# Space Settlement the Easy Way

The first one is the hardest, so

make it close
make it small
build up to it incrementally

Al Globus, San Jose State University
Stephen Covey, DSI

# The Short Story

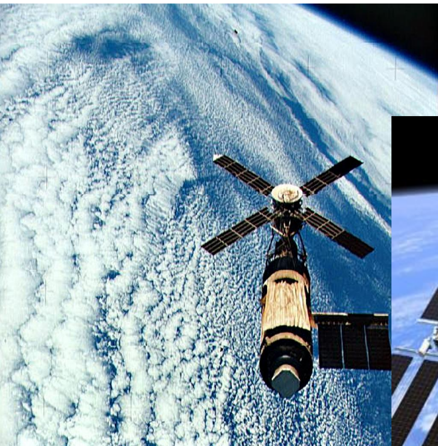
- Mother Earth has given us a small slice of space with little radiation. Equatorial LEO.
- Evolution has given us rotational tolerance, at least to 4-6 rpm, meaning 50-100 m diameter.
- This is hundreds of times closer and vastly less massive than we've thought the first settlements must be.
- Civilization has given us a tourism industry to pay for incrementally larger and larger space hotels.
- Caveat: this is preliminary! Verification necessary.

# What is a ‘space settlement’?

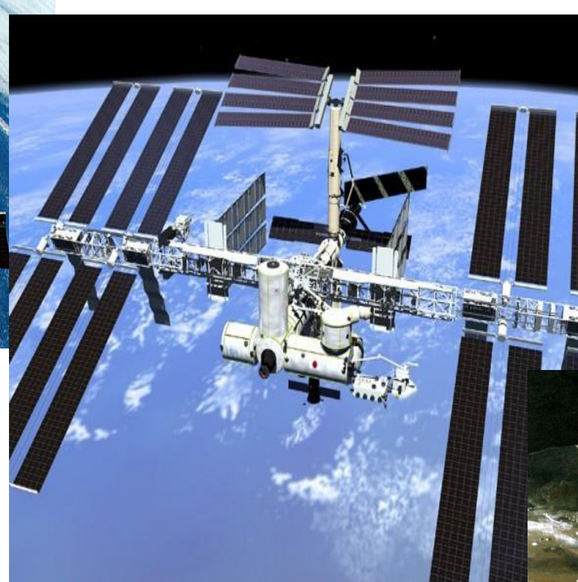
You go to a space station to work
You go to a space hotel to play
You go to a space settlement to live*

*and raise your kids

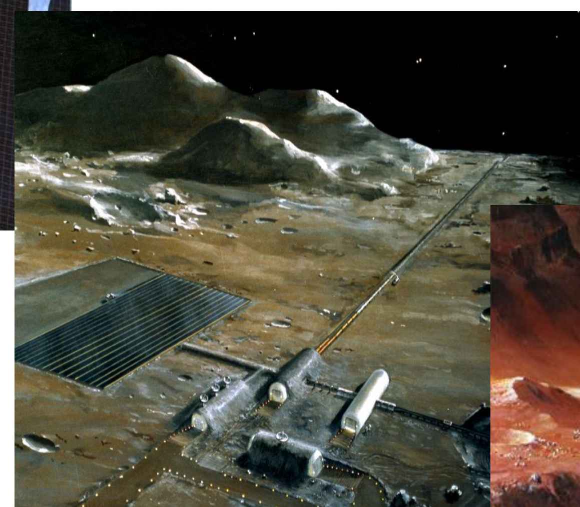
# Free-space vs Moon/Mars: Consider Bases



Skylab
1970s



ISS
now



Lunar base
2020s?

Martian base
??????

