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Do Humans Have a Future in Moon or Mars Gravity?

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Abstract

Before the space age, designers assumed artificial gravity for crewed facilities. Concerns about crew health in microgravity receded after the 2-week Gemini 7 mission. But far longer stays on Skylab, Russian stations, and ISS have uncovered a wide range of health problems, including changes in bones, muscles, eyes, fluids, and immune response. Exercise, diet, and drugs help but do not eliminate these problems. Surprisingly, all 13 solar system bodies with 9% to 250% of earth surface gravity cluster in 3 narrow bands, all near earth, Mars, and Moon gravity. The 4 planets with earth-like gravity, Venus, Saturn, Uranus and Neptune, all pose problems for settlement. The 8 smaller bodies near Moon or Mars gravity all seem far more practical, and also have far lower two-way ΔVs. Viable plans for settling in Moon or Mars gravity requires that we evaluate the health implications and countermeasures in sustained Moon and/or Mars gravity, on large numbers of people. A rotating "Moon-Mars dumbbell" in LEO can find whether humans can live on the 8 bodies with gravity near Moon or Mars, and possible constraints on later returns to earth gravity. An inflated tunnel can allow crew shirt-sleeve transfers between Moon and Mars levels. Additional tunnels added later can also grow crops, using filtered sunlight and/or LEDs. Such tunnels may also be useful in settlements. The paper argues that ground-based rotating-room tests have different sensory effects, so we don't yet know how fast facilities can rotate without excessive negative crew reactions. We can test rate effects as Gemini 11 did, using crew vehicles on the way to ISS. Rotation tests can determine the diameter and hence minimum mass and cost of rotating free-space settlements. A new test concept allows Moon then Mars gravity in one crew module. A 1-rpm Moon-Mars dumbbell would be ~500 m long. Easy transfer between free-fall, Moon, and Mars gravity levels may attract far more "space tourists" than free-fall-only designs. The paper shows how to build and expand a commercial LEO facility.

Keywords: Artificial gravity, partial gravity, Moon gravity, Mars gravity, countermeasures, space tourism

1. Introduction

This paper updates designs and strategies from a 2010 IAC paper [1] for an artificial gravity "dumbbell" in LEO. It is designed to evaluate the effects of long-term Moon and Mars gravity levels on people.

Surprisingly, as seen in Figure 1, all 13 solar system bodies with 9% to 250% of earth surface gravity cluster in 3 bands, near earth, Mars, and Moon gravity [2].

Venus, Saturn, Uranus and Neptune pose practical challenges for exploration or settlement. Most of the 8 bodies near Moon or Mars gravity seem more practical to explore, and also have far smaller two-way delta-Vs.

Before the space age, designers assumed artificial gravity in long-term crewed facilities. Concerns about microgravity receded after success of the 2-week-long Gemini 7 mission. Over the last half century, we have learned that humans can tolerate the absence of gravity for nearly a year and live normally after return to earth.

But long stays on Skylab, Russian stations, and now ISS have uncovered a wide range of problems. Bones lose calcium and muscles lose mass and strength. The immune system, eyes, and brain are also affected.

Diet, exercise, and drugs reduce but do not eliminate these problems. Other biological tests also show various anomalies. Fertilized mouse eggs do not grow normally. Surprisingly, even some single-cell microorganisms respond to the absence of gravity.

Most current interest in artificial gravity focuses on crew health on deep-space expeditions lasting several years. This paper discusses that, but its main focus is on evaluating the feasibility of humans in sustained partial gravity, including supporting ecosystems in settlements.

We already know the effects of earth gravity. The key value of a partial-gravity research facility is to find the effects of sustained Moon and Mars gravity levels on humans, and then on crop-based ecosystems we will need to feed ourselves off earth. Such a facility can shed light on what futures we might have on the 8 bodies in our solar system with gravities near Moon or Mars.

Crews could live in a large centrifuge on low-gravity bodies, but this complicates the designs of facilities on

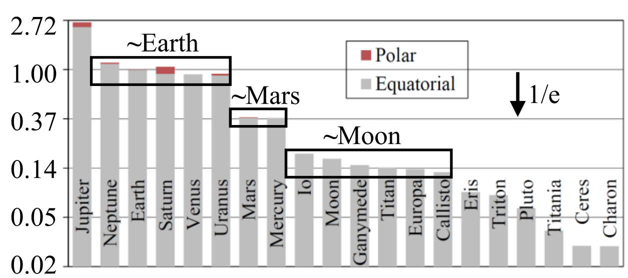

Figure 1. Clustering of surface gravity in our solar system

bodies with non-trivial gravity. We also don't yet know if "commuting" between free fall and a rotating facility will cause adaptation problems in each cycle.

Such a facility can also do relevant tests on effects of various spin rates and hence the diameter of free-space settlements that rotate to provide artificial gravity. Spin rate constraints drive required minimum diameter and cost. As discussed in Appendix A, vertical-axis rotating room tests are not relevant because they do not cause the same sensory effects as artificial-gravity facilities.

Most human health problems in microgravity were found only after months. Some do not asymptote even after a year. The only human experiences of Moon and Mars gravity are 1-3 days on 6 Apollo moon landings, and <1 minute parabolic flights. Finding whether multi-year missions or even longer stays in partial gravity may require crews to stay a year or more. The main constraint may be from galactic cosmic ray (GCR) doses in orbits like ISS. But low doses in equatorial LEO (ELEO) may allow stays up to ~5 years. Such facilities can test ideas for ELEO settlements, as proposed by Al Globus [3].

Moon-Mars-Earth surface gravity levels are also usefully spaced apart by factors of ~1/e. This makes them seem useful as test levels for initial basic studies of the effects of different partial gravity levels. The next 1/e step below Moon gravity is 0.06g. It is easy to make room for tests at that level. Values near 0.06g may also be near the lower limit for intuitive activities like sitting in a chair, working at a desk, eating at a table, or rolling over in bed without continuing the roll onto the floor

Gravity test crews will need to stay at one level, but other crew and "space tourists" can enjoy all 4 levels: Mars and Moon, 0.06g, and free fall. Some may spend most of their time at 0.06g, if it eases accommodation to free fall, or if they don't enjoy free fall as much as they expected. With enough room, partial gravity also allows novel gymnastics, dances, break dancing, etc. (Envision what Jackie Chan might do at these 4 gravity levels.)

Overall, the key payoff of such a facility will be to answer the question posed in the title of the paper:

Do humans have a future in Moon or Mars gravity?

This may drastically affect plans for human space exploration. If the human health challenges found in free fall persist in Moon or Mars gravity, then realistic plans for permanent human settlements in space will have to focus on higher gravity levels. Given the serious challenges with living on Venus or gas giants, rotating settlements seem more realistic than settling on planets.

If our future in space will be in rotating settlements rather than on bodies near Moon or Mars gravity, then both the payoff and real interest in human exploration of the Moon or Mars may decrease. Realistic interest will shift to near-earth objects as accessible resources for settlements, and finding suitable settlement rotation rates, which drive early settlement size, mass, and cost.

If this argument makes sense, then a "Moon-Mars in LEO" facility can help humanity focus future human expansion earlier and better. It can help us choose a fork in the road driven not by the solar system, but by our physiology. Or as Shakespeare put it 400 years ago,

The fault is not in our stars, but in ourselves.

I have been interested in a Moon-Mars facility for 35 years, but I did not see this implication until this month.

The rest of the paper addresses these topics:

1. How to test Moon and Mars gravity in LEO
2. Useful tests enabled by Moon-Mars facilities
3. Facility assembly and later expansion
4. Facility development tasks and challenges
5. Conclusions and recommendations

The paper has 4 appendices. Appendix A explains why "rotating room tests" cannot tell us what rates are usable for artificial gravity. Appendix B describes tests that appear feasible on future crew flights to the ISS, during the hours to days the crew spends "phasing" to catch up with ISS. Appendix C proposes an affordable scenario for early tests of the sustained effects of Moon and/or Mars gravity on humans, in LEO. Appendix D estimates key mass penalties of using artificial gravity on crew exploration missions to Mars or NEOs.

My main focus in my 36 years in aerospace has been analyzing and developing applications for space tethers. I am not an expert in human spaceflight, human factors, physiology, biology, farming, or ecology. But making human expansion off earth viable requires evaluating the effects of artificial gravity and/or partial gravity, both on people, and even on the ecosystems people will need to develop to support their lives there. I will try to shed as much light on these issues as I can.

2. Testing Moon and Mars Gravity in LEO

In 1984 I suggested rotating asymmetrical dumbbells in LEO, to test the effects of long-term Moon and Mars gravity on people. I found no interest then, but tried again in 2009. I tried to find data on allowable rotation rates, but John Charles of JSC pointed out that rotating-room tests on the ground have different sensory effects because of the difference in rotation axis relative to the felt gravity. I discuss this in detail in Appendix A.

Spin rate uncertainty is doubly frustrating, because halving the rotation rate does not require a 2X longer facility, but rather a 4X longer one. This is so because $\mathbf{a} = \boldsymbol{\omega}^2/\mathbf{r}$. Uncertainty in rotation rate seemed enough to drive facility length enough that several different radial structure designs seemed needed. That led to 3 different radial structure designs in Figure 2 on the next page, for rotation rates of 2, 1.5, 1, and 0.55 rpm.

