APPLICATIONS OF TETHERS FOR PLANETARY MISSIONS

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Mans reach goes beyond Earth orbit into deep space, and as you
know, there has been growing interest in trying to decide what will come
beyond the Space Station. In fact, such inquiries are being made today
by the National Commission on Space, for example, to decide and to
justify, in part, the Space Station itself.

The Space Station in the large sense could be considered to be part
of what might eventually be an infrastructure; that is, part of a system
of capabilities which will eventually take man back to the moon, and
then to Mars and beyond.

What roles can tethers play in deep space? With the current
interest in long-term space activities, this question is presently being
addressed. In Advanced Programs, we held sort of a one-day workshop
with a few people from NASA centers at NASA Headquarters to consider the
applications of tethers for planetary missions. The contributors for
this one-day workshop are here today, which is very fortunate. I would
encourage them to specifically attend the Science Applications Panel and
expand on their ideas; the ideas which they contributed to the meeting
at NASA Headquarters.

I will start with the Moon and work outwards (Figure 1). At the
Moon, one proposal which Giusseppe Colombo proposed was simply an
instrument package tethered from a satellite in orbit about the Moon.
It would be in a polar orbit so that complete coverage of the Moon could
be obtained. The satellite could be at a high and safe altitude, say
300 km. Because of the Sun and Earth perturbations, the lifetime of a
lower satellite could be short, perhaps a few months, before it would
impact the Moon.

Now the tethered instruments could be as close to the Moon as
desired, perhaps a few kilometers, with the satellite remaining in a
stable lunar orbit. It may be necessary to adjust the tether length

occassionally to prevent impact of the instrument package. This mission would result in high resolution data for gravimetric measurements, gamma ray spectrometer measurements, and so forth.

Now I will move on to something which is much more in the future and this is an idea by Joe Carroll (Figure 2). He'll probably discuss it in a panel session. This idea is to build a sling on the surface of the Moon which would take solar energy, for example, and build up momentum of the sling. Two payloads would be at the tips of the sling and each would be released at a precise time. The payload at each end, assumed to be rocks, would be only ten kilograms. The advantage is that 10kg could be launched every five minutes, amounting to 1,000 tons per year. Once certain amounts were in orbit, they would be collected by a Lunar Orbiting Tether Station (LOTS) (Figure 3).

Half of these rocks would then be loaded into an Aerobraking Ferry Vehicle (AFV), deployed on a tether, spun up, and released to transearth injection. The momentum lost by the station would be recovered by ejecting the other half of these rocks back to the Moon. This allows transportation of lunar material to the Earth without use of propellants. The problem of lunar orbit debris still has to be addressed. At Earth, the AFV aerobrakes into LEO and rendezvous with a Tether and Materials Processing Station (TAMPS). An unloaded AFV is then returned to the Moon to repeat the process.

Now, moving on to Mars (Figure 4), there is a Mars Aeronomy Orbiter (MAO) being planned by NASA. This is different from the Mars Orbiter which is currently planned for launch in the late '80s. The MAO mission would be launched in '94 or '96, and is included in NASA's Solar System Exploration Committee (SSEC) Core Program.

This application would simply use a tether to enhance the planned Mars orbiter. The purpose of the mission itself is to analyze the atmospheric composition and chemistry for one Martian year. The idea of the tether would be to send instruments to lower altitudes periodically for in-situ measurements. That is, a tether, say 200 km in length,

would not simply be deployed and left deployed. The instrument package would be deployed periodically, maybe every two months, for a period of a few hours and then retrieved. During deployment, the instrument package would make measurements of the upper atmosphere of Mars at that lower altitude. This would enhance the science benefits that you would get from just the orbiter. Cost, of course, would increase.

In a radically different application, it is proposed that a tether can be attached to an asteroid during a spacecraft flyby and, holding the length of the tether fixed, to cause the spacecraft to rotate around the asteroid at a fixed radius (Figure 5). The tether can then be released and the spacecraft will go off in a different direction.

This is exactly what happens with the gravity assist technique. The gravity of a large body causes the direction of a spacecraft to change thus producing a gravity assist. For example, Voyager 2 flew by Saturn in '81, and will reach Uranus this coming January. It could not have done that without the gravity assist of Saturn. In this application, an asteroid could be chosen which was between Earth and Mars and used essentially in what would be an artificial gravity assist mode.

At launch, then, the total energy would not be necessary. Only the energy to get to the asteroid would be needed. The tether attachment and fly around would provide the gravity assist. The length of the tether need only be one or two kilometers long. You would have to have some means, of course, of flinging the tether and attaching it to the asteroid, and then detaching it after you swing around the asteroid. You would need, according to the velocities that would be required for the fly-by, a material which was two or three times stronger than Kevlar.

That incidently is something that should be considered in general. That is, we talk about Kevlar, and sometimes we restrict our analysis to the strength of Kevlar. In most cases, this is quite appropriate. However, that doesn't mean it should be exclusive. We

should also look at possible missions, even in Earth orbit, which may require materials which are stronger than Kevlar. And, as Joe Carroll has said, there are materials which are stronger than Kevlar. This will expand the types of applications that we can look at.

Now, lets go on to artificial gravity. It's possible to have a manned mission to Mars and physiologically require artificial gravity. If that turns out to be the case, how do we get artificial gravity?

We can get it through rotation, and I have shown here in Figure 6 two possible concepts of a transfer vehicle which would go from the Earth to Mars. The concept on the left is based on the planned space station technology. There would be four manned modules two at each end of a rotating beam. Two manned modules are shown at the bottom of the station. The length of the structure from the center of mass, where the solar dynamic power system is located, is 100 meters. Now, you would not rotate the whole system. The solar dynamic power system itself would be despun and pointed to the sun. The part that spins is simply the beam to which two manned modules at each end are attached. This would be a dual spinning system.

Also, in order to service the subsystems, and transfer men and supplies to the modules, an elevator which travels along the rotating beam would be ued. It would carry men to the center hub and also to the other side of the two modules. This system would remain spinning until it reached Mars, and then it could be de-spun with the rocket motor shown below the modules.

It is also possible to rendezvous with this spinning system. There would be a de-spun docking platform off the center hub where docking would occur. Then when the rotating beam aligned with the docking system, it would attach to the rotating system. The men and supplies would then transfer to the rotating beam.

Now the system could be simplified by using a platform, as shown on the right side of Figure 6. The platform for economy could use solar

arrays instead of a solar dynamic system. The subsystems are at the center, including the reel mechanism for the tether system. The two manned modules (this is only a two module system), would be extended on a ten kilometer tether and then use a propellant motor, located underneath the manned modules, to spin the total system. The solar panels, however, would be de-spun. This is obviously a much simpler system; a smaller system and less costly. This would, in fact, be a better system for artificial gravity, because now, for Mars gravity, for example, the rotating arm length is three kilometers, not just a hundred meters. The disadvantage of this system is the high spin velocity required, i.e., 125 meters per second, versus 20.

In Figure 6, the rotation rates are given in the tables. For a level of 1-g, the station would rotate once every twenty seconds. This rate is quite fast and may introduce strong Coriolis forces. The tethered platform system on the other hand would rotate roughly once every hundred seconds resulting in considerably lower Coriolis forces.

Now, concentrating on Mars itself, it is possible to use tethers to provide a transportation system for payloads which are coming to the surface from escape, and which are leaving Mars and escaping from Mars itself (Figure 7). This method utilizes the two satellites of Mars; Phobos and Deimos. These satellites, 10-20 km in diameter, are large enough to be considered to be stations in orbit about Mars. At each, tethers could be extended upwards and downwards with the lengths given in Figure 7. At Phobos for example the downward tether is 1160 km, and the upward tether is 940 km as shown on the left. At Deimos, the downward tether is 2960 km and the upward tether is 6100 km.

These are quite long, and it turns out they can weigh a few to many tons. A Kevlar tether, with a diameter of three or four millimeters is quite strong enough to handle 20,000 kg payloads.

To understand how this system would work, consider a payload tethered upward 375 km from a spacecraft in a 400 km altitude orbit. When released, the payload would rise to an altitude 1160 km below

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Phobos, and have the right velocity to rendezvous with a hanging tether from Phobos.

To continue the operation, the payload would then have to climb that 1160-kilometer tether to the other side of Phobos and up the 940-km tether. It could then be released and be on an orbit whose altitude is sufficient to reach the lower tip of the 2960 km tether at Deimos. There would be no velocity difference there (or anywhere else) so that no propellants are used at all, except for corrections and rendezvous. When the payload is released at the end of the 6100-km tether at Deimos, it will escape from Mars. A spacecraft which is coming into Mars on an escape trajectory could rendezvous with the 6100-km tether and be brought down to Deimos and then to Phobos, and then to low orbit. The tether mass here, using Kevlar, ranges anywhere from three-tenths of the payload mass to roughly five. This is quite acceptable for a system which is intended to have repeated use. Novel ideas will be needed to construct and maintain this system. Also, we still have the problems which Joe Carroll alluded to, and that is micrometeoroid impact causing the tether to be cut. This can be handled with redundant systems and rapid repair.

There has been considerable study at the Jet Propulsion Laboratory on collecting comet or asteroid samples and returning them to Earth. Of particular interest is a comet sample return. The conventional approach would be to rendezvous with the comet or asteroid and release a lander (Figure 8). The lander would drill for a core sample, return to rendezvous with the oribter, and finally the sample would be brought back to Earth. The cost estimate is $1 billion or more, somewhat like the Viking mission to Mars.

A tether approach would be not to rely on a lander for sample collection but simply to have tethered penetrators which could collect samples. The rendezvous with the comet or asteroid may be very close, such as 50-100m, so that the tether need not be very long. The tethered penetrator would be ejected from the spacecraft into the comet, and samples would then be returned via the tether to the spacecraft itself.

What could the penetrator look like? First, the penetrator would have enough force to dig into the comet, and the shell of that could remain with the comet (see Figure 9). Holes in the shell would allow material to enter a cup inside the shell. A means other than holes may be devised. After penetration, an explosive charge could force a cap to seal the cup, and blow the cup from the shell. Using rotation to cause tension in the tether, the spacecraft could then reel in the cup (this may be a complex procedure) and store it into a compartment for return to Earth.

Now with several of these penetrator/sampler systems on a spacecraft it is possible to collect samples from different spots on the comet, as opposed to the lander, or to collect samples from other bodies. The lander and penetrator methods are complementary. The lander provides single very deep sample, whereas the penetrator can provide smaller samples from different parts of the comet or asteroid.

Combinations of tether techniques discussed so far may be used in an ambitious main belt asteroid tour and sample return, as shown in Figure 10. Now, I will discuss the fascinating area of electrodynamic tethers at Jupiter (Figure 11).

Jupiter has a strong magnetic field, about twenty times that of Earth. However, distances of Jupiter orbits are also larger, which tend to counterbalance the effects. We know that strong electric fields are present in Jupiter's magnetosphere; because of Io's flux tube, for example. Thus, if electrodynamic tethers work well at Earth, they should work even better at Jupiter. This, of course, has to be shown.

What we can do is make the computations for Jupiter that are made for Earth, and an important parameter is the induced voltage in a conducting wire. In computing this, how does the rapid rotation of Jupiter affect the calculations?

Specifically, this is a question which I wish to throw out to you. With Jupiter's rapid rotation of one revolution per ten hours, it turns out that if you get beyond 2.2 Jupiter radii (1.2 in altitude) the magnetic field is rotating faster than the satellite. If that is the case, then Jupiter's magnetic field is rotating faster than a satellite in circular orbit. That means that you not only get power with an electrodynamic tether, but also thrust.

At the Earth, below the geosychronous orbit, the satellite is moving faster around the Earth than the magnetic field, and so you get drag. That is, you lose orbital altitude when you use the electrodynamic tether to draw power.

At Jupiter, the electromagnetic field is going faster above 2.2 Jupiter radii, so that means that you get thrust, in addition to power with the tether.

I would assume that this is the case. This should be looked at, of course. And so, when I show here minus 150 volts per kilometer of conducting tether at the Earth, I'm indicating drag. If you had a low Jupiter orbit, the orbital period is faster than the rotational period, and it's minus 10 kilovolts per kilometer. You switch from 150 volts to 10 kilovolts. If you go up to Io's orbit, the voltage per kilometer is a plus 108 volts per kilometer, which is of the order of low Earth orbit, but positive.

So, the strong Jupiter magnetic field, because you are further away, gives you the equivalent of Earth's magnetic field at Io.

Then, of course, if you go further out, you get lower magnetic field strength, and hence lower voltages per kilometer of tether reducing the power that you could get from the system.

The applications of such a tether at Jupiter are numerous. Close in to Jupiter, the spacecraft could sample the atmosphere or produce drag. At higher altitudes, the thrust on the tether could aid satellite

tours, increase orbital inclination, or rendezvous with a Galilean satellite. In general, the electrodynamic tether would simply help you wherever thrust and power are needed.

The Sun also has a strong magnetic field and a large solar wind. These may be used to draw power, or create drag or thrust as proposed by the Nobel prize winner Hans Alfven. (Figure 12)

Finally, there are other ideas (Figure 13) which I will just throw out here.

1. Anchored lunar satellite proposed by Jerome Pearson in 1979. This is a very long tether off the moon, in order to fling lunar material out towards the L5 point, for example.

2. Use tethers to catch aerobrake vehicles from GEO, Moon and Mars. This would decrease the propellant requirements.

3. Rotating tethers for sensitive gravimetric measurements. Long tethers for sensitive gravity wave detection. The latter was proposed by Bertotti and Thorne.

4. Sample atmospheres of planets using tethers, or scoop the atmosphere for propellant production. Gather up oxygen, for example, with a tethered scooper.

5. Use a ribbon tether for cosmic dust collection, or fly by a comet using a ribbon tether. That is, as you fly by, the comet dust would stick to a deployed ribbon tether, and then be reeled in to be returned back to Earth.

6. Use a tether to capture particles in Saturn's rings. You could orbit Saturn very close to the rings; even above it using low thrust, so that you are in a minor circle instead of a major circle in orbit about Saturn. As the spacecraft orbits above the rings, it can extend a rotating tether, for example, to collect particles in the rings themselves.

Some of these are naturally very futuristic type applications, but we can start thinking about these ideas today.

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Applications of Tethers in Space Workshop

Venice, Italy

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Pasadena, California

Office of Space Flight
Advanced Programs
NASA Headquarters

A TETHERED LUNAR SATELLITE FOR REMOTE SENSING

- CLOSE LUNAR SATELLITES ARE UNSTABLE BECAUSE OF EARTH AND SUN PERTURBATIONS

- AN INSTRUMENT PACKAGE COULD BE TETHERED 50km ABOVE THE SURFACE FROM A SATELLITE IN A STABLE 300km ORBIT

- SENSITIVE MEASUREMENTS OF THE MOON'S MAGNETIC FIELD, AND GRAVITATIONAL ANOMALIES COULD THEN BE MADE CLOSE TO THE MOON AND FROM THIS STABLE ORBIT
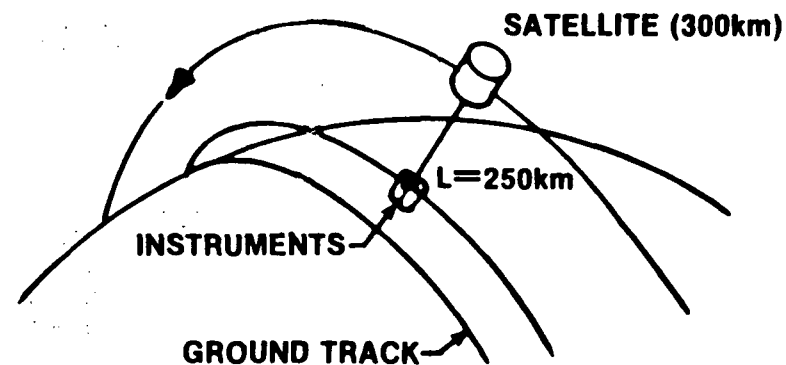
SATELLITE (300km)

L=250km

INSTRUMENTS

GROUND TRACK

FIG. 1

LUNAR EQUATOR SURFACE SLING (LESS)

- "MINIMAL MASS-DRIVER" TO LAUNCH 10Kg PAYLOADS INTO LUNAR ORBIT
  (RELIABLE LOW TECHNOLOGY SYSTEM)

- SYSTEM SHOULD FIT IN 1 SHUTTLE.

- 1000m TETHER AT 16rpm IMPOSES < 300 GEES ON PAYLOADS

- 2 LAUNCHES/10 MIN USES < 100kw, BOOSTS 1,000 TONNES/YR

- TETHER MASS/PAYLOAD RATIO = 4
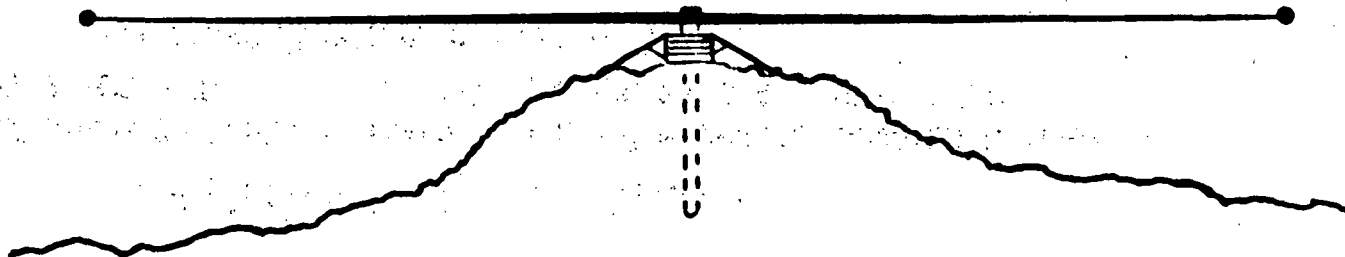
- COLLISION & DEBRIS GENERATION MAY BE A MAJOR PROBLEM

FIG. 2

EARTH-MOON TETHER-TRANSPORT INFRASTRUCTURE

AFV (AEROBRAKING FERRY VEHICLE)

1. AEROBRAKES AND IS CAPTURED BY TAMPS   3. IS TETHER/ROCKET BOOSTED TO MOON

2. IS UNLOADED & REFUELED   4. IS CAPTURED & LOADED BY LOTS

     5. IS SLUNG BACK TOWARDS EARTH BY LOTS

AFV

**LESS
(LUNAR EQUATOR SURFACE SLING)**

THROWS → 10kg MOONROCKS INTO LOW-LIFETIME
(1 MONTH) EQUATORIAL ORBITS

LOTS

AFV

TAMPS
(TETHER AND MATERIALS PROCESSING STATION)

