How to inhabit the Solar System

Pekka Janhunen(*)
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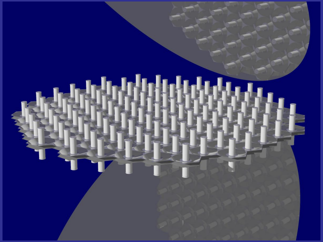

(*)Finnish Meteorological Institute
Also at Aurora Propulsion Technologies

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Hannes Alfvén's legacy in our context

Acceleration of charged particles:

- Electric rockets
  - Hall effect thrusters – the workhorse
  - Gridded ion engines – higher specific impulse but more complex
- Electric solar wind sail – efficient but doesn't scale to crewed missions
- Galactic cosmic radiation
  - High energy particles, only metres-thick shields can stop them
  - More than 6–12 months lifetime exposure to them is risky
  - Major effect on human space travel and space habitats
  - This is how the electromagnetic universe affects us

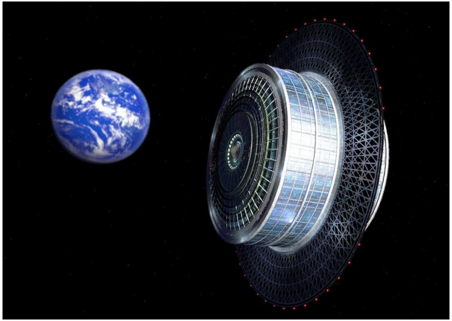
Life spreads

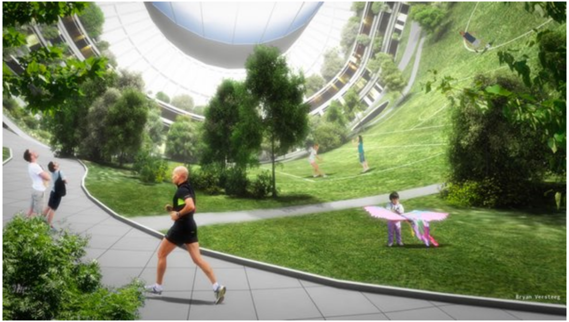
- Life spreads – it is its basic property
- Every place is already taken, so some individuals settle unusual environments
- Life would spread also outside Earth, if it could
- Other species cannot do it, but we might

Mars?

- Children in Mars would grow in $0.38\,g$ gravity
- Muscles and bones would probably not develop normally
- Could they choose to move to Earth as adults? Would their body be fit to it?
- If not, would they and their offspring be effectively prisoners of Mars?

Unplanetary living in free-space habitats





- Gerard O'Neill (1974): rotating cylindrical habitat (artificial gravity)
- We can select it to be $1\ g$
- The cylinder has a maximum radius (wall tensile strength restriction), so sooner or later one needs more than one of them
- How to travel between them? Rocket propellant is a non-renewable resource
- Orbital dynamics tends to spread the fleet

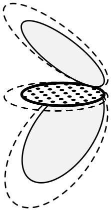
Requirements of a good living environment

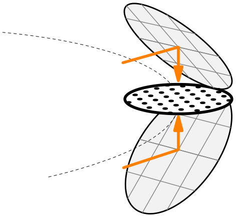
- Earthlike ...
  - Cosmic radiation shielding that corresponds to Earth's atmosphere ($\sim$ 10 ton/m^2)
  - Normal nitrogen-oxygen atmosphere
  - Normal gravity ($1\ g$)
  - 24-hour diurnal cycle, $\sim$130 W/m^2 insolation (like e.g. in southern Germany)
  - Healthy and tasty food from agriculture
  - Plants, trees, parks, insects, birds, mammals, mushrooms
  - Population density not too high, e.g. 500 persons/km^2 like in the Netherlands
  - Socially stimulating environment, large enough population
  - Travel possible and easy between any points A and B
  - Safe, redundant, modular and fixable technical systems
- ... and potentially better than Earth
  - No natural catastrophes
  - Potentially eventually larger living area than Earth
- Long-term sustainable
  - All atoms circulate
    - No daily rocket propulsion, because propellant molecules cannot be circulated