Most prior studies have tried to determine the fastest acceptable rotation, to minimize length and weight. But if radial structure is light enough, that is less important.

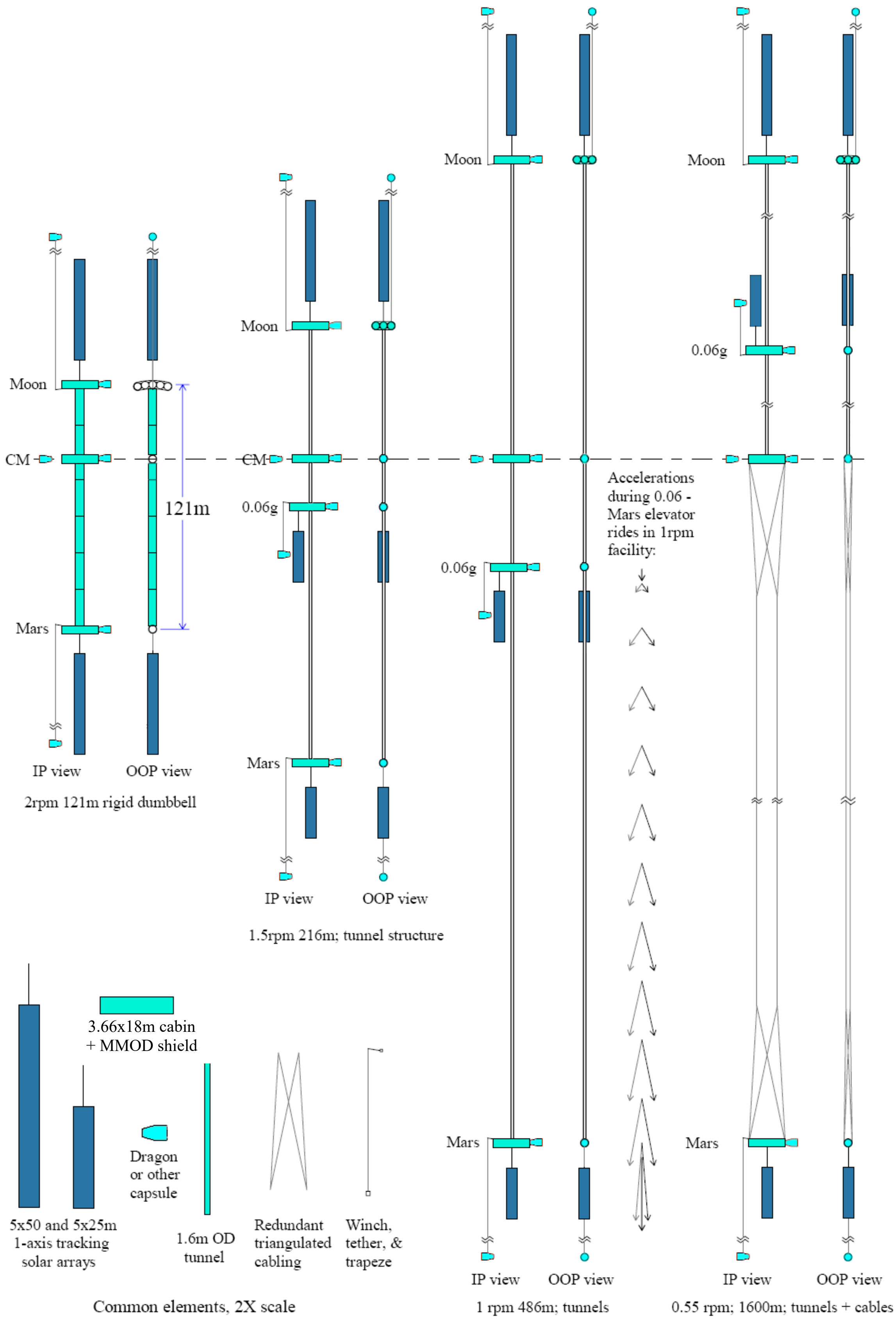

Figure 2. Different dumbbell radial structure and length options using mostly common elements

For "short enough" facilities, one can mate a series of rigid modules end-to-end. For longer designs, radial module mass and drag become dominant. An "airbeam" tunnel can be far lighter. It still allows crew shirtsleeve access to all levels. But even that may get too heavy for km-long designs. So then one may need cables for much or all of the length. But that complicates crew access.

Despite differences in structural design vs length, these designs have 4 mostly-common novel features:

First, hanging solar arrays that track only around the "hang axis" require more array area for the same power, but they can be lighter and perhaps more reliable. Extra electric power is available when the sun is far from the orbit plane. That can be used for high-Isp reboost, and for heat pumps to reject heat at higher temperature. It may also make sense to use 3 5x50m (or even 6x60m) arrays, rather than one 5x50m one plus 2 5x25m ones.

Second, 3 of the 4 designs use inflatable "airbeam" tunnels. They are used in field hospitals and hangars. They can roll up to stow for launch, and can easily be patched after small impacts.

Third, the long axis of each module is aligned with the rotation axis, to reduce Coriolis-induced weight changes while walking in the long direction. This may require either reaction wheels or cantilevered masses to keep the modules aligned with the spin axis.

Fourth, conventional vehicle approaches can be done at the center of mass module (but from out of the orbit plane), but one can also do "trapeze captures" at points far from the center of mass. Such captures can save 100 m/s, and can also eliminate 120 m/s deorbit burns. They also allow visiting vehicles to be safed before berthing. Water tanks and pipes between modules allow CG and MOI adjustments to keep gravity levels accurate.

Ref 1 analyzes these and other concepts in detail.

3. Useful Tests for Moon-Mars Facilities

Before mankind spends money to develop long-term bases, settlements, or colonies on the Moon or Mars, it is prudent to see if Moon and Mars gravity are enough to avoid most negative health trends people experience in sustained microgravity [4,5,6]. If the same problems persist after months at Moon or Mars gravity, then we need to either develop effective countermeasures, or limit the times spent at lower gravity levels. Learning this in LEO rather than far from earth can reduce schedules, costs, risks, and radiation doses.

3.1 Questions Affecting Human Expansion into Space

- What spin rates and settlement diameters are needed?
- Are lunar or Mars gravity levels high enough for good health, even including indefinite human stays?
- If special exercises, diets, and/or medicines are still needed in partial gravity, what protocols seem best?
- How long can people safely live in partial gravity and then safely return to earth, and with what problems?
- Does reproduction work properly in rats, monkeys, and eventually humans, at Moon and Mars gravity?
- Can rats, monkeys, and eventually humans raised in partial gravity adapt to full earth gravity?
- Overall, do many people like living in partial gravity?

3.2 Recycling and Manufacturing

The terms base, settlement, and colony each have different connotations of self-sufficiency. Bases and settlements can rely on suppliers "back home" for key supplies that cannot be affordably produced locally. But I think most colonists will want to expand their colony. That seems likely to require local resources and efforts, rather than large sustained net investments from earth.

When I give talks about partial gravity concepts, I often ask the audience who would be more important in an early space colony:

recycling experts or rocket experts?

Sometimes they laugh, but nearly everyone agrees that recycling experts are more critical. The resources of the solar system are huge, but the options do not allow "next day delivery" as on earth, but getting deliveries within a year or so. Colonies will "mine the midden" because it has most needed materials, in known forms, nearby and available now, rather than >1AU and ~1 year away. And it requires no rocket propellant mass or funding to get it. Viable space colonies are likely to recycle far more than nearly any organization on earth.

Recent additive manufacturing tests done on ISS by MadeInSpace are useful, but clever "demanufacturing" may be far more central to long-term sustainability. This is true both on and off planet earth, and not just for human activities, but even robotic activities. DARPA's "Phoenix" program is an early effort in this direction [7], and NASA has funded several others [8,9,10]. Questions that are worth early consideration include:

- How may partial gravity and rotation effect handling?
- How much mass delivered can be usefully recycled?

3.3 Effects of Gravity Levels on Crops and Ecosystems

Growing crops is not just a matter of selecting crops and fertilizers, but of selecting, adapting, and managing (not "controlling") an agricultural ecosystem. Biosphere 2 discovered many of their key problems only well into their experiment. Thinking about human expansion into space suggests questions like these:

- Will long thin translucent tunnels be useful to grow crops on Mars or in rotating free-space colonies?
- What current or novel crop types may be most useful for food production in partial gravity?
- What soil-based, hydroponic, aeroponic, aquaponic, or other techniques may be most practical?

- What microbes, worms, pollinators, and other support species do we need besides crops?
- What pests can occur, and what controls may work?
- What valuable new insights will partial-gravity tests give us about crops currently important on earth?
- What new perspectives on important crops may challenge key aspects of current theories?
- How much of the diet can be fish, meat, or analogs?
- And as a practical matter (suggested by Jim Logan), when can hops, barley, and grapes be grown?

3.4 Basic Biological Research

Besides research on people, recycling, and crop-focused ecosystems, a partial-gravity research facility focused on biology can also address more basic biology questions. The questions below result from discussions with Lynn Harper of NASA Ames:

- What changes in gene expression and metabolism occur at Mars, Moon, and lower gravity levels?
- Can partial gravity tests advance basic bio research?