1. CATCHES AEROBRAKED AFV, RETRIEVES & UNLOADS IT
2. PROCESSES MOONROCKS INTO LO_2, ETC
3. FUELS AFV & REBOOSTS IT TOWARDS MOON
4. RECOVERS MOMENTUM W/ELECTRODYNAMIC TETHER
5. ALSO CAPTURES, REFUELS, REBOOSTS AFV'S GOING
   TO GEO & DEEP SPACE

LOTS
(LUNAR ORBITING TETHER STATION)

1. CATCHES ROCKS, SPINS-UP, CATCHES AFV
2. LOADS AFV WITH ½ OF ROCKS
3. SPINS-UP & THROWS AFV TO TEI
4. DESPINS & LOADS OTHER ROCKS
   ON TETHER
5. SPINS-UP & DEBOOSTS ROCKS FOR
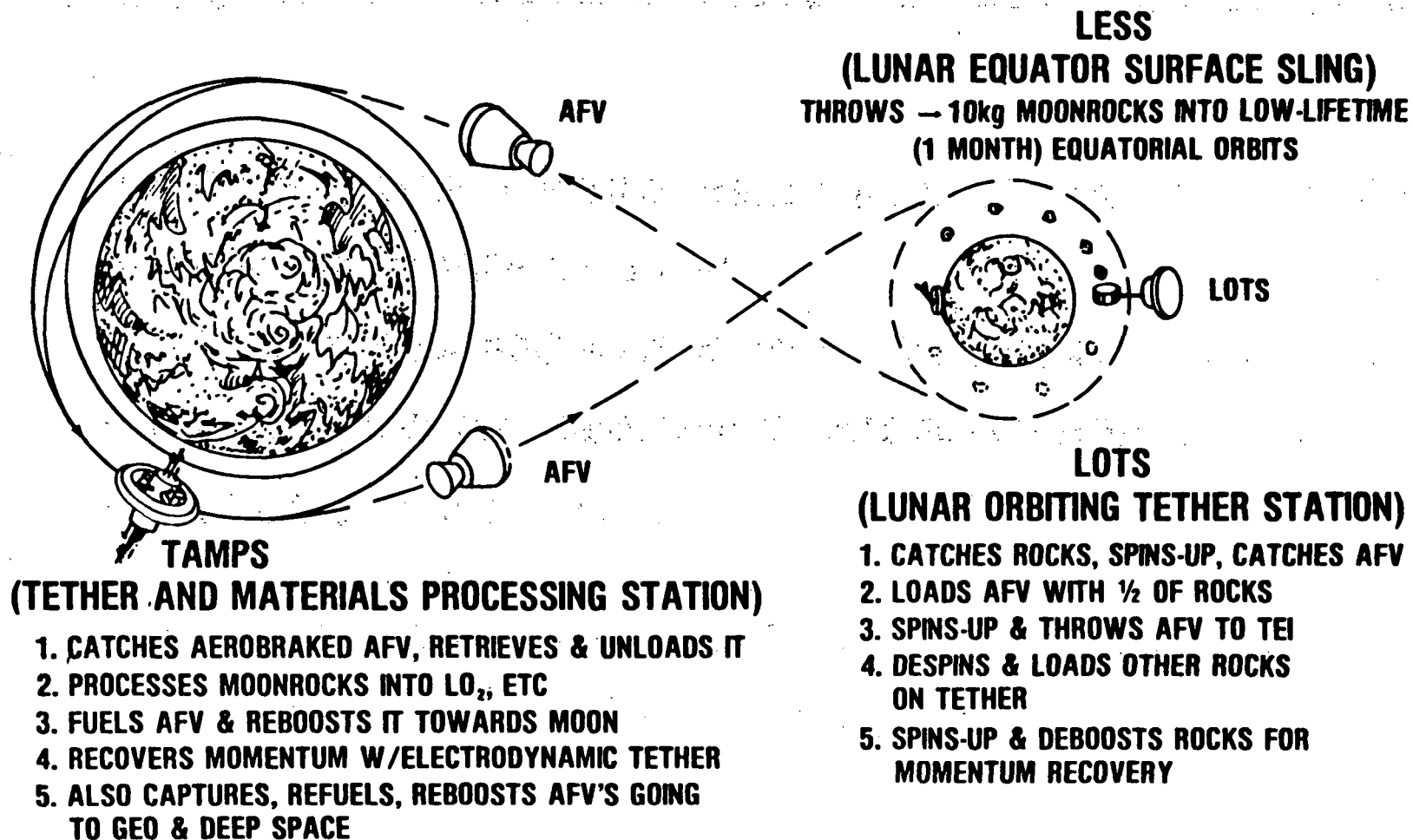   MOMENTUM RECOVERY

FIG. 3

MARS AERONOMY ORBITER WITH A TETHERED SATELLITE SYSTEM

PURPOSE

- ANALYSIS OF ATMOSPHERIC COMPOSITION AND CHEMISTRY FOR ONE MARTIAN YEAR. DEPLOY INSTRUMENTED SUBSATELLITE PERIODICALLY TO OBTAIN IN-SITU MEASUREMENTS

SPACECRAFT

- USE OBSERVER CLASS WITH A 200km TETHER SYSTEM CAPABILITY. ORBITER ALTITUDE IS 350km
- PROVIDE ORBITER ΔV(200m/s) CAPABILITY FOR ALTITUDE MAINTENANCE

BENEFIT

- NO OTHER MEANS TO OBTAIN THIS DATA
- SUPPORTS ATMOSPHERIC SCIENCE, AND POSSIBLY MANNED PLANETARY MISSION DEFINITION

OPPORTUNITY

- NASA CURRENTLY PLANS AN OBSERVER MAO FOR LAUNCH IN 1994 OR 1996
- TSS AND OTHER TETHER EXPERIENCE AVAILABLE FOR USE

COST

- TYPICAL OBSERVER COST, $250M + OPERATIONS
- DELTA FOR TETHER SYSTEM AND SUBSATELLITE ESTIMATED AT $100M

FIG. 4

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ASTEROID GRAVITY ASSIST FOR MARS MISSIONS

METHOD

- A TETHER IS USED TO ATTACH THE SPACECRAFT TO A NEAR-EARTH ASTEROID TO PRODUCE AN ARTIFICIAL GRAVITY ASSIST TO AID EARTH-MARS TRANSFERS