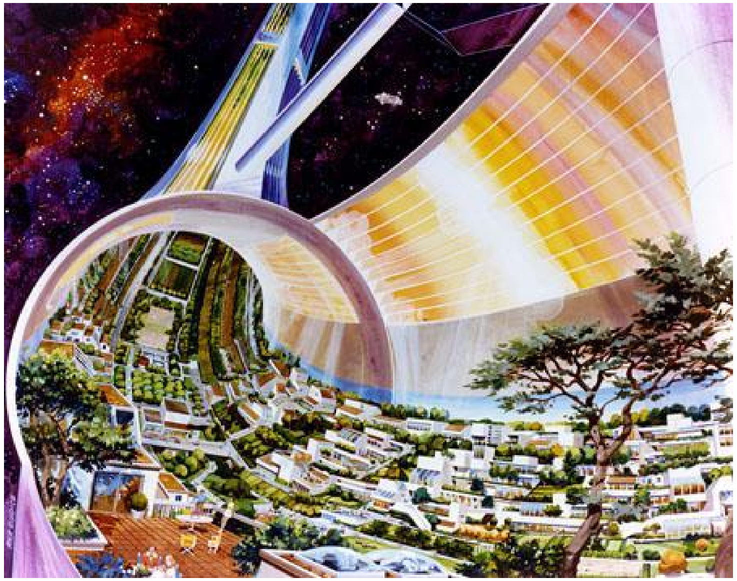
# Better for raising kids

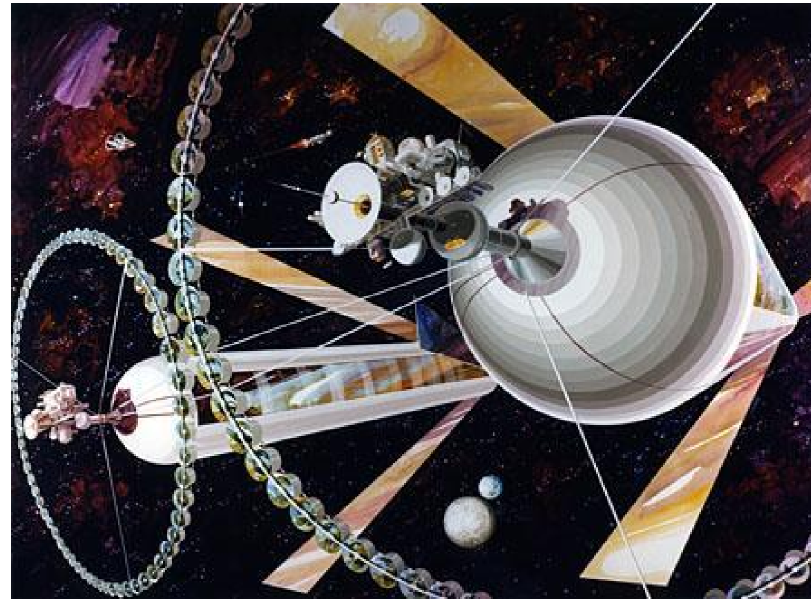
Killer trade: kids raised on the Moon or Mars grow up weak.  Kids raised in free space will experience 1g artificial gravity via rotation and grow up strong.

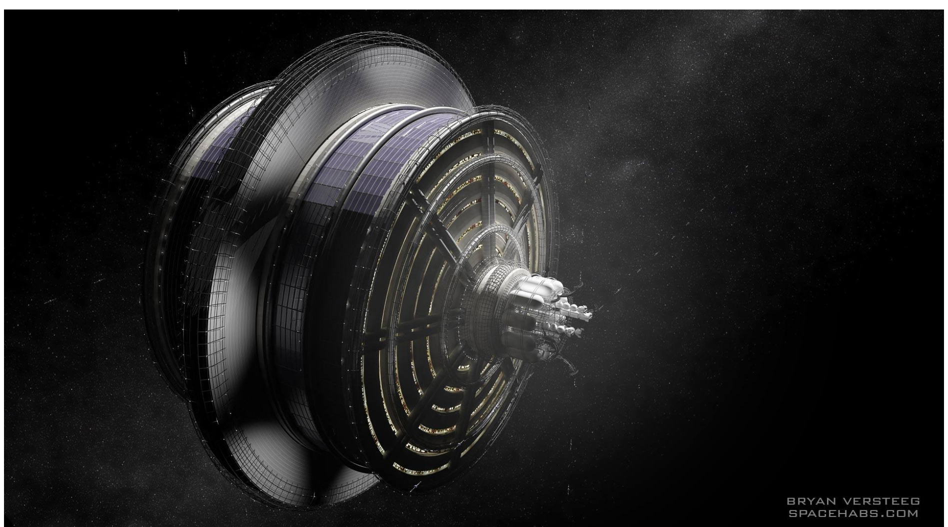
Other advantages:

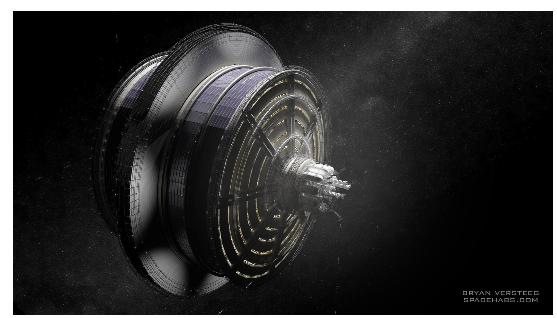
- Great views of Earth
- Rapid resupply
- Service Earth markets
- Reliable abundant solar energy
- Weightless recreation
- Easier construction
- Much greater growth potential

# Early Settlement Designs








Shrink to 50-100 m diameter and place in LEO!

# Rotate Faster to Reduce Size

- To get 1g, radius scales as inverse square of rotation rate
- Structural mass scales as cube of radius
  - Surface by square
  - Pressure shell stress linearly
- Atmosphere scales as cube of radius
- Furnishings scale as square
- 2 -> 4 rpm reduces mass by 16-64 x

# Negative Effects of Rotation

- Motion sickness
    - fatigue
    - stomach awareness
    - nausea
    - vomiting
- Inaccurate limb motion
- Difficulty in throwing accurately

# Space Settlement Rotation Rate

- Recommendations
  - Up to 2 rpm should be no problem for residents and require little adaptation by visitors.
  - Up to 4 rpm should be no problem for residents but will require some training and/or a few hours to perhaps a day of adaptation by visitors.
  - Up to 6 rpm is unlikely to be a problem for residents but may require extensive visitor training and/or adaptation (multiple days). Some particularly susceptible individuals may have a great deal of difficulty.
- “Space Settlement Population Rotation Tolerance,” Al Globus and Theodore Hall survey paper in development