3.5 A recap: how to find the health impacts of gravity

To summarize our current knowledge of the effects of sustained gravity on health, consider Figure 3 below:

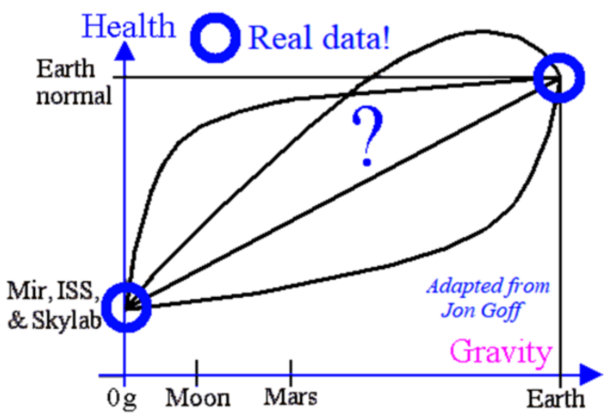

Figure 3. Data on the health effects of gravity

Human physiology is very complex. The "gravity prescriptions" for different aspects of human health are likely to vary. Moon or at least Mars gravity may be enough to provide most of the benefits of earth gravity for some aspects of human health, while others may need much higher gravity, or many countermeasures now used (but not yet sufficient) in microgravity.

Learning this in LEO rather than on the Moon or Mars allows far earlier, cheaper, better, and safer tests. Moon-Mars dumbbells in equatorial LEO orbit can have low enough radiation doses to match those in Moon or Mars facilities buried several meters below the surface.

Rotating LEO facilities can also sling sample capsules back to earth every few days if desired. This allows far better testing than feasible at Moon or Mars bases.

4. Facility Assembly and Expansion

I assume here that the tests discussed in Appendices A-C will limit the range of rotation rate enough to select a radial structure type and its interface to the modules. It seems likely to be like one of the options shown earlier, in Figure 2.

4.1 Early single-module tests

Even before the facility is assembled, useful tests are feasible using the first module launched. This lets later modules be improved. Many normal human activities like walking, sitting at a table, and sleeping in a bed are more feasible in a long module than in a crew vehicle on its way to ISS. The first module should include months of crew supplies and redundant life-support systems.

Appendix C describes this single-module concept in more detail. Instead here I focus on how to reuse the early modules, up to at least a 3-module level. At the end of the first mission, the tether can be released from the module to deorbit the counterweight stage and tether where desired. The next step is to launch another large module and hard-mount it side by side to the used one. This might be done by the crew vehicle for the second mission. A longer tether and/or heavier tether may be needed given the second module mass. The choice will depend on data from the first mission, as to what spin rate should be used this time, and whether the next test should provide only Moon gravity, or Moon gravity first and then Mars gravity. or possibly even something else.

4.2 Assembling a 6-module dumbbell

For simplicity, Figure 4 assumes use of airbeam tunnels for the radial structure:

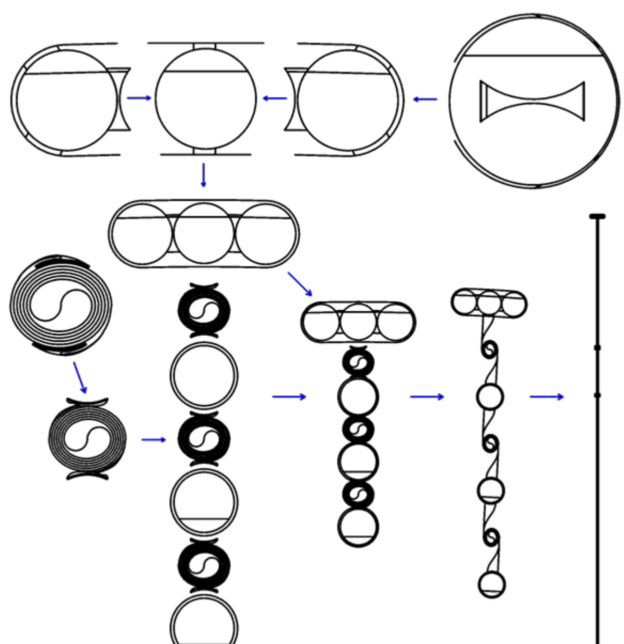

Figure 4. Assembly sequence from 1 to 6 modules

Some kind of robotic two-handed arm seems needed to position and align modules for attachment, after each is launched. Or a vehicle with 1 or 2 arms can capture and maneuver modules into position. Inflated actuators of some kind may also be a viable option.

Note that the final structure length and rotation rate need not be finalized until after 3 modules are launched and joined. Modules 2 and 3 can each be used in a new single-module test. Each test allows a new tether length and combination of gravity level and spin.

The key novelty after full assembly will be the new radial structure. Various integrity tests will be needed. The facility can spin up to higher gravity, especially if the structure is sized for later expansion. Local tether triangulation seems needed for outrigger modules.

4.3 Expanding a dumbbell from 6 to ~16 modules

Figure 5 below shows 10 new modules added at the same time. Some might be far larger inflatable modules, particularly if the CM and/or 0.06g levels are popular.

Obviously, adding 10 extra modules makes sense only if a 6-module facility is successful and 10 more (or some other number) have clear value.

It may make sense to completely despin the facility and even balance it at the unstable horizontal to attach new modules. But if trapeze captures work well with lighter visiting vehicles, a lower spin may be enough to capture modules using trapezes sized for lighter masses.

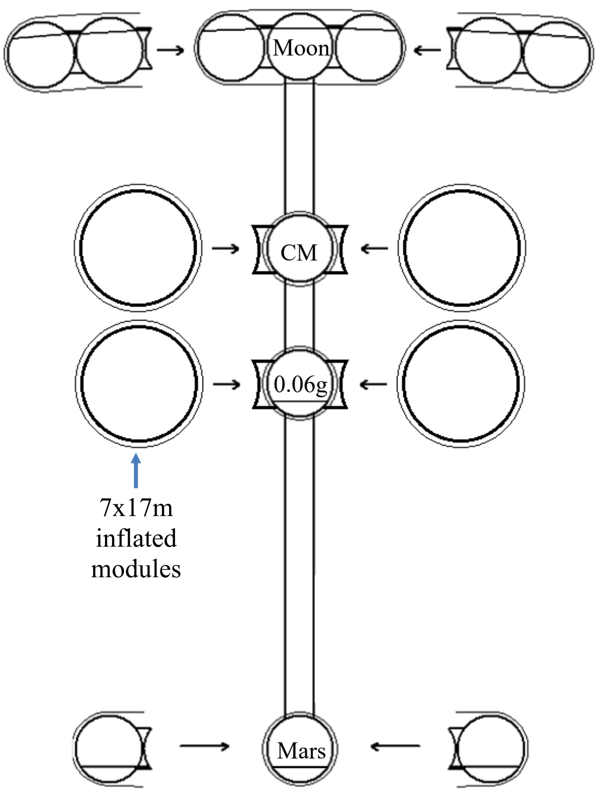

Figure 5. Assembly expansion from 6 to 16 modules

5. Facility Development Tasks and Challenges

Key early steps in developing such a facility are to do better tests on the ground and in orbit to understand the effects of spin, as discussed in Appendix A.

"Moon-Mars in LEO" is a large manned facility. It also depends on some novelties. But most have easier alternatives if these novelties require miracles and not just good engineering. Below I discuss most key tasks, challenges, and rationales for them:

5.1 Developing and testing inflatable airbeam tunnels

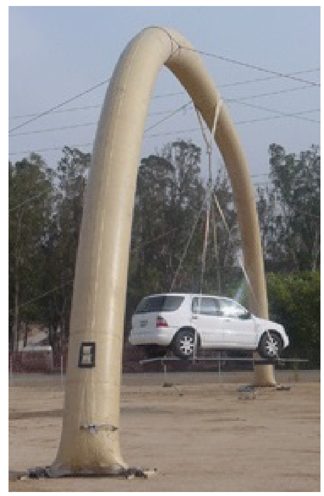
Figure 6. Airbeam load test

Airbeams like the one in Figure 6 are used in military shelters [11]. This one can be carried by two people, when not supporting a car.

Airbeams are like Transhab envelopes [12]. They have distinct tear-stop straps to protect against grazing impacts. Existing airbeams have diameters <1m, and are not designed for space. See [13] for a review of inflated airlocks. Fig. 7 shows a stowage option.

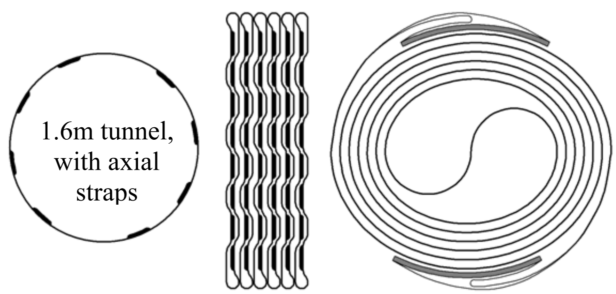

Figure 7. Airbeam cross-sections, deployed & stowed

Long airbeams will need a standoff MMOD barrier, and acoustic and electrical sensors to triangulate impacts to ease detection and quick repair of air leaks.