ADVANTAGES

- ABOUT 50% FUEL SAVINGS POSSIBLE
- LOWER APPROACH VELOCITY AT MARS

SYSTEM

- MANY ATEN ASTEROIDS ONLY 1km DIAMETER WOULD BE CANDIDATES ($\sim$2500)
- TETHERS 2—3 x STRONGER THAN KEVLAR DESIRED
- WITH MANY CANDIDATES, PHASING SHOULD BE NO PROBLEM
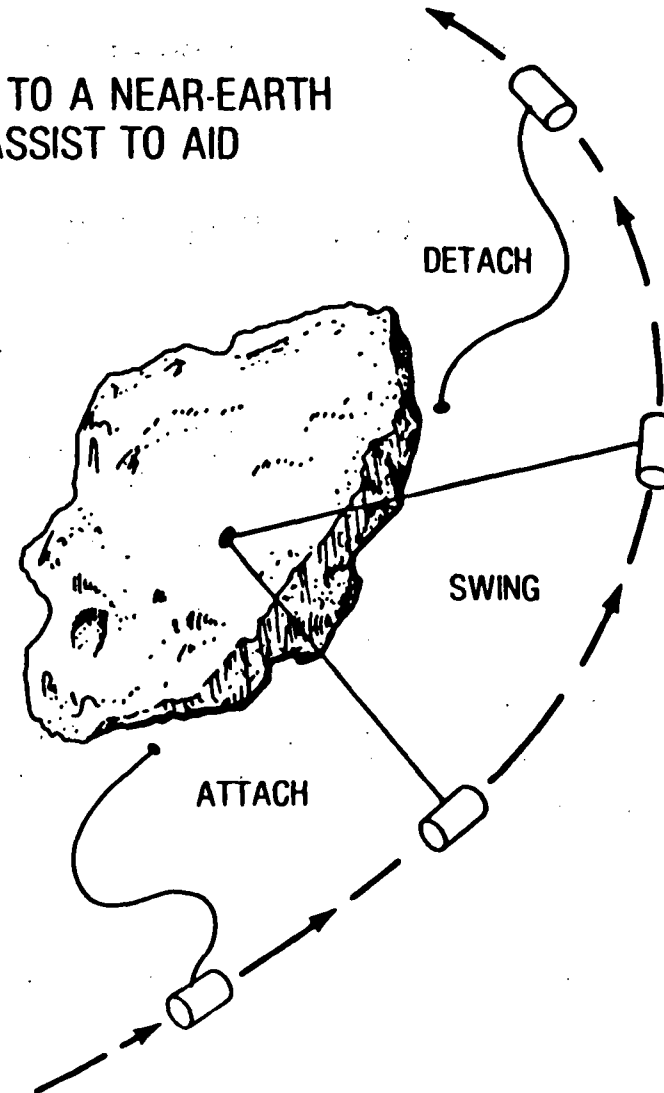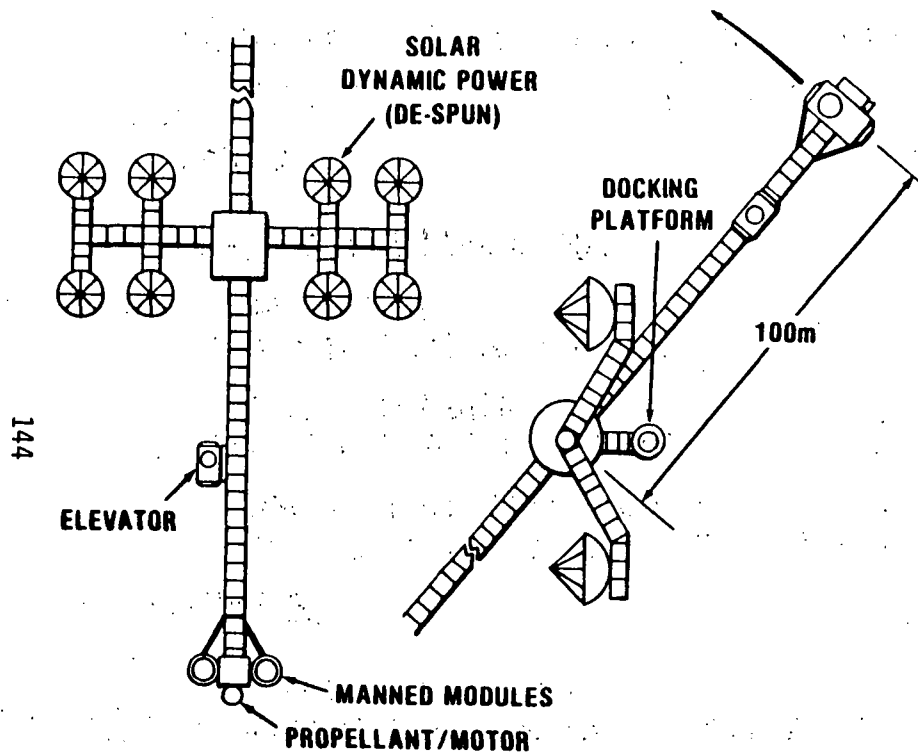
- NEEDS FURTHER STUDY

DETACH

SWING

ATTACH

FIG. 5

ARTIFICIAL GRAVITY FOR EARTH—MARS TRANSFER VEHICLE

STATION CONCEPT

SOLAR
DYNAMIC POWER
(DE-SPUN)

DOCKING
PLATFORM

100m

ELEVATOR

MANNED MODULES

PROPELLANT/MOTOR
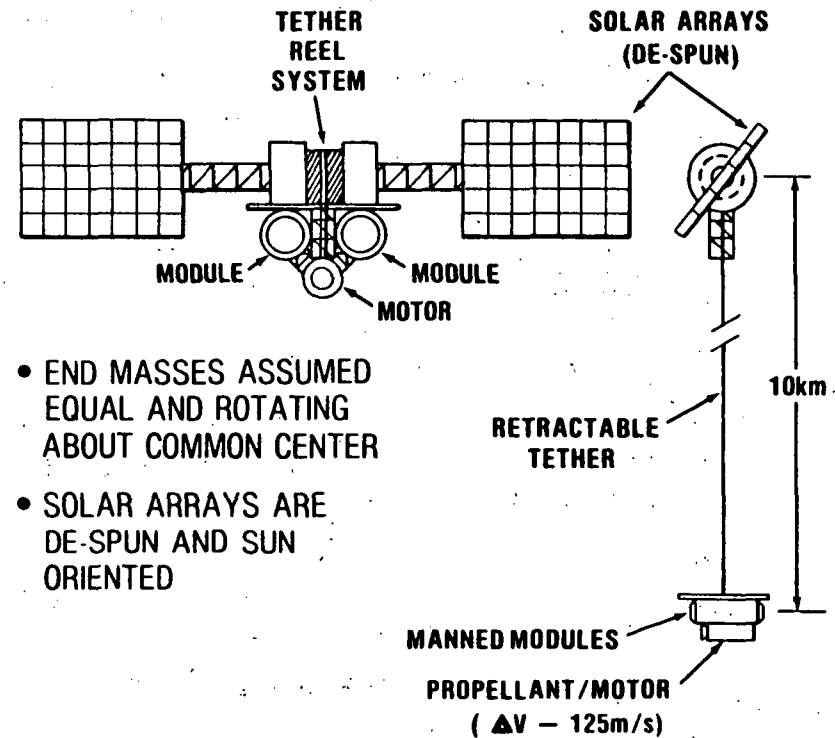
- 4 MODULES, 2 AT EACH END ROTATE ABOUT A COMMON CENTER

- ELEVATOR TRANSFERS MEN, SUPPLIES TO EITHER END

RPM	ΔV	G-LEVEL
1	10 m/s	0.11
2	20 m/s	0.45
3	30 m/s	1.00

TETHER PLATFORM CONCEPT

TETHER
REEL
SYSTEM

SOLAR ARRAYS
(DE-SPUN)

MODULE   MODULE

MOTOR

10km

RETRACTABLE
TETHER

- END MASSES ASSUMED EQUAL AND ROTATING ABOUT COMMON CENTER

- SOLAR ARRAYS ARE DE-SPUN AND SUN ORIENTED

MANNED MODULES

PROPELLANT/MOTOR
(ΔV — 125m/s)

RPM	DEPLOYED LENGTH	g—LEVEL
0.75	4km	1.25
0.48	5km	0.65
0.33	6km	0.38
0.20	8km	0.16
0.12	10km	0.08

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Figure 6

MARS SURFACE TO ESCAPE TETHER TRANSPORTATION SYSTEM

OBJECTIVE

- TO TRANSPORT PAYLOADS (P/L) BETWEEN 400km LOW MARS ORBIT (LMO) AND ESCAPE FROM MARS

SYSTEM

- PLACE TETHERS UPWARDS AND DOWNWARDS AT PHOBOS AND DEIMOS

OPERATION

1. TETHER PAYLOAD UPWARDS 375km FROM "SHUTTLE" IN LMO—RELEASE

2. RENDEZVOUS P/L WITH DOWNWARD TETHER FROM PHOBOS

3. TRANSPORT P/L TO UPWARD TETHER AND RELEASE

4. REPEAT (2),(3) FOR DEIMOS

BENEFITS

- THIS SYSTEM USES MOMENTUM OF MARS SATELLITES FOR TRANSFER. SAVES 1.6km/s PROPELLANT

- SYSTEM WORKS IN BOTH DIRECTIONS. CAN HANDLE HEAVY TRAFFIC

- MINIMUM COMPLEXITY SIMPLIFIES SYSTEM MAINTENANCE/REPAIR

- KEVLAR STRENGTH ADEQUATE FOR TETHERS
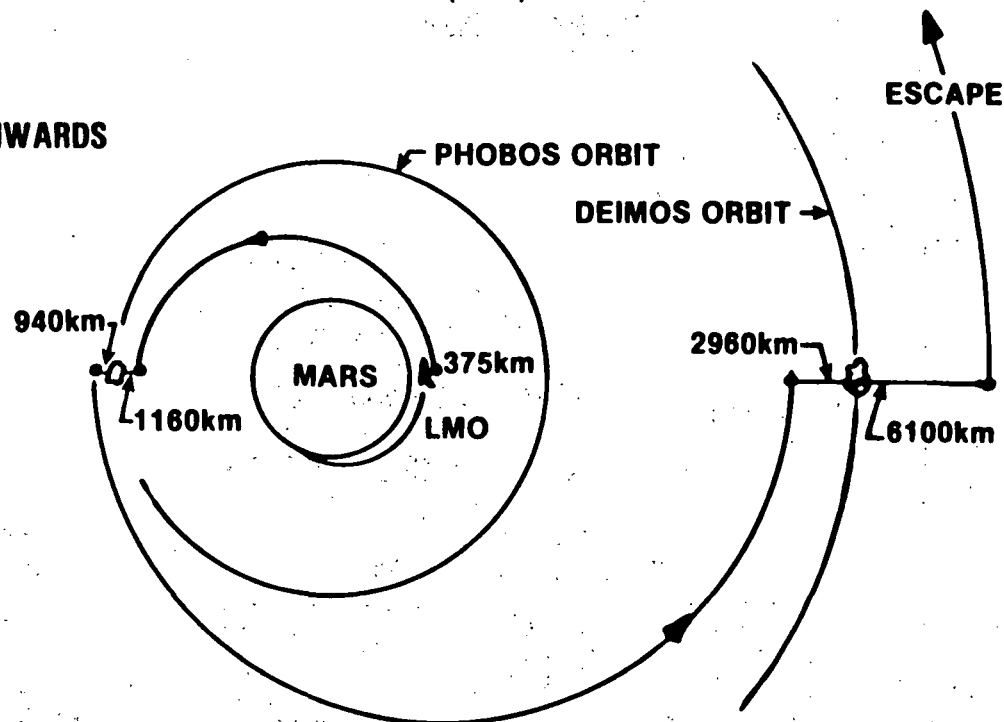
- TETHER MASS TO P/L RANGES FROM 0.3 TO 5

ESCAPE

PHOBOS ORBIT

DEIMOS ORBIT

940km

1160km

MARS

375km

LMO

2960km

6100km

FIG. 7

COMET/ASTEROID SAMPLE RETURN

CONVENTIONAL APPROACH

- RENDEZVOUS WITH BODY
- RELEASE LANDER, DRILL SAMPLE
- RETURN TO ORBITER, RENDEZVOUS
- RETURN SAMPLES TO EARTH
- COST ESTIMATE, $1.0B

TETHER APPROACH

- RENDEZVOUS WITH BODY
- EJECT PENETRATORS (SAMPLER ON TETHER)
- RETRIEVE SAMPLES
- RETURN SAMPLES TO EARTH
- COST ESTIMATE, $750M