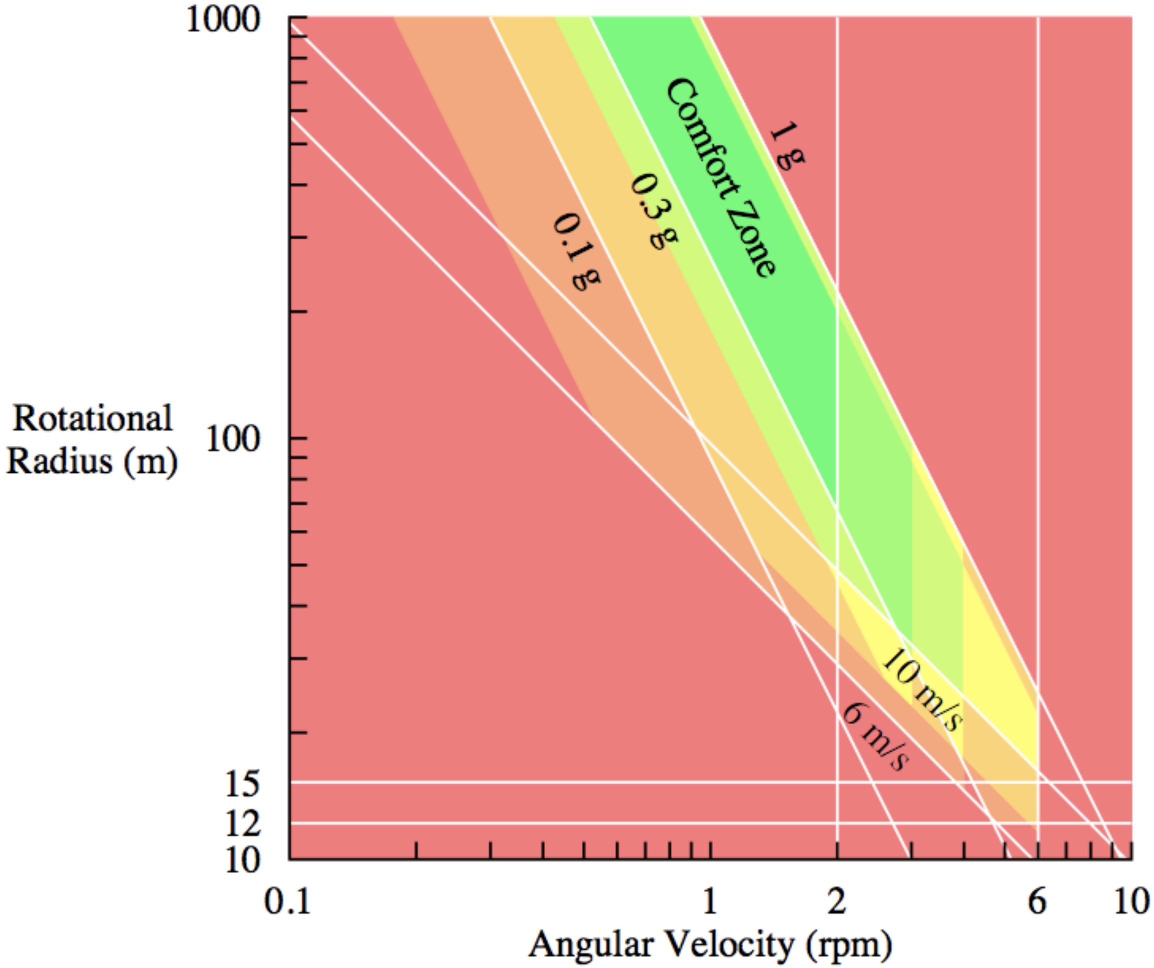
| Rate (rpm) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Radius (m) | 895 | 224 | 100 | 56 | 36 | 25 | 19 | 14 | 11 | 9 |

# Graybiel's Rotation Room

"In brief, at 1.0 rpm even highly susceptible subjects were symptom-free, or nearly so. At 3.0 rpm subjects experienced symptoms but were not significantly handicapped. At 5.4 rpm, only subjects with low susceptibility performed well and by the second day were almost free from symptoms. At 10 rpm, however, adaptation presented a challenging but interesting problem. Even pilots without a history of air sickness did not fully adapt in a period of twelve days."

Pensacola Slow Rotation Room at the Naval Aerospace Medical Research Laboratory (Pensacola, Florida). 4.57 m (15 ft) diameter, 2.1 m (7 ft) high, could rotate within 2.5% of any desired speed up to 10 rpm

# Summary of Rotation Tolerance Synthesis



# Rotation Rate Caveats

The studies

- have very few subjects, usually 10 or less.
- show great variability in rotation tolerance from person to person.
- sometimes chose subjects for higher than normal rotation tolerance.
- have only adult subjects.
- are only a few weeks or less in duration.
- use rotational experiment environments with very short radii of rotation, typically under 4 m (there is one exception). This means the effects observed in these experiments are likely much more severe than in a settlement as most effects attenuate with larger radii.
- are almost all on the surface of the Earth and there is evidence that the negative effects of rotation are much less in an otherwise weightless environment.