5.2 Developing module designs, rigid and inflatable

Two key decisions are to select module diameter and rigid vs inflatable. I have assumed rigid tanks the same 3.66m diameter as the Falcon 9 and Heavy tanks (plus MMOD barriers that can deploy in orbit). They can be built on the Falcon rocket production line. Bigelow Expandable Activity Modules (BEAMs) [14] may make sense as low-mass outrigger modules, particularly at the CM and 0.06g levels. How to attach them, pass loads, and allow crew transfer all must be worked out and tested. Architect Ted Hall has done several studies for layouts for artificial gravity modules [15].

Figure 8 below shows a Falcon Heavy with standard fairing, plus a 21m-long 3.66m-dia module that should have similar peak bending loads at the fairing interface:

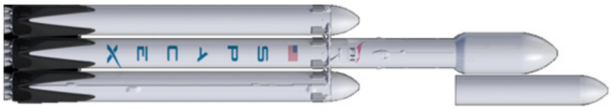

Figure 8. Falcon Heavy with 21m long tank-dia. module

Figure 9 shows module layouts with 3.66, 4.2, and 5.2m diameters. The larger ones do have more volume, but a longer 3.66m module may have more usable room.

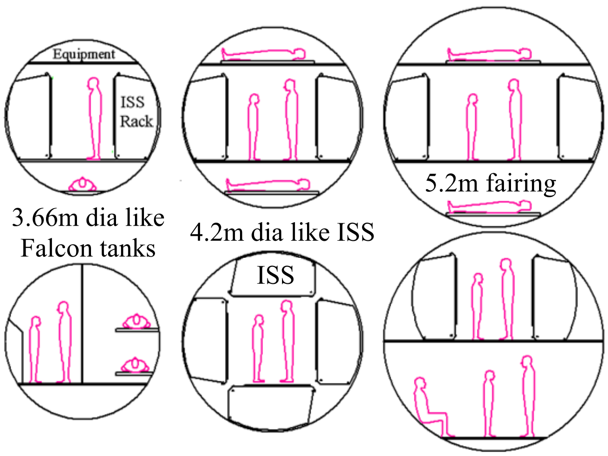

Figure 9. Three module diameters and possible layouts

5.3 1-axis tracking of hanging solar arrays

Solar array tracking by satellites usually involves one rotation per orbit, but here the tracking may be 0.5-2 rpm. Illumination and power are lowest when the sun is in the spin plane. Clocking at fixed rate reduces power ~20%, but reduces array twist dynamics then. At high beta angle, the best performance uses an oscillation about the spin plane. MOI effects encourage this, but large amplitudes slow down the resonance and require forcing the motion. The best control strategy is likely to include modest oscillations, twist, and forcing.

5.4 Developing trapeze captures of visiting vehicles

A good way to understand trapeze captures is in reverse. Envision releasing a visiting vehicle when it is at the bottom of a dumbbell, rotating backward. Release slings the vehicle back into a lower-perigee eccentric orbit. Extending the vehicle on a tether can lower the perigee. Running this maneuver in reverse (extremely accurately!) lets one capture vehicles from low-perigee MECO orbits, saving ~100 m/s ΔVs for circularization.

Tether reeling plus vehicle hovering allows more time for capture, but with GPS, prox-op sensors, and computers, it seems far better to gradually null out errors in advance and avoid seconds of panic. Trapeze capture tests on the ground should be practical, since facility trapeze tip accelerations are of order 1g.

It is not clear that this will work reliably enough, but the payoffs are substantial compared to berthing at the CM, partly since vehicles can also get ~120 m/s sling deorbit ΔVs free, while also providing more facility boost than they borrowed after capture. Dale Stuart did an MIT ScD thesis on this [16]. Others and I analyzed a range of trapeze capture cases since then [17,18,19,20].

5.5 Reducing launch costs by reducing mass/seat

Reducing crew launch costs allows larger crews to test partial gravity and countermeasures. The usual focus is to reduce launch cost per kg, but one can also reduce capsule mass per seat. I don't think any crew orbital vehicle has ever weighed less per seat at launch than the 1400 kg of Mercury, despite many later large improvements in power systems, electronics, structures, heat shields, and flight experience. Those together may compensate for the later more challenging missions.

One key is to select launch dates that limit phasing to a few hours. Then capsules can resemble buses more than motor homes. (Crews on far longer flights should spend most of their time in larger quarters.) Days of phasing are now accepted to help accommodate crews to free fall, but that isn't needed in partial gravity tests.

The most expensive part of an IVA pressure suit for launch and reentry may be the elbow room that drives seat width and hence crew capacity. The space activity suit proposed by Paul West may significantly reduce seat width and suit mass [21]. One can also offset adjacent seats 10-15cm so elbows can overlap. In addition, one might use varying seat sizes and prices, as airlines do.

Not all of these ideas may be workable, but most of their net impact may be achievable. A lean "Dragon bus" might fit up to 15-20, and still launch on Falcon 9.

In [1], I noted a related puzzle about space facility mass. Consider this list below, in metric tons/person:

<1	Commercial airliners, loaded and fueled
15	Aircraft carriers and typical cruise ships
30	Skylab
40	Mir
60	ISS (with the intended crew of 7)

Space stations provide more life-support than aircraft, but I don't know why mass/person is 2-4X that of large ships, when launch mass costs so much. The reason for high capsule and space facility mass/person may be at least partly because the needed staff only get the needed funding for bigger systems. That may be less of a factor in commercially-driven designs.

5.6 Testing plant growth in translucent tunnels

As shown in Figure 10, adding two new translucent plant-growth tunnels from "Moon to Mars" can allow a large area for testing crops. Using two plant tunnels will ease airflow. Inspection and management might be done mostly from the ground, and gradually automated.

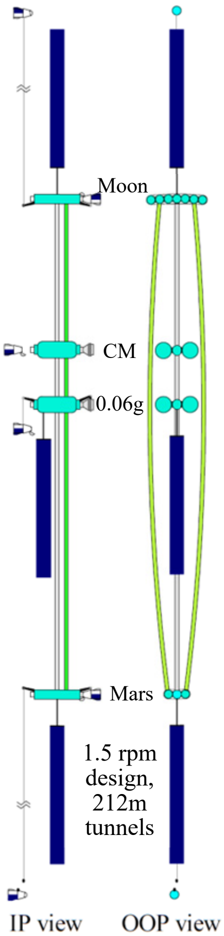

Fig. 10. Evolution, with 7m inflatables and 2 crop tunnels.

LEO orbits will have up to 36 minute eclipses every 96 minutes, if we use translucent tunnels to deliver filtered sun to crops. The ratio of red to far red light at start of eclipse affects plants. Some LED light may be needed at the start of eclipse. Ground tests can quantify this.

Aquaculture tests show that fish can eat most plant waste productively [22]. Some insects can be useful for providing some nutrients [23].

Plant tunnels can also allow backup crew transfers if a part of the central tunnel is unusable.

5.7 A few other challenges

Crew EVA will need some kind of winching and rappelling. If a winch jams, the crew might use a ratcheting ascender to climb up the line to the airlock.

Some cables can triangulate between tunnels and modules to keep assemblies aligned at each end, despite local shifts in mass. Water can be pumped between tanks at different locations to manage CG and MOI, whenever vehicles are captured or released anywhere other than at the CM.

6. Conclusions and Recommendations

The "Moon-Mars in LEO" concepts described in this paper and precursors in the appendices should allow far better planning of future human expansion into space, by uncovering data that may constrain our future in space.

If lunar gravity is enough for long-term health, we can live on 6 large moons in the solar system, not 1. If Moon gravity is not enough but Mars gravity is, then settlements on 6 large moons in our solar system are out, but we may have futures on the 2 small rocky planets. And if we need countermeasures to live in those places, we can develop and refine them in LEO.

If we need higher gravity much of the time, we can determine what is needed. Rotating free-space "O'Neill cylinders" can provide full earth gravity, but only at one radius, typically near the rim. Most of their volume will provide lower gravity. The inner volume is too expensive to not use it for people, crop growth, and/or industry.

There are scientific reasons for human exploration of the Moon and Mars, but if we cannot later live on them, political will and funding may be hard to find.

Low but non-zero gravity, such as Mars, Moon, and 0.06g, may be very enjoyable, but healthy only in finite doses. This is also true of many other things, like sugar, fat, salt, intoxicants, TV, gossip, sex, and even sleep.

A research facility that lets visitors sample Moon and Mars gravity plus free fall and 0.06g should create a far larger "space tourist" market than with only free fall or Moon gravity. Such tourists may typically stay for a few weeks with little loss of health, while gravity test subjects stay mostly at one level for months, and some perhaps eventually for years, to verify countermeasures.

Consider cruise ships, where tourists stay for days to weeks but staff stay for months at a time. Not all staff will need astronaut training, but like flight attendants, safety training is central. More on-board professionals may be technicians than researchers.

My 2010 IAC paper [1] estimated facility mass but not population or cost. I do not estimate any of those items here, because there are too many uncertainties.

Note that a rotating "donut" facility has useful area near one gravity level, but it is not usable at all until launch and assembly are complete. A dumbbell can provide both Moon and Mars gravity. A dumbbell also allows early spin rate tests with one module plus a crew vehicle at one end.