ADVANTAGES

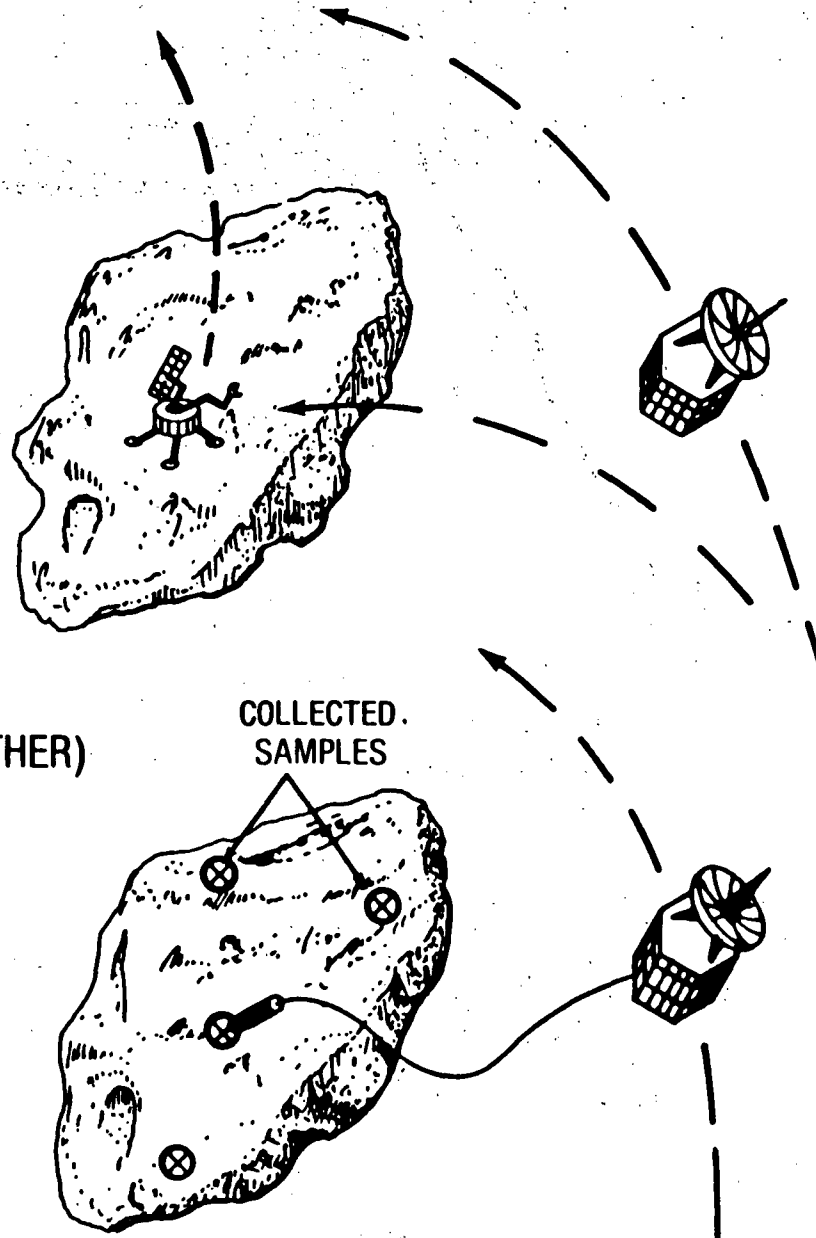- SAMPLES COLLECTED FROM SEVERAL LOCATIONS
- LOWER COST

COLLECTED SAMPLES

FIG. 8

COMET/ASTEROID SAMPLER SYSTEM

SEQUENCE OF EVENTS

- TETHERED PENETRATOR AT 100m IS SHOT AT TARGET

- ON IMPACT OF PENETRATOR, SAMPLE ENTERS HOLES OF SHELL INTO CUP

- EXPLOSIVE CHARGE SEALS CUP AND EJECTS CUP FROM PENETRATOR SHELL

- VELOCITY CAUSES ROTATION OF TETHER AND TENSION IN TETHER

- S/C THRUSTERS ARE USED TO CONTROL RETRIEVAL OF CUP

- OTHER PENETRATOR/SAMPLERS RETRIEVE SAMPLES FROM OTHER AREAS, OR OTHER BODIES

- S/C WITH SAMPLES RETURN TO EARTH

HOLES   TETHER

SAMPLE CUP

CUP SEALING CHARGE

PENETRATOR

MT-85-230
11/14/85

FIG. 9

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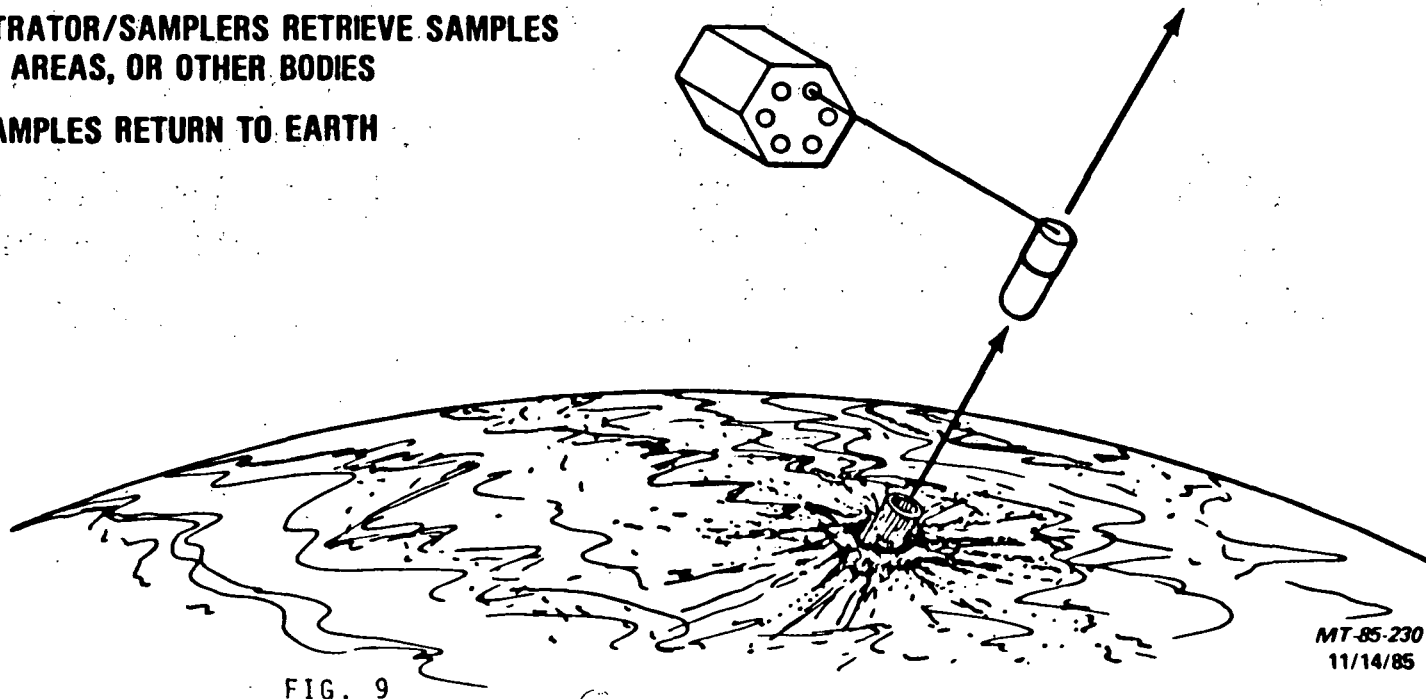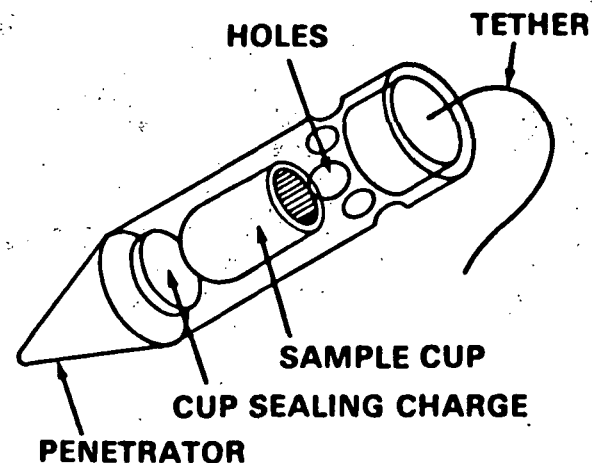
MAIN BELT ASTEROID TOUR/SAMPLE RETURN

PURPOSE

- SEND A SPACECRAFT INTO THE MAINBELT FOR MULTIPLE ASTEROID FLYBYS AND SAMPLE COLLECTION

METHOD

- USE A TETHER SYSTEM TO COLLECT SAMPLES AND ATTACH TO ASTEROID FOR ARTIFICIAL GRAVITY ASSIST

ADVANTAGES

- MILLIONS OF SMALL ASTEROIDS PROVIDE MANY TARGETS OF OPPORTUNITY. OPTICAL SENSORS AND LASER RANGING ALLOWS S/C TO MANEUVER FOR FLYBY OF ASTEROIDS

OPERATION

- AFTER MANY SAMPLES ARE COLLECTED OVER A TEN YEAR PERIOD, THEY ARE RETURNED TO EARTH FOR ANALYSIS

FIG. 10

ELECTROMAGNETIC TETHERS AT JUPITER

PHYSICAL PRINCIPLES

- USE THE ELECTRODYNAMIC TETHER IN JUPITER'S STRONG MAGNETIC FIELD FOR THRUST/DRAG

- JUPITER'S RAPID ROTATION PERIOD (10hr) CAUSES THE MAGNETIC FIELD TO MOVE PAST THE GALILEAN SATELLITES. THIS PRODUCES THRUST ON A CONDUCTING TETHER INSTEAD OF DRAG, DRAWING ENERGY FROM JUPITER'S ROTATION.