# Radiation Shielding in Free Space

| | polyethylene | | water | | lunar regolith | |
|---|---|---|---|---|---|---|
| tons/m$^2$ | mSv/yr | mGy/yr | mSv/yr | mGy/yr | mSv/yr | mGy/yr |
| 1 | 193 | 85 | 199 | 86 | 274 | 109 |
| 2 | 136 | 52 | 146 | 54 | 261 | 82 |
| 3 | 90 | 31 | 100 | 34 | 221 | 62 |
| 4 | 57 | 18.5 | 66 | 21 | 172 | 48 |
| 5 | 35 | 10.8 | 42 | 12.5 | 126 | 37 |
| 6 | 20.9 | 6.3 | 26.3 | 7.5 | 89 | 28 |
| 7 | 12.2 | 3.6 | 16 | 4.4 | 61 | 20.9 |
| 8 | | | | | 40 | 15.1 |
| 9 | | | | | 26.1 | 10.5 |
| 10 | | | | | 16.6 | 7.1 |

Threshold 20 mSv/yr for the general population and 6.6 mGy/year for pregnant women. Data from OLTARIS calculations

# Equatorial LEO Radiation Shielding

| shielding | 500 km | | 600 km | |
|---|---|---|---|---|
| tons/m$^2$ | mSv/yr | mGy/yr | mSv/yr | mGy/yr |
| ~0 | 16.7 | 1.02 | 23.4 | 1,559 |
| 0.01 | 16.3 | 3.6 | 21.7 | 101 |
| 0.025 | 15.6 | 3.7 | 19.8 | 50.6 |
| 0.05 | 14.6 | 3.9 | 17.5 | 21.8 |
| 0.075 | 13.9 | 4 | 16.1 | 12.5 |
| 0.1 | 13.3 | 4 | 15 | 8.9 |

With 20 mSv/yr for the general population and 6.6 mGy/year for pregnant women limits mean space settlements in equatorial LEO may not require any shielding.

"Orbital Space Settlement Radiation Shielding," Al Globus and Joe Strout, May 2015.

# Shielding Mass from 1975 Study

| Mass model based on 1975 study | | | mass tons | |
|---|---|---|---|---|
| name | struct mass | air mass | shielding mass | total/non-shielding |
| multiple dumbbells | 75,000 | 37,000 | 9,900,000 | 89 |
| multiple torus | 100,000 | 10,400 | 9,700,000 | 89 |
| banded torus | 112,000 | 13,200 | 7,000,000 | 57 |
| single torus | 4,600 | 1,900 | 1,000,000 | 155 |
| cylinder | 775,000 | 299,000 | 19,400,000 | 19 |
| sphere | 64,600 | 35,200 | 3,300,000 | 34 |
| dumbbell | 400 | 200 | 1,400,000 | 2,334 |

NOTE: mass model does not include internal furnishings, solar arrays, and many other items that are not significant compared to shielding mass, but are important if no shielding is required.

# Much Smaller and Closer

- 16 x 19 = 304 x less mass LEO vs L5
  - 16 x minimum reduction faster rotation
  - 19 x minimum reduction no shielding
- 760 x closer in km (LEO vs L5)
- Implications
  - Launch from Earth!
  - Extraterrestrial mines not on critical path

# Kalpana One Mass Reduction

## Stephen Covey

| Measure | Kalpana One | | |
|---|---|---|---|
| rotation (rpm) | 2 | 4 | 6 |
| radius (m) | 224 | 56 | 25 |
| Hull (kT) | 194 | 3.8 | 0.5 |
| Internal Struct (kT) | 65 | 3.8 | 0.8 |
| Shield (kT) | 4,026 | 0 | 0 |
| Non-struct (kt) | 23 | 1.4 | 0.3 |
| Air (kt) | 42 | 0.66 | 0.06 |
| Total Mass (kT) | 4,351 | 9.6 | 1.6 |
| Mass ratio | 1 | 197 | 2,812 |