Meeting the requirements

Proposed solution:

- Attach rotating cylinders to a rigid frame (the **megasatellite**)
  - The frame is lightweight, because it is in microgravity
  - Use magnetic bearings to avoid physical wear
    - *Inductrack* -type magnetic bearings are passively safe
- Geometry that enables **self-similar growth**
- Collect sunlight by mirrors





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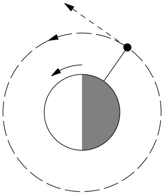
Prefer Ceres as the material source

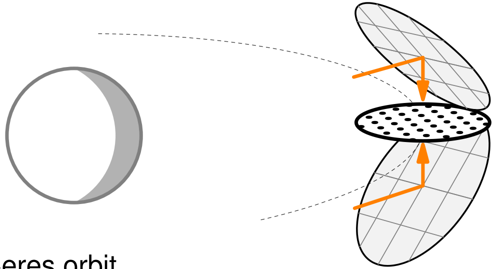
Dwarf planet Ceres: diameter 940 km, largest body of the asteroid main belt

- Ceres has **nitrogen**
  - N_2 is a necessary ingredient of habitat atmosphere
  - (One could also use a large carbonaceous asteroid, but sufficiently large ones with sufficiently circular orbit are as far as Ceres, and probably have less nitrogen)
- The habitat orbits Ceres
  - The habitat remains in vicinity of Ceres, the source body
  - High circulat orbit (e.g. 50,000 km) minimises tidal forces
- Space elevator is one economical way to lift material from Ceres
  - Besides low gravity, fast spin also helps (9-hour rotation period)
  - Elevator cable length 1024 km
  - Tensile strength requirement of the cable is not very high
  - Only 54 kJ/kg of electric energy used in lifting
  - One needs also a small 30 m/s kick to enter the circular orbit



- A sling would also work, and of course rockets
  - Ceres has plenty of volatiles for making rocket propellant