Research on the effects of these gravity levels can be done far more cheaply in a spinning facility in low earth orbit, than "in-situ" on the Moon or Mars, and with far lower radiation exposure, particularly in equatorial low earth orbit (ELEO). A rotating LEO facility also allows far better analyses, since it can do frequent targeted tether deorbit of samples for analysis on the ground. This can be similar to the tethered deorbit and targeted reentry of the SEDS-1 payload in 1993 [24].

For far more detail on facility design and operations, including contingency operations, solar array trades and power profiles, and management of facility orbit, CG, and angular momentum, please download and study [1].

Gravity is an analog parameter. To date, study of its implications on humans has treated it only as a digital parameter, either 0 or 1. We can do better. I encourage those interested in that to contact me, at tether@cox.net.

Acknowledgments

I would like to thank my wife and daughters for their patience, and their help with simple tests that helped clarify my thinking about rotation effects. I would also like to thank John Charles, Jim Logan, and Lynn Harper for discussions mentioned in the paper; Henry Cate, Al Globus, and John Oldson for their feedback, Ted Hall for insights in his papers (in particular, the value of aligning the module axis with the spin axis); and Dave Lang for details of the Gemini tether tests.

Appendix A: Why Don't We Know What Spin Rates Are Acceptable?

Early in the space age, tests were done on the accommodation of six young soldiers to conditions in a rotating room over two days. After that the rotation stopped and they remained in the room for added tests on the third day. The room was round, windowless, and 15 foot in diameter, and smoothly rotated around a vertical axis, at rates from 1.71 to 10 rpm. The results are reported in [25]. Some subjects reported mild general malaise, nausea, or headaches even at 1.71 rpm, and one vomited at 2.21 rpm. The frequency and severity of reported negative reactions increased at 3.82 and 5.44 rpm. But one subject had minimal negative reactions even at 10 rpm. In addition, a control subject who was deaf and also lacked normal vestibular function had little response to rotation.

Since then, NASA analysts have developed various criteria for constraining the spin rate and size of artificial-gravity facility designs, based on data from these and related tests and other factors, including head-to-foot gravity differences and changes in weight caused by walking with or against the rotation.

John Charles of NASA JSC suggested to me that those rotating room tests may not be relevant for finding the maximum allowable spin-rates of orbiting artificial-gravity facilities, since the rotation axis is parallel to gravity, rather than normal to it as in an artificial-gravity facility. A footnote in ref. 14 also notes this issue. At first this seemed like a very subtle difference, but I gradually realized that this difference may be very important.

Two distinct effects need discussion: rotation itself, and Coriolis accelerations. Room rotation rates of order 1 rpm may be detectable even when people are still, but people seem to tolerate that. They can even adapt to reversals in rotation direction, but time may be required for accommodation. But in artificial gravity facilities, the direction of felt rotation depends on which way you are facing at the time. Turning around reverses felt rotation immediately. Turning around even has different effects at each azimuth: one turn shifts sensed rotation one way, and the next causes an opposite shift in sensed rotation. This is a key difference between ground-based rotating-room tests and orbiting artificial-gravity tests.

Now consider Coriolis accelerations. To a person sitting or standing anywhere in a room rotating about a vertical axis, purely vertical motion causes no Coriolis effects. Horizontal motion can cause substantial Coriolis acceleration. In a room rotating clockwise (when you look down), the acceleration is to the left of the motion. It equals twice the room rotation rate times the horizontal velocity. If you walk at 1 m/s in a room that is rotating clockwise at 1 rpm (=0.1047 rad/sec), you must lean 1.2° to the right, or 1.2° to the left if you step backward. This may be annoying initially, but it is consistent, so you may adapt to it fairly quickly and thoroughly. As long as the spin direction and rate stay the same, the side acceleration is independent of location and orientation in the room. Every time you walk at a given speed, or reach your arm out at a given speed, you feel the same perturbation, in the same direction in your body coordinates.

Contrast this with an artificial-gravity facility. Both vertical and horizontal motions cause perturbations. The felt effects of both motions vary with which direction you face. Vertical (radial) motion causes a horizontal force aligned with the direction of rotation. Typical vertical motion is stroke limited (eg., standing up), so the total impulse is limited and may be tolerable. When you stand up, you may raise your CM by ~0.4m. In a facility with 1 rpm rotation, that is like standing up from a wheeled chair moving at 42 mm/sec (1.6"/sec) in a fixed direction, independent of which way the chair is facing. That is probably tolerable, because people usually need to adjust their balance anyway while they are standing up.

But now consider horizontal motion with or against the direction of rotation. If you walk only 2.5% as fast as the facility moves at your radius, you get 5% heavier, since weight scales with V^2/r. But if you walk in the other direction, you get 5% lighter. If you walk at right angles to the rotation, weight does not change.

Such changes are relevant because typical elevators have ~0.05g acceleration when starting and stopping. People often stumble a bit if they are taking a step when an elevator starts or stops. (A better test than intentionally walking at such times may be to slave the vertical motion of a large motion-base simulator to for-and-aft horizontal motions of a single occupant.) Such tests may show that people may detect or be affected by weight changes as little as ~1% when walking.

Another key issue is that the threshold for conscious detection and that for negative effects like malaise or nausea may be different. It is not clear which may be lower. The threshold for negative effects may be well above the threshold of conscious detection. But malaise or queasiness may possibly be problems even when you are not consciously aware of rotation artifacts. Consider the implications of a possible threshold for undesirable negative effects that range from $\pm$1 to $\pm$3% weight change at a modest walking speed of 1 m/s. This occurs at facility rotation rates of 0.47 to 1.41 rpm, and overall lengths of 240-2200 meters for a Moon/Mars dumbbell.

An important related question is what happens to thresholds for detection and negative effects in lower gravity. Coriolis accelerations scale with rotation rate but are independent of radius, so walking in a facility rotating at 0.47 to 1.41 rpm will cause weight changes equal to $\pm$1 to $\pm$3% of ***earth*** gravity, whether you are at earth, Mars, lunar, or a lower gravity level.

Detection threshold for changes in sensory input often nearly scale with input level, but at "low enough" levels, this should fall off. If detection thresholds do drop with gravity level, then allowable facility rotation rate will be limited more by effects at the lunar node than the Mars node. But even if thresholds for negative effects scale down only with the square root of partial gravity level, then the allowable rotation rate in lunar gravity may be only 40% of a 0.47 to 1.41 rpm range relevant at earth gravity, and could be as low as 0.19 rpm (requiring a 14 km facility length!).

Such rates are far below what others have assumed acceptable. Good design decisions really do require relevant tests. Those tests must be long enough to allow accommodation if needed, and should involve enough people to characterize personal variations, which may be large if sea-sickness gives any relevant indication.

For very long slow-rotating facilities there is one more effect to consider: periodic gravity variations between horizontal and vertical, due to gravity-gradient effects pluse induced variations in rotation rates. This effect scales linearly with length. This does not require occupant motion, so people may be more sensitive to it than to comparable variations caused by walking, for the same reason that people seem more prone to motion sickness when they are passengers than when driving.

Moon/Mars dumbbells near ISS altitude have a total range of gravity variation of 1% per 6.75 km dumbbell length, with maximum weight at the vertical and minimum at the horizontal. On the other hand, this is a smooth and slow sinusoid, with a period of 1 minute for a 2 km dumbbell rotating at 0.5 rpm. For a ~500m 1 rpm facility, the period is 30 seconds, but the total range of variation is only 0.07%.

Based on the above discussion, I suspect that the most detectable artifact in a slowly-rotating facility, and the best candidate for an upper limit to rotation rates, may be direction-dependent weight changes when people walk with or against the direction of rotation.

A key feature of the facility design may be long thin aircraft-like cabin layouts, with narrow "aisles" aligned with the spin axis. Ted Hall recommended this in a 1993 paper [15]. It does require reaction wheels or masses on long booms to keep the cabin axis aligned with the spin axis. But it seems worth doing, because then most walking will be nearly parallel to the axis of rotation, and walking-induced weight changes will be low. Steps across the aisle will be at much lower speed since there is so little room to start and stop.

A useful supporting design feature might be a décor-ative floor covering with an intuitive directional pattern like arrows showing rotation direction, to help people anticipate rotation effects. This could be very useful in hallways between adjacent cabins. Such a detail may be important. If a good layout and floor covering allow use of even 10-20% higher facility rotation rates without problem, those features would enable 17-31% shorter facility lengths.

It also seems important to keep rotation artifacts too low to trigger negative effects in ***most*** people who could spend time at a facility, without limiting personnel selection significantly. Many people suffer seasickness. The levels of acceleration and other sensory inputs required to trigger it can be modest for many of them.

Rather than trying to find the highest acceptable spinrate, it may make sense to try for the lowest spinrate (and hence longest length) consistent with an affordable and easy to use facility design. This may involve limiting rotation rates to 1.0 rpm or less. This requires lengths of at least 500 m. Figure 2 showed radial options suited to a very wide range of facility lengths.

Possible ground tests to reduce uncertainty in spin rate

We can mimic some but not all effects of turning around in a partial-gravity facility, by rotating a room or even a reclining seat at ~0.5-2 rpm, and then smoothly reversing rotation direction. This still does stimulate the wrong perceptual axis. But if such tests are easy, they may help quantify sensitivity to changes in rotation.

It also appears feasible to explore the effects of weight changes caused by walking, using the Vertical Motion Simulator at NASA Ames. The VMS allows 18m vertical motion, and 12 and 2m horizontal strokes. The VMS has 4 interchangeable cabs, including one with a 1.8 x 3.7m floor. This is large enough to get up some speed walking in different directions.

What is needed is to outfit the largest cab with suitable interior layouts, add an occupant motion sensor, write code to move the cab in response to occupant motion, and do all needed safety reviews to make sure that the tests can be done safely. The VMS even allows simulation of Coriolis impulses caused by standing up and sitting down. The VMS can also simulate the periodic long-facility gravity variations for facilities up to 2 km long, without needing occupant sensors or feedback control.

Such tests will not eliminate uncertainty but they can limit it. This can be useful if it bounds the design space, or if it identifies questions for study in crewed orbital flight tests like those described next, in Appendices B and C.

Appendix B: Rotating Tethered Orbital Tests Using Crewed Vehicles

A precursor: rotating tethered flight test on Gemini 11

The Gemini spacecraft program actually began after Apollo, to answer time-critical questions that Mercury could not answer. Gemini resolved most of those key questions well before its last flight. This provided an opportunity to add additional tests that could be readied quickly. These tests included rotating tether operations on Gemini 11, and passive stabilization by weak gravity gradient effects on Gemini 12. The time to develop the Gemini 11 test was <1 year.

The plan for Gemini 11 already included rendezvous and docking with a separately launched Agena stage, as on missions 8 and 10. What was added was a 30 meter seatbelt-like tether stowed in the Agena docking collar. The tether was held for launch by weak "rip-stitching" designed to break under modest tension. During an EVA, the crew attached the free end of the tether to a releasable docking bar on Gemini.

Later they undocked from the Agena and fired the Gemini's thrusters to slowly drift away and pull out the tether. They had difficulty keeping the tether taut until they fired the Gemini thrusters to slowly spin up the system, first to 40^{o}/minute, and then 55^{o}/minute. This provided only 0.2-0.4 milli-g acceleration, but that was enough to stabilize the dynamics.

The test was uneventful enough that the crew took a a lunch break during the test. After 3 hours they released the tether and moved away. The Gemini 11 mission movie is available on YouTube [26], and describes this test starting at 10:40 into the movie. Narrator comments in the movie indicate more interest in passive station-keeping than in sensible levels of artificial gravity. This test was 9 months after the Gemini 7 crew spent 13.7 days in free fall without significant problems.

It seems to take much longer than a year to plan crewed flight tests today, but it need not take much longer to develop an analogous test that provides far higher artificial gravity levels. A strong seatbelt-like strap can be stitched into place as on Gemini. The test can actually be simpler than on Gemini, if it uses the booster's upper stage as the counterweight. Then neither docking nor EVA are needed, since the stage is attached to the crew vehicle before launch, and the tether can be too. (But it must be released quickly if a launch escape is necessary).

An alternative is for Dragon to separate, turn around, and come back to attach to the tether. This might use a modified Dragon ascent nose cap with cameras and attach features, if the resulting cap loads are acceptable.

The rest of this appendix discusses 4 key aspects of such tests: goals, scenarios, mass penalties, and safety.

Possible goals

Current human spaceflight vehicles do not have large enough cabins to let the crew walk around. Tests may be limited to better characterizing other constraints on allowable spin-rate, and how they vary with gravity level. If such tests prove easy enough to do, more ambitious goals may be possible. For example, low levels of partial gravity such as 0.06 or 0.16g may ease crew adaptation to microgravity. If so, spinning-tether operations might become a standard part of crew launches to ISS or other facilities. If such operations are continued for days, it may be feasible to directly detect physiological differences in crew response to partial vs micro-gravity. John Charles has told me that data from the several days that Apollo astronauts spent in lunar gravity did not provide an unambiguous difference compared to their colleagues who remained in free fall in the command module. In addition, any such signal might be due more to their spacewalks on the surface than to the lunar gravity itself. With today's biochemical and other monitoring capabilities, especially once crews arrive at ISS, it may be feasible to get useful signals from partial gravity experiments lasting only a few days, over a range of partial gravity levels.

Such tests should also allow refinement of the design of later more ambitious tests involving crews docking with a separately-launched module large enough to live in and walk around in for weeks or even months. Such tests can also allow testing of sensors and many other aspects of guidance to trapeze captures as shown in Figure 2 and discussed in section 5.4, without requiring capture hardware or even very close approaches.

Possible mission scenario

Crew vehicle thrusters usually have lower I_{sp} than the booster upper stage, but discarding stage mass often more than makes up for this. So the crew vehicle can be more efficient at orbit raising than the booster, if it has room for enough propellant to complete its mission.

Usually the crew vehicle separates from the spent booster stage right after MECO, coasts to apogee, and uses its maneuvering thrusters to raise perigee. It then stays in a low "phasing orbit" to catch up with the ISS, often several days later. Phasing is needed because launch must occur when the earth's rotation moves the launch site through the ISS orbit plane, whether or not the ISS is nearby at the time. The lower the vehicle orbit is compared to that of ISS, the faster it will catch up to ISS. Using a "depressed launch trajectory" can also reduce peak reentry g-loads during a worst-case abort of a crew launch. It also increases payload, if there is no heavy fairing to discard on the way to orbit. The best MECO condition may be near the perigee of a parking orbit as low as 120 x 200 km.

The scenario described below provides lunar gravity at 1 rpm rotation. It assumes a Dragon 2 launched by Falcon 9, during phasing on the way to ISS. Similar scenarios might use the CST-100, Soyuz, Shenzhou, or any other crew vehicle delivered to low orbit by a booster stage that can then be used as a counterweight.

I assume that a Dragon 2 has enough propellant to start in a 120 x 200 km MECO orbit, climb to and berth with ISS, and later accurately deorbit itself. I assume also that MECO is near perigee. Lunar gravity at 1 rpm spin requires Dragon's crew to be 148 m from the CM. If the loaded Dragon mass is 2-3X that of the Falcon 9 spent second stage after venting of residual propellant, the total tether length needs to be 3-4X the Dragon-CM distance, or ~444-592m.

Dragon can coast until 25 minutes past perigee, to climb to 170 km before it separates from Falcon. This reduces aero heating and AO erosion of the tether. Then Dragon pitches up 60^o and thrusts directly away from Falcon at 1 m/s. The thrusters used must be located and oriented so their plume does not damage the tether. Seven minutes later, Dragon reaches 187 km altitude, the full tether length is deployed, and Dragon is nearly straight above Falcon and moving at the same inertial velocity. Stronger rip-stitching in the last few % of the tether paid out can slow deployment passively, to reduce any tendency to rebound.

The tension rise near the end of tether deployment also cues Dragon to start thrusting, to start a prograde spin. This uses thrusters at right angles to the tether, so impingement heating need not be an issue. Thrust might continue until Dragon is ~30^o forward of Falcon in an LVLH frame. If the thrusters used for this provide 1200 newtons thrust and Dragon weighs 9000 kg, the thrust lasts 65 seconds and provides an 8.7 m/s tangential ΔV to Dragon relative to Falcon. This gives a prograde inertial rotation rate of 67^o/minute (63^o/minute in an LVLH frame). This is similar to the 55^o/minute peak spin rate on Gemini 11, but it provides far higher gravity since the tether is 15X longer.

Five minutes after the first spin-up impulse ends, Dragon has rotated 300^o in the LVLH frame, and is again within 30^o of straight above Falcon. Hence it can again efficiently boost the center-of-mass orbit while spinning up the system. This time it will be within 30^o of local vertical above Falcon for less time since it is already moving forward. It might thrust during ~1/6 of each LVLH rotation thereafter. It is useful to split the spin-up impulses into at least two episodes, one or more orbits apart. One might provide 60% of the spin-up ΔV during the first orbit, during ~90^o of orbit centered on apogee. This plus the initial 1 m/s separation ΔV will raise the orbit of the tether system center of mass from 120 x 200 km to 210 km circular. The inertial spin rate is then 0.6 rpm. This is a useful spin rate to test, and it provides 0.06g of felt gravity inside Dragon. If this aids the crew's later accommodation to free-fall, it might be done routinely during some of the orbit phasing period on most later crew missions to ISS. Note that space shuttle crews experienced ~0.06g during OMS engine firings, but only for minutes, not hours or days.

Completing the spin-up during a later orbit increases the inertial rotation rate to 1 rpm, raises the felt gravity level to lunar gravity inside Dragon, and can boost the assembly's center of mass into a 230 km circular orbit. The crew can do any desired tests at this rotation and gravity level, for as long as desired during phasing toward ISS.

Dragon can end the test by releasing the tether whenever it is directly above Falcon. Then it always has all the orbital momentum added during spin-up. With the assumed 2:1 masses, release boosts Dragon from a 230 x 230 km orbit into a 230 x 281 km orbit, and drops Falcon and its attached tether into a very short-lived 125 x 230 km orbit. Any changes in mass ratio, spin ΔV, orbit altitude or eccentricity, or phasing at release will affect the final Falcon perigee altitude. Surprisingly, some cases with mass ratios >2:1 can even target deorbit of the spent stage. This is possible because tethers can change the booster's orbit shape, raising apogee and dropping perigee.

