for electrodynamic tether use, with a stronger magnetic field (12 B_e) and higher radius (11.2 R_e). Magnetobraking could be used to capture into Jupiter orbit a probe to the Jovian moons; once captured, the electromagnetic tether could be used as a propulsion system throughout the Jupiter magnetosphere [6]. Alternatively, used in reverse, a magneto-gravity-assist could be used to propel a probe to Saturn or beyond.

Finally, a deep-space or interstellar probes could use a magneto-assist in the Sun's gravity field. By making a ΔV maneuver deep in the sun's gravity well, considerable leverage of the ΔV is produced.

References

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