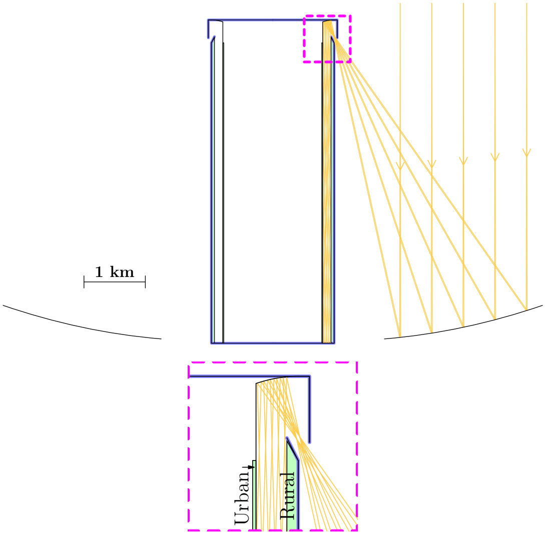
Growing megasatellite in Ceres orbit

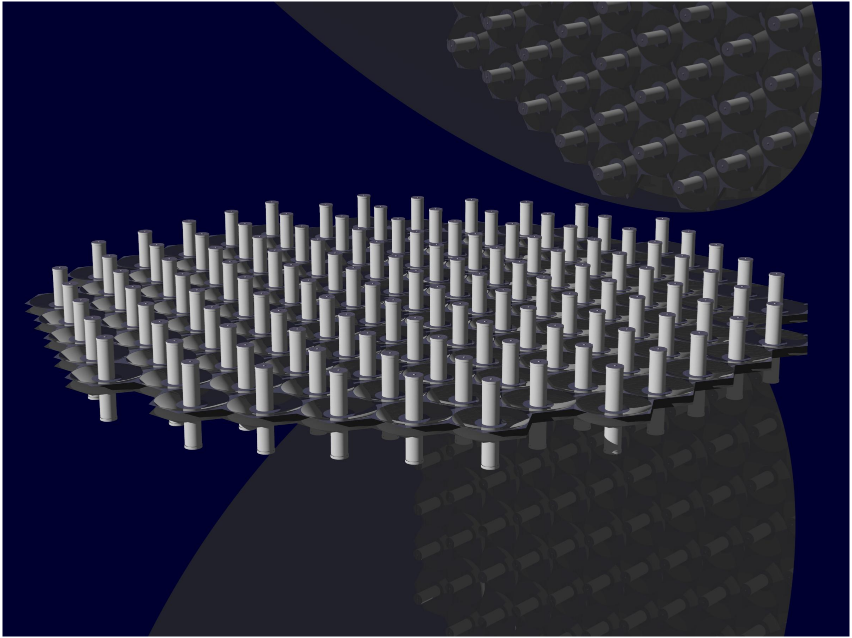


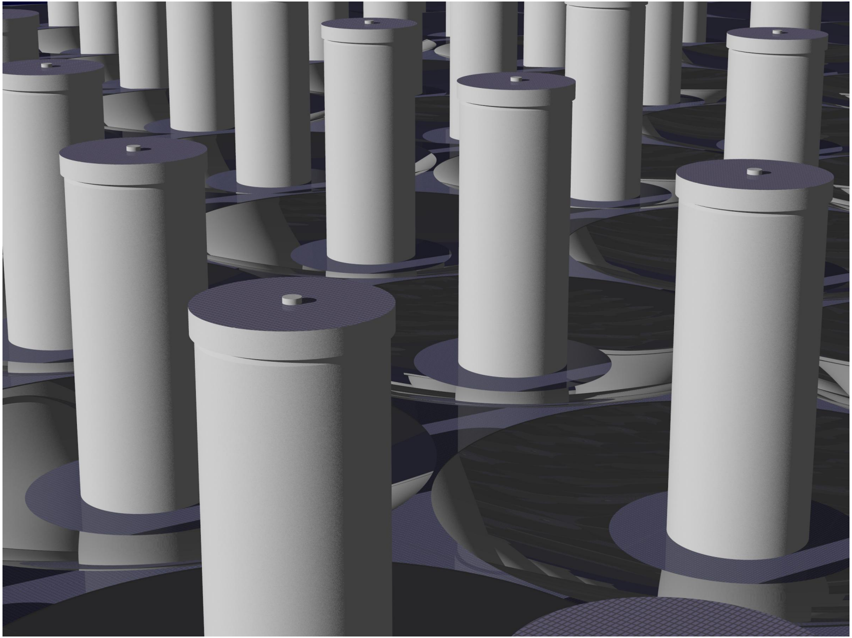
- Disk-shaped megasatellite in equatorial Ceres orbit
- Rotating cylindrical habitats attached to both sides of the disk
- Mirrors angled by 45$^{\mathrm{o}}$ collect sunlight
- No reaction wheels needed for attitude control
  - Tidal torque vanishes to leading order if mass distribution is symmetric
  - The heliocentric orbit of Ceres is elliptic which causes $\pm 8.7^{\mathrm{o}}$ libration, can be handled by tilting the elements of the mosaic mirrors
- Like any city, grows at the edges, the mirrors are extended correspondingly

Natural lighting

- Cylinder radius 1 km, length 5 km
- Parabolic main and auxiliary mirrors produce parallel light in light channel
  - Light channel width 137 m comes from the apparent angular diameter of the Sun
- 50 m high rural space,
  1100 m^2/person,
  1.5 m soil upgradable to 4 m
- 15 m high LED-lit urban space,
  900 m^2/person, in $0.81\,g$ gravity