Mass penalties (tether, propellant, test supplies, etc.)

The easiest direct mass penalty to calculate is the tether itself. If Dragon weighs ~2X as much as Falcon after Falcon vents residual propellants, then the total required tether length is ~3X the desired Dragon radius of rotation. The tether needs a coating to protect against atomic oxygen, which can cause serious erosion of a polyethylene tether in days of exposure near ~230 km orbit altitude. The required tether strength is simply the Dragon mass during the test, times the planned peak centrifugal acceleration, times a suitable tether safety factor. In a test providing lunar gravity levels to the crew inside a 9000 kg Dragon, a 436m Spectra tether with a safety factor >5 may weigh only 20 kg. Stowage interfaces and structural attachments and release mechanisms will add to this.

With the above assumptions and spin-up by Dragon (unfortunately, the heavier end of the tethered pair), the propellant mass needed to spin up may be ~8X the tether mass. But if thrusting occurs only when Dragon is rotating forward, ***and*** the tether is later released at the same spin phase, then nearly all of the spin-up impulse also ends up boosting Dragon towards ISS altitude. If the spin is in the orbit plane, and thrusting is done during 1/6 of each spin, when Dragon is thrusting within 30^o of the best direction, then Dragon's boost cosine losses are only 4.5%. Then the ΔV penalty is only 2.1 m/s of the 46.5 m/s spin-up ΔV, plus 0.5 m/s of the initial 1 m/ ΔV that was pitched up 60^o. The propellant mass penalty may be only ~9 kg, less than half as large as a ~20 kg tether mass penalty.

If a longer tether is used to provide the same gravity level, the tether mass scales with length, but spin-up ΔV scales with Sqrt(Length). And if faster spin is used, for Mars rather than lunar gravity, tether tension and required mass scale with the desired gravity level, while the spin-up ΔV scales only with Sqrt(Gravity). Hence the main penalty in more ambitious tests seems likely to remain the tether itself, not the propellant mass penalty.

One must also consider reboost propellant due to the large area and low altitude. The average CdA of a ~0.05 x 436m twisted flat tether spinning in the orbit plane will be ~20 m^2. The CdA of the full assembly may be ~100 m^2. About 8 kg/day of propellant may be needed to stay at 230 km altitude, vs 2 kg/day for Dragon by itself at 230 km.

There is another category of mass penalty: supplies required to make partial-gravity tests useful. Food, water, and other crew-support supplies should not change as long as the partial-gravity test is completed in the time needed for orbit phasing on a specific mission. But if these tests appear useful enough, there may be interest in extending this period, so added supplies will be needed. In addition, each test may trigger interest in later tests, many of which may require dedicated test supplies, or crew exercise or monitoring equipment beyond what is normally carried. Advocates of each such test will have to justify the direct and indirect mass penalties their experiments impose.

Safety issues

A tape-like tether seems more likely to survive micrometeoroid or orbital debris impact than a round tether, and a ~230 km phasing altitude greatly reduces local debris populations. But any tether size or shape can be severed, and other unrelated failure modes can also trigger unplanned tether release. Such events can be made very unlikely but not entirely precluded. So one basic concept is to ensure that worst-case tether severances are at least survivable.

If a tether is severed or released under design load, it will recoil at ~50 m/s toward its attach point. System spin will make the “pileup point” accelerate away from the attach point, but some tether will hit Dragon and may foul on it. The remaining length may wrap around it, as the released Gemini 11 tether apparently wrapped and unwrapped around its Agena stage in slow motion. It may be feasible to “blow away” and possibly melt a recoiling flat tether, using Dragon’s RCS thrusters. If this does not work, one may have to cancel the planned visit to ISS.

High-strength oriented polyethylene fibers like Spectra and its European analog Dyneema have the highest usable strength/weight of any commercial fiber.

They also have a low melting point (147C), so an exposed flat tether should melt during reentry, even if exposed only to afterbody reentry heating. So it should be feasible for Dragon to reenter wrapped in a fouled tether, without that tether being able to prevent parachute deployment after reentry. This is critical, so it can be tested on an earlier Dragon mission by mounting short lengths of candidate tethers in suitable places.

A tether failure when Falcon is on top and moving forward can also sling Falcon and the attached length tether into a higher orbit. A 1 rpm spin with 444 m CM separation and 2:1 mass ratio can boost Falcon’s apogee by up to ~107 km. If the test is done in 230 km orbit, Falcon could reach 337 km. As long as ISS is safely above 337 km altitude, or some other altitude for other specific test cases, there need be no risk of the Falcon or its tether reaching ISS. This plus faster phasing, lower debris populations, and a possibility of passively targeting deorbit of the spent-stage counterweight in some cases are the main benefits of doing spinning-tether tests at the lowest practical altitude.

If tests that use longer tethers or faster spins can reach ISS, additional measures are needed to protect ISS. One measure may be to add a weak springy insert to the tether so it folds up on itself when nearly slack. This can reduce the effective dimensions of the Falcon +tether as a collision target. The combination of tether recoil and rotation will energetically wrap the tether around each endmass, allowing dissipation of the recoil energy. Another measure is to use a spin plane angled to the orbit plane, so a released Falcon is likely to oscillate through the ISS orbit plane (depending on when in the orbit the severance occurs), rather than necessarily remaining in the orbit plane. If there is enough orbit phase separation to provide enough lead time, and we have accurate orbit data from a GPS receiver on Falcon, ISS might also do a ~1 m/s contingency reboost to shift the timing of phase coincidence so Falcon is then above, below, or to one side of ISS. Choosing a launch date that requires a larger launch phasing angle when the launch site passes through the ISS orbit plane can provide additional lead time for such measures. But again, such measures are needed only for missions in which the highest thrown-stage apogee cannot be kept safely below ISS.

There will clearly be additional safety issues and other complications to this test concept, but the ones discussed above seem likely to be the most serious ones directly tied to the use of a tether. And they can probably be avoided by using a low-melting-point tether and keeping the worst-case stage apogee well below ISS altitude.

Appendix C: Moon-then-Mars LEO Tests

I am drafting this appendix the day before the 2019 IAC paper submission deadline. It suggests an obvious option for early partial-gravity testing, but did not occur to me until Jim Logan suggested that the first partial-gravity crew tests might best be done at Mars gravity.

The rationale is that if the human health problems seen in microgravity persist even at Mars gravity, that plus the implications of Figure 1 in this paper will force serious changes in any attempts at realistic visions for human expansion beyond earth. Humans will be able to explore low-gravity places. But if we cannot easily live on them, interest in exploring such places may decrease. Our plans may focus on O'Neill-type rotating colonies.

An attractive early path to such colonies is rotating facilities in near-equatorial low earth orbit. Papers by Al Globus since 2016 have evolved this concept [3].

A key feature of equatorial LEO ("ELEO") is that total ionizing radiation doses from cosmic rays, trapped radiation, and neutron albedo are far lower than nearly any other exposed place in the solar system. Colonies may not need dedicated shielding. Equivalent whole-body doses predicted by OLTARIS [27] are below. The cases are for a year starting on September 18, 2015, with total shielding by 1cm of aluminum-lithium +10cm of water:

Table C-1. Total 1-Year mSieverts at 400 km

Orbit Inclin.	Total Dose	GCR dose	Trapped + albedo
1.0°	16	15	1
10.0°	17	15	1
15.0°	25	16	9
20.0°	47	18	29
28.5°	82	23	59
40.0°	70	38	32
51.6°	94	65	29
80.0°	131	109	22

Even less shielding seems workable, because GCR doses vary more slowly with shielding changes than other doses. ISS crews get a total dose in 1 year that should take 5.5 years to get in ELEO <10°.

Doses in early crew tests <1 year should not be a problem in ISS-like orbit. Reduced shielding would increase doses less at 51.6° than 28.5°, at the cost of ~5% lower launch payload from the higher inclinantion.

I assume an ISS-like orbit below. The best orbit for ISS safety may be in-train with ISS, but phased far from it. Any debris created should be unable to damage ISS. Ground stations can handle another facility passing ~45 minutes before and after ISS during the same general time of day. In addition, crew launch options and scenarios including recovery after a launch abort or facility problem have already been worked out for ISS orbit. That should reduce planning costs. The basic concept is shown in Figure C-1, and described below:

Possible scenario

1. Launch ~45 ton facility near ISS, on Falcon Heavy.
2. Then crew launches and docks, but does not enter.
3. Falcon Heavy stage 2 leaves & pays out 2 km tether.
4. Stage starts spin-up, which peels taped bridles loose.
5. After both bridles deploy, crew enters the facility.
6. Stage does 225 m/s ΔV, for Moon gravity at 1 rpm.
7. Later, 115 m/s more ΔV gives Mars gravity at 1.5 rpm.
8. Months later, cut bridle to target stage+tether reentry.
9. Crew secures facility, leaves, & reenters.

Key questions include:

1. Can high-temp bridles stay taped to rocket to orbit?
2. Will bridles reliably peel off early in the spin-up?
3. How long can 7 crew live in a 45-ton 200m^3 facility?
4. Are 1-1.5 rpm low enough in Moon & Mars gravity?
5. How should we berth more modules, for later tests?