## Joe Strout

| Measure | Kalpana One | | |
|---|---|---|---|
| Rotation (RPM) | 2 | 4 | 6 |
| Shielding ($t/m^2$) | 6 | 0 | 0 |
| Radius (m) | 224 | 56 | 25 |
| Length (m) | 325 | 77 | 35 |
| Hull (kT) | 5,450 | 11.5 | 1 |
| Radiators (kT) | 39.1 | 6.7 | 0.9 |
| Air (kT) | 50.2 | 0.7 | 0.07 |
| Total Mass (kT) | 5,539.3 | 19 | 2 |
| Mass ratio | 1 | 292 | 2,717 |

# Stanford Torus Mass Reduction

## Stephen Covey

| Measure | | | |
|---|---|---|---|
| rotation (rpm) | 1 | 4 | 6 |
| outer radius (m) | 895 | 56 | 25 |
| tube radius (m) | 65 | 7 | 4 |
| Hull (kT) | 14.5 | 0.1 | 0.03 |
| Internal Struct (kT) | 102 | 0.7 | 0.2 |
| Shield (kT) | 12,727 | 0 | 0 |
| Non-struct (kt) | 74 | 0.5 | 0.1 |
| Air (kt) | 88 | 0.07 | 0.01 |
| Total Mass (kT) | 13,196 | 1.43 | 0.35 |
| Mass ratio | 1 | 9,245 | 38,208 |

## Joe Strout

| Measure | | | |
|---|---|---|---|
| Rotation (RPM) | **1** | **4** | **6** |
| Shielding (t/$m^2$ ) | **6** | **0** | **0** |
| Major Radius (m) | 900 | 49 | 21.5 |
| Minor Radius (m) | 65 | 7 | 4 |
| Hub Radius (m) | 100 | 10 | 5 |
| Spoke Radius (m) | 10 | 3 | 3 |
| Spokes | 6 | 4 | 2 |
| Hull (kT) | 14,500 | 0.435 | 0.062 |
| Air (kT) | 81.1 | 0.051 | 0.007 |
| Total Mass (kT) | 14,581 | 0.486 | 0.070 |
| Mass ratio | 1 | 30,002 | 209,408 |

# Killer App: Tourism

- Currently a sellers market
  - $50 million for 7-10 days at ISS
    - Learn Russian, months at Star City
    - Waiting list
  - $95-250 thousand for five minutes in space
    - Hundreds paid deposit

| price/ticket (1994 $) | passengers/year |
|---|---|
| 1,000 | 20 million |
| 10,000 | 5 million |
| 100,000 | 400 thousand |
| 250,000 | 1,000 |
| 500,000 | 170 |

Crouch, G. I., "Researching the Space Tourism Market," Presented at the annual Conference of the Travel and Tourism Research Association, June 2001

# From ISS to First Settlement

- ISS longest dimension almost 4 rpm diameter (112m)
- Bigelow inflatable space station in development
  - Target market: national space programs
- NSS policy: replace ISS with multiple privately owned, commercially operated stations with NASA help and anchor tenant
- A hotel is simpler than a station
  - NSS policy: allow Commercial Crew to fly tourists
- In time, hotels may rival size of 4-6 rpm settlement!
  - Must develop efficient life support
  - For high end, must grow food
- Rotate reinforced design to get settlement artificial

# Future Work

- Verify
  - Archived data, mission to measure radiation in 450-650 km equatorial orbit
  - Program to assess radiation on tissue
    - ISS
    - Dedicated facility in correct orbit
  - Program to verify rotation findings
- Construction and maintenance techniques
- Promote Space Tourism
- Promote CATS (Cheap Access to Space)
  - 10-100 x reduction in launch cost
  - ASD: $3.5 billion prize for RLV
- Clean up LEO debris

# Conclusion

- Development of the first space settlements may be radically easier than the 1970s studies suggest by
  - Placing them in equatorial LEO
    - Eliminates radiation shielding
  - Rotating at 4-6 rpm to make them smaller
  - Building incrementally larger space stations and hotels starting with the ISS
- This approach
  - Mass reduced by two orders of magnitude
  - Distance from Earth reduced by 760 x
  - Extraterrestrial mining not necessary
  - Technology and infrastructure developed incrementally driven by tourist paid profit

Ad Astra Baby!