- INDUCED VOLTAGE:

    —150v/km (LEO)   108v/km (IO)   21v/km (GANYMEDE)

    —10kv/km (LJO)   50v/km (EUROPA)   7v/km (CALLISTO)

- DRAG-TO-THRUST CROSSOVER IS ABOUT R=2 JUPITER RADII

APPLICATIONS

- SAMPLE JUPITER'S ATMOSPHERE

- ASSIST GALILEO TYPE SATELLITE TOUR (ALL EQUATORIAL)

- INCREASE ORBIT INCLINATION

- RENDEZVOUS WITH A GALILEAN SATELLITE

BIG QUESTION

- WILL ELECTRODYNAMIC TETHERS WORK BETTER/WORSE THAN AT EARTH?

FIG. 11

HELIOCENTRIC ALFVEN ENGINE

PHYSICAL PRINCIPLE

- ALIGNING A CONDUCTING TETHER WITH THE E FIELD OF THE SOLAR WIND PRODUCES 2V/km.   CLOSE CIRCUIT TO PRODUCE POWER (ALFVEN — 1972)

SYSTEM

- USE A 1000km NIOBIUM-TIN SUPERCONDUCTING WIRE TO PRODUCE 1000amps (2MW)

- PLACE IN ALUMINUM TUBE WITH FLOW OF SUPERCOOLED ($2^{\circ}k$) HELIUM

- INSULATE TUBE AND PLACE REFRIGERATION SYSTEMS AT EACH END

- MAKE ELECTRICAL CONTACT AT ENDS WITH SOLAR WIND

APPLICATIONS

- USE DRAG ON WIRE TO SPIRAL INTO (OR OUT FROM) SUN, OR TO MOVE OUT OF ECLIPTIC

- USE POWER TO DRIVE ION ENGINE

QUESTIONS

- WHAT ARE COMPETITIVE SYSTEMS? SOLAR SAIL? NUCLEAR?

- FEASIBILITY NOT ESTABLISHED

- CONTROLLABILITY NOT ESTABLISHED

FIG. 12

ADDITIONAL IDEAS FOR PLANETARY MISSIONS

- ANCHORED LUNAR SATELLITES (J. Pearson, 1979)

- USE TETHER TO CATCH AEROBRAKED VEHICLES FROM GEO, MOON, MARS

- ROTATING TETHERS FOR SENSITIVE GRAVITY MEASUREMENTS

- LONG TETHERS FOR SENSITIVE GRAVITY WAVE DETECTION (B. Bertotti , K. Thorne)

- SAMPLE ATMOSPHERES OF PLANETS/SATELLITES FOR ANALYSIS OR PROPELLANT
  PRODUCTION

- USE RIBBON TETHER FOR COSMIC DUST COLLECTION

- USE TETHER TO CAPTURE PARTICLES IN SATURN'S RINGS

FIG. 13