I agree with Logan that a Mars test is more critical. But it is easy to add time at Moon gravity as well. Trips to Mars will take months, and can provide any desired gravity level, free fall or artificial. Time spent at Moon gravity can extend our 1-3 day Apollo data and will be useful on its own. It may also allow any asymptotes of Mars gravity effects to occur earlier in a crew test, by speeding up low-gravity effects. It may also complicate analysis, but time at Moon gravity may have substantial overall net benefit. The best time to decide when to shift from Moon to Mars gravity may be well into a mission.

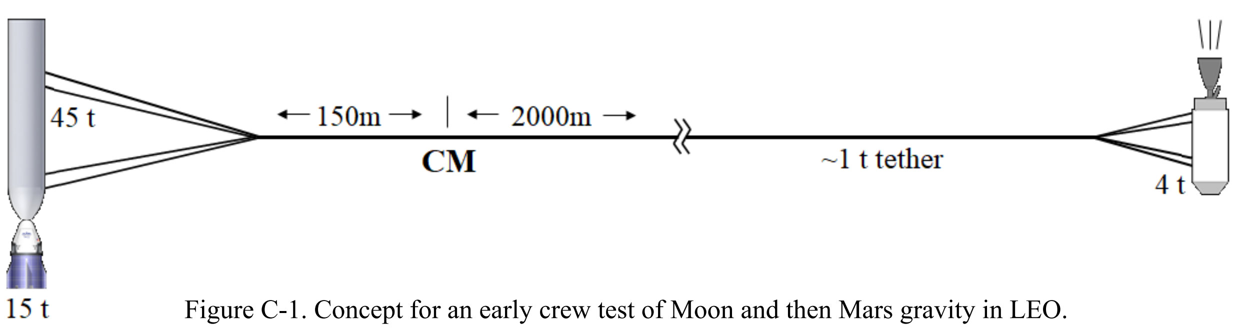

Figure C-1. Concept for an early crew test of Moon and then Mars gravity in LEO.

Appendix D: Artificial Gravity in Crew Exploration Vehicles

Below I show a way to affordably provide partial artificial gravity for a generic crew exploration vehicle. I end by listing key questions relating to this concept that might be addressed by crew tests in LEO.

Appendices B and C in this paper describe rotating-tether test on Gemini 11, and more ambitious tests that might be done on future crewed missions in LEO, using a spent booster stage as counterweight. The same idea can also be used on any long-duration crew exploration mission, if the mission scenario involves a staging event after boosting from low earth orbit to escape. Using a spent stage as counterweight lets all critical equipment stay at the crew end, so if the tether fails for any reason, it affects only the gravity level. It does not directly impact crew survival. In addition, if the tether does fail and releases the counterweight, the lower total system mass makes more propellant available to adjust spin plane, so the still spinning vehicle can keep its fixed solar arrays facing the sun.

Below I estimate crew exploration vehicle mass penalties resulting from this way of providing gravity for the crew, first for a specific case, and then more generally. The specific case assumes Mars gravity level, a 1 rpm spin, and a spent stage 10% as massive as the crew vehicle. This requires a 3.3 km long tether. With a decent safety factor, a multi-strand tether might be ~3% as massive as the crew vehicle. The tether and spent stage can be cut loose before capture into Mars orbit, or retained during the Mars orbit capture and departure maneuvers, as shown in Figure D-1 below.

Thrusting normal to the spin plane makes the "flat spin" conical, as shown at right. A spin that provides Mars gravity in the crew vehicle provides 3.3g at the light counterweight. This allows adequate maneuver thrust at the crew end without much coning. This can minimize gravity ΔV losses incurred while entering and leaving Mars orbit. A large solar array can hang from the crew vehicle, and a smaller one from the spent stage.

Rather than having solar arrays actively track the sun, they can be fixed and the spin plane slowly torqued using ion thrusters on the spent stage. If the I_{sp} is 2500 seconds, the required propellant mass is only 1.1% of the crew vehicle mass per solar orbit. A spin plane nearly normal to the sun direction is also suitable for Mars orbit capture and departure maneuvers as shown in Figure 3, and can ease thermal design (especially for cold "space-storable" propellants like LO_2/CH_4), since the same sides of the crew vehicle always face toward and away from the sun.

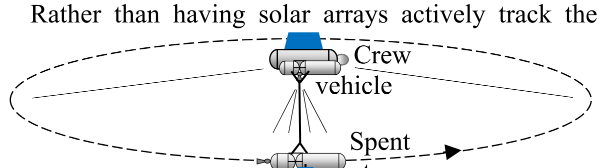

Figure D-1. Thrust with spent stage & fixed solar arrays

Spin-up requires a 350 m/s ΔV at one end. It takes far less propellant to do it at the low-mass spent stage end. One might use evaporated residuals and pressurant in the spent stage to provide some spin quickly, to ease deployment and control of the solar arrays. If half of the spin-up is done at a "blowdown I_{sp}" of 260 seconds, the spin-up propellant mass is 0.8% of crew vehicle mass. The ion thrusters can provide the rest of the ΔV to raise vehicle gravity to Mars level over the next week or two, at a propellant mass of 0.1% of crew vehicle mass.

Capture into an elliptical Mars orbit requires an 800 m/s high-thrust ΔV directed roughly sunward. Using a highly elliptical Mars orbit eases thermal design by reducing heat soak into cold propellant. An 800 m/s ΔV at 350 second I_{sp} uses a LO_2/CH_4 mass of 26% of the post-burn mass. Keeping the stage plus tether through this maneuver adds 13% to system mass and required propellant mass. Also taking the stage and tether back to earth at the end of the stay costs 26% more, since the departure propellant is there through the capture ΔV.

As a first approximation, relative to the crew vehicle mass on the way to Mars, the added mass needed to provide Mars gravity onboard is 3% for the tether, plus 0.9% for spin-up (partly stage residuals), 3.4% during capture into Mars orbit, and another 4.3% to leave Mars orbit. This is 11.6% of crew vehicle mass.

One must also add 1.1% of crew vehicle mass per solar orbit, to keep the spin plane normal to the sun. But spin plus spin plane tracking allow use of simple fixed hanging solar arrays, which should be both lighter and more reliable than rigid arrays that tolerate Mars orbit capture and departure deltaVs. Accurately identifying and assessing all indirect penalties and benefits requires a far more detailed trade study. The many effects of this approach on system mass, affordable power levels, and reliability all merit inclusion in such a study.

On the way home, the crew vehicle should be much lighter than on the way to Mars. Even with age-based derating of allowed tether tension, the crew might have higher gravity than Mars on the way home, if desired.

Discarding the tether and stage before capture into Mars orbit saves 7.7% in propellant mass. But that eliminates benefits of on-board Mars gravity thereafter, and complicates high-thrust maneuvers with a large attached "hanging" solar array. (The array will actually cause a small acceleration in the crew vehicle, in the direction opposite to that previously provided by tether tension.) And if one wants gravity on the trip home, a new tether and counterweight are needed. So there are benefits to retaining the original tether and spent stage throughout the full mission.

If one doubles the allowable spin-rate to 2 rpm, that cuts the required tether length and mass by 72% and spin-up and spin plane control needs by 53%. But it saves less on propellant to retain the stage and tether through Mars orbit capture and departure, since that is driven more by spent stage counterweight mass than tether mass. The result is a 7.7% penalty plus 0.5% per solar year for spin plane tracking. So a 2 rpm vs 1 rpm spin saves about 3.9% plus 0.6% per solar orbit. Modest changes in the ratio of spent stage to crew vehicle mass scale the tether mass roughly inversely with stage mass. Propellant mass requirements nearly scale with stage plus tether mass, divided by propellant I_{sp}.

A rotating exploration vehicle can also serve near a NEO. This lets the crew live with gravity but explore a NEO in near-microgravity. If each "commute" from partial gravity to free fall EVAs causes accommodation problems, then a NEO exploration vehicle might also use a 338 m pressurized radial tunnel to a hub at the CM, as in Figure 2. Then crew members might stay in free fall between EVAs, but could do a "shirtsleeve" transition to partial gravity whenever desired.

The partial-gravity facility versions shown in Figure 2, and even the precursor tests in Appendices B and C, allow useful early tests of spin rate and gravity level effects on people and equipment, and tether design and operation tests. Precursor test tethers might be stowed as "stitched-down seatbelts," as on Gemini 11 and 12. To avoid complicating launch aborts, the crew vehicle can make with the tether interface on its spent stage, much as Apollo vehicles mated with their lunar modules.

The above concept can be compared with a NASA design described by Joosten [28]. It used nuclear electric propulsion. It used the reactor and its shielding as counterweight. That study baselined 4 rpm spin and full earth gravity.

More generally, Ted Hall's website is a very useful repository of papers and links on artificial gravity. Designs like that above or on Hall's website raise many questions. Some key ones are listed below. They are discussed in ref. [29]:

- Should we provide artificial gravity (how much?) while crews travel to/ from Mars or NEOs?
- What spin rates and vehicle architectures may be suitable during such multi-month cruises?
- Can crews easily adapt to frequent free-fall EVAs on NEOs, if they live in a nearby spinning facility?
- What countermeasures may still be needed if we use much less than full earth gravity?

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