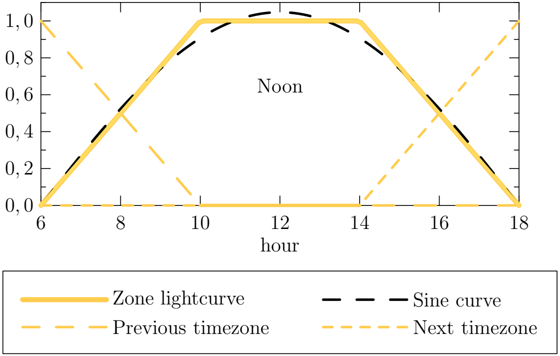


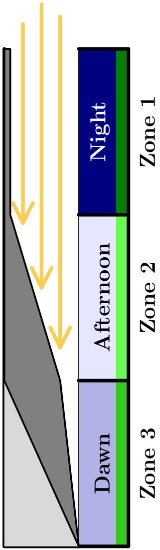




Diurnal cycle

- 3 timezones, ± 8 h time differences
- Light channel ceiling can be inclined
- Light sum over the timezones is constant, so all sunlight is utilised

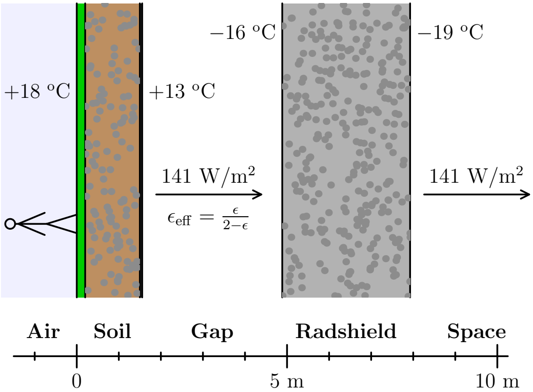




Thermal design

- Vacuum gap between rotating soil and non-rotating radiation shield
- Inside soil, heat is transferred by fluid circulation or heat pipes
- And also in the radiation shield, e.g. ammonia loop

- Even at Ceres distance, cooling is a bigger issue than heating!



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Travel inside megasatellite

Travel must be easy. To be sustainable, it cannot use rocket propellant.

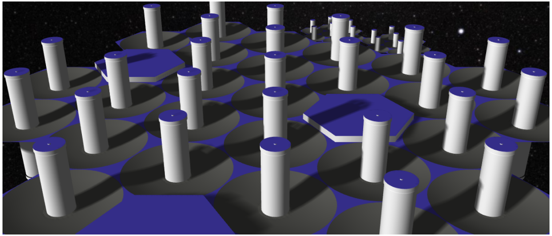
- If microgravity exposure during trip is OK, things are straightforward:
  - Buses move in tunnels in microgravity
  - Boarding is at cylinder axis, in microgravity
- If one wants to avoid microgravity during the trip, it gets harder:
  - People enter the bus at cylinder surface, the tunnel is tangential to it
  - At the right moment the bus drives into the tunnel (a critical manoeuvre)
  - The tunnel is curved or/and the bus accelerates to get triptime artificial gravity
- The tunnels can be vacuum, air-filled or e.g. 0.15 bar pure oxygen
  - Depends on many things, including abundance of nitrogen on Ceres
- Should have redundant traffic networks
- Maybe no thick radiation shielding of the tunnels, because people spend relatively short time travelling
  - Although even full protection would not overwhelm the mass budget

Internal redundancy, maintenance, servicing and rebuilding

- Each cylinder is a closed ecosystem, or it might be sectioned into several
- Inter-cyl exchange of gases and materials is possible by the traffic network
- A cylinder probably has finite (but long) lifetime due to corrosion
- For maintenance or rebuilding, a cylinder's rotation can be stopped

- The cylinders don't have to be identical in size and shape
- There can be non-rotating microgravity industrial facilities among them
- The cylinders don't have to be placed in a regular grid

The megasat is like New York City, and the cylinders are its skyscrapers



https://www.electric-sailing.fi/ceres

Megasatellite mass budget

Assumption: 2000 m^2/person (rural+urban)

Rad-shielding walls	$\sim$ Ceres material	6712 t/person	69 %
Soil and biosphere	$\sim$ Ceres material	2482 t/person	25 %
Tensile structures	Music wire (Fe)	484 t/person	5 %
Air	N_2, O_2	97 t/person	1 %
Mirrors, frame, etc.			< 1 %
Total	$\sim$	10,000 t/person	100 %

- 94 % of the mass is radiation shield, soil and biosphere, and those are obtained from Ceres soil almost without processing
- Most of the production energy goes to making the tensile structures
  - Baseline is carbon steel (music wire, ASTM A228, 98 % iron, which is abundant)
  - Other alternatives: dyneema fibre, carbon fibre, glass fibre, basalt fibre ...
- Nothing is abandoned because the radiation shields can be any material, as long as Ceres soil has $\gtrsim 0.75$ % of nitrogen for the atmospheres

Ceres resource limits and megasatellite bootstrapping

- Mass per living area 5000 kg/m^2, 10^7 kg/person
- Production energy per living area 5 GJ/m^2, 10^{13} J/person
- For example 10^{18} kg megasatellite for 10^{11} people needs 0.1 % of Ceres mass (and 3 % of its angular momentum if material is lifted using space elevator)
  - Then living area is 200 million km^2 – larger than Earth's continents
- If power production doubles every 4 months, growth to this takes 10 years
  - 30 doublings, from kilowatts to terawatts
  - The space elevator is not a bottleneck, since it can lift its own mass in less than a day
  - Fast 10-year bootstrapping would not be impossible from the physics point of view
- Surface area of Ceres limits the growth rate, but the limit is high:
  - If 20 % of Ceres is covered by solar panels, we get 5 TW for lifting material
  - This can lift $3 \cdot 10^{15}$ kg per year, which suffices to build homes for 300 million immigrants per year
  - For comparison: Earth's population growth is 80 million per year at the moment

Travel to Ceres is a challenge

- Ceres is at 2.8 au from the Sun
- Travel to Ceres takes longer and requires more delta-v than travel to Mars
- Speeding it up would be good, because long trip is boring and increases passenger's radiation dose
- Especially the aphelion braking phase would benefit from electric propulsion (ion engine, Hall effect thruster etc.)
- Electric propulsion can be improved: for example, one could use cheap water or oxygen as propellant, instead of xenon and krypton which are expensive
    - Such Hall thrusters have been tested already, although for a different purpose (airbreathing electric propulsion for low-orbiting satellite)
- If Ceres is too far away for the present tech, one could build a megasat in Mars orbit from Deimos resources
    - Deimos mass is $1.5 \cdot 10^{15}$ kg, 10 % of it suffices for 15 million people (10^7 kg/person)

What's wrong with the Earth?

Living on a planet means fighting against the seasons:

- Store food and energy for the winter
- Transport goods and food from afar
- Occassional dry season or flood

Life needs 1) energy, 2) water and 3) nutrients, but:

- continents have nutrients and light, but moisture varies
- sea surface has water and light, but lacks nutrients
- seafloor has nutrients, but no light

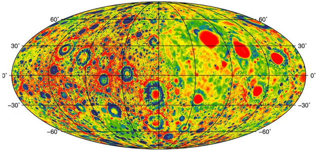
We are used to Earth's challenges. In megasatellite, the challenges are different. Some things are easier, some are harder. Food is near but gravity, air containment and radshield are artificial.

The megasatellite has everything

- No energy problem, because permanent sunshine
  - Dim Sun is no problem: in weightlessness, parabolic mirrors are lightweight
- Plants grow every day, so no need to store food or transport it over longer distance
- The plants keep the air clean
- Everything is easily accessible, interconnected
- No volcanoes, no earthquakes, no hurricanes, no tsunamis
- No resource competition... unless someone creates it
- A megasatellite is million times more mass-efficient way to produce living space than a natural planet

Lunar resources to help bootstrapping

- Need to build many Ceres (or Deimos) -going spacecraft in orbit
- Lifting raw materials from the Moon is cheaper than lifting them from Earth
- It's even better if one can lift lunar material without consuming propellant
- One can use a sling (or electromagnetic gun, but it requires a capacitor bank energy storage), but the projectile falls back onto Moon unless it has some control propulsion to circularise its orbit
- We found (Janhunen, 2025) that by choosing the launch location suitably, the lunar gravity anomalies do the job for us, for long enough time ($\sim$ one week) that an electric propulsion spacecraft can rendezvous and grab the object
- This enables passive and small projectiles made of sintered lunar glass
- Useful for bootstrapping: radical reduction of capex



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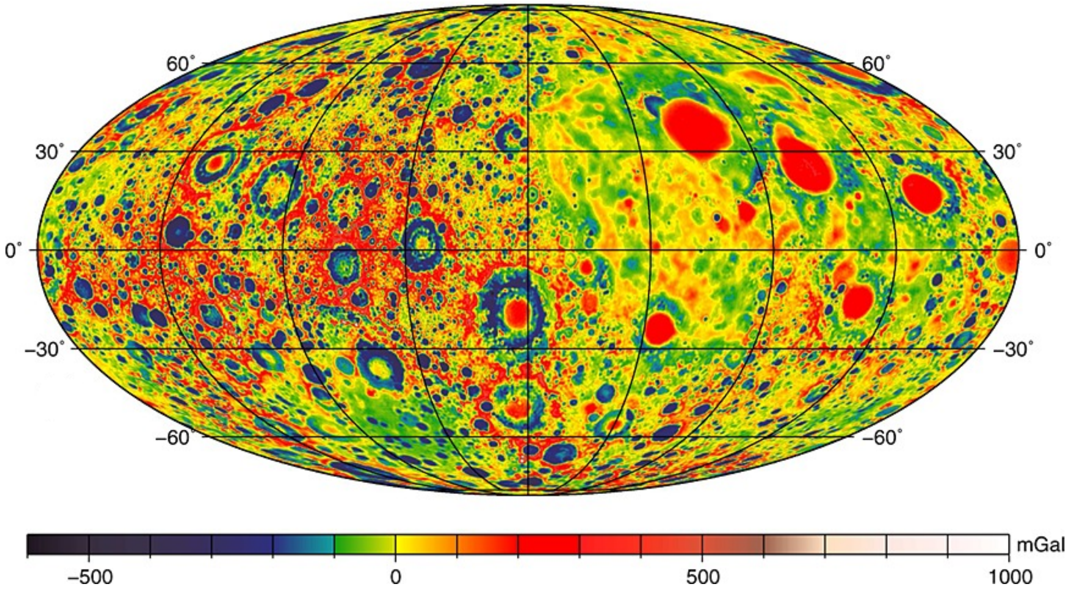

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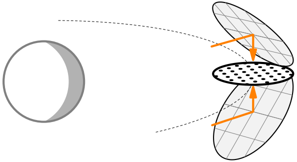
Conclusions



- Earth is the only *planet* where we can meaningfully live
- That said, unplanetary living in Ceres megasatellite seems possible and potentially attractive
  - No natural disasters, paradise-like environment
  - For example 1.5–4 m soil, natural light, normal diurnal cycle
  - Population density e.g. 500 /km^2 like in the Netherlands
  - If wanted, could grow beyond 100 billion population
- Economical to build, because material can be lifted from Ceres by space elevator
- No waste, because waste can be utilised as radiation shield
- Long-term sustainable, all atoms circulate
- Bootstrapping resources from the Moon, by slinging passive projectiles with help of gravity anomalies

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