Terraforming the dwarf planet: Interconnected and growable Ceres megasatellite world

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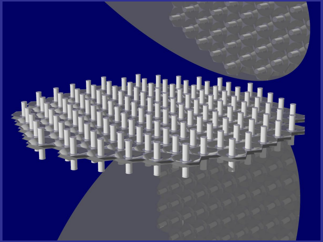

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Outline

How people wish to live

- Earthlike...
  - Earthlike radiation shielding
  - Earthlike atmosphere
  - 1 g gravity
  - 24 h diurnal cycle with 130 W/m^2 insolation, like in southern Germany
  - Nature, fields, parks, forests
  - Population density 500 /km^2, like in the Netherlands
  - Large, interconnected world
- ... but better than Earth:
  - No adverse weather
  - No natural disasters
  - Growable to larger living area than Earth
- Long-term sustainable
  - All atoms are circulated

Satisfying the requirements

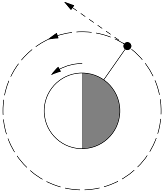
- Moon and Mars: wrong gravity, and smaller living area than Earth
- Free-flying rotating cylindrical settlements: lack of interconnectivity with each other (except using rocket propulsion, which is not long-term sustainable because propellant atoms cannot be circulated)
  - The cylinder radius has an upper limit coming from the tensile strength of the walls
  - Formation flight of cylinders might work, but bears the collision risk, and propellantless travel between the cylinders is a challenge

The solution:

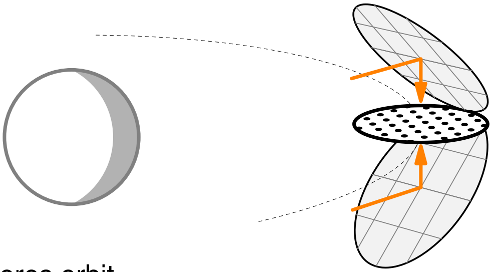
- Attach rotating habitat cylinders to a rigid frame (**megasatellite**)
  - The frame is $< 1\,\%$ of the mass budget, because it is in microgravity
- The geometry is selected to be **self-similarly growable**
- Use magnetic bearings, then there are no sliding/wearing surfaces
  - Inductrack-type bearings are passively safe

Ceres as source body

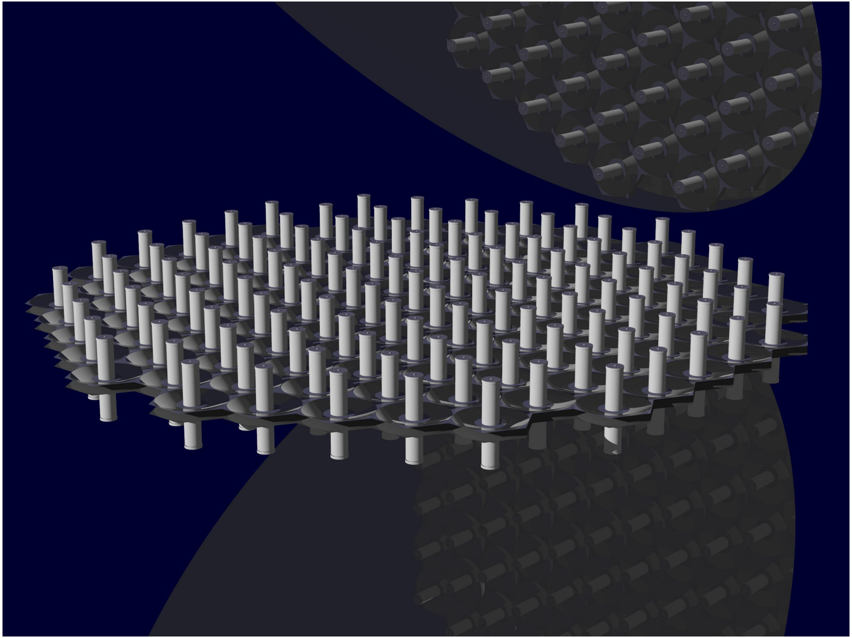
- Dwarf planet Ceres: 940 km, largest body of the main belt, 30 % of belt mass
- Ceres has **nitrogen**
  - N_2 is necessary for the settlement's atmosphere
  - (One might also select a carbonaceous asteroid, but those of sufficient size and low eccentricity are almost as far as Ceres, and they probably have less nitrogen)
- Orbit Ceres
  - So that we do not drift away, to keep material transfer time short
  - Use high circular orbit to minimise tidal forces: adopt 100,000 km orbit (Hill's sphere radius is 207,000 km)
- Space elevator is an economical way to lift the material
  - Elevator cable length is 1024 km
  - Cable strength requirement is straightforward to meet
  - Lifting needs only 54 kJ/kg of energy
  - After elevator, need 20 m/s of delta-v to circularise orbit

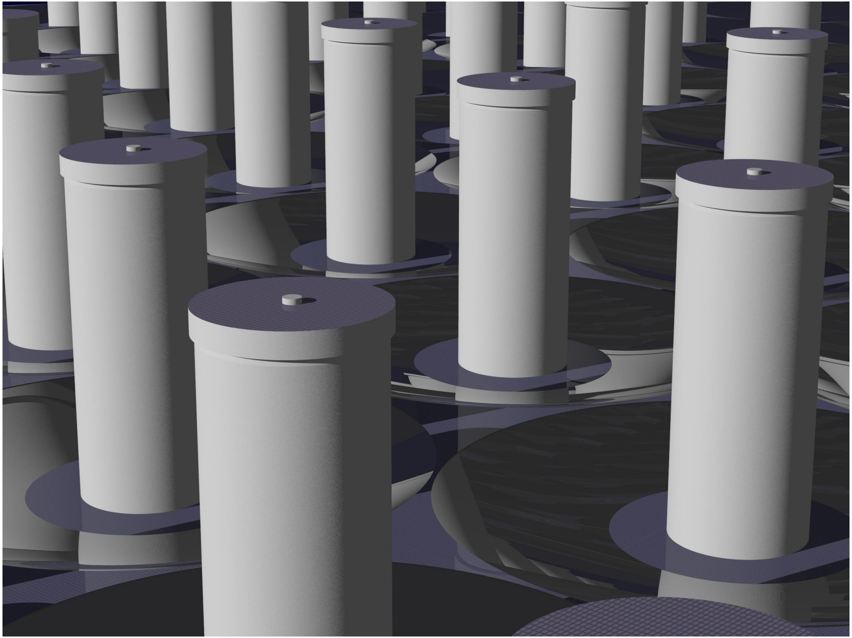


Growing Ceres megasatellite



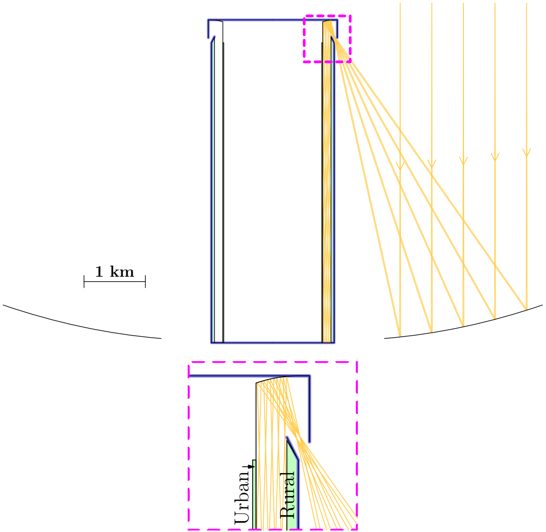
- Disk-shaped megasatellite in equatorial Ceres orbit
- Spinning habitats on both sides of the disk
- Add 45° inclined mirrors to gather sunlight
- Reaction wheels are not needed
  - No tidal torque because of disk symmetry
  - Ceres orbit eccentricity makes $\pm 8.7^{\circ}$ nutation, but handled by tilting mirror elements
- Self-similarly growable at the edges, like any city





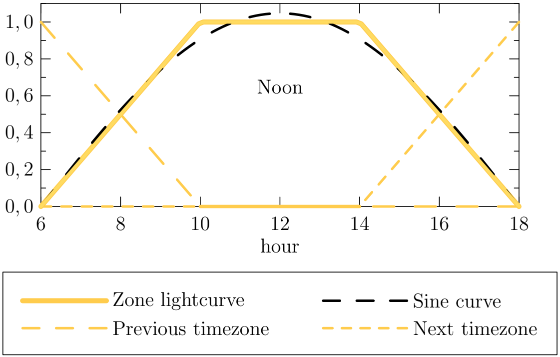
Concentrating sunlight into the habitats

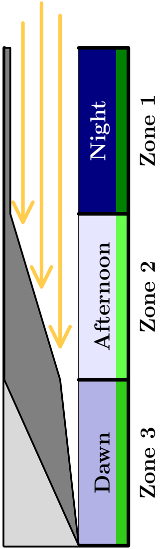
- Cylinder radius 1 km, length 5 km
- Primary and secondary mirrors inject parallel light into light channel
  - Light channel width 137 m follows from Sun's angular diameter
- 50 m high sunlit rural space, 1100 m^2/person, 1.5 m of soil to enable trees (upgradable to 4 m, at cost of doubled manufacturing energy)
- 15 m high LED-lighted urban space, 900 m^2/person, 81 % gravity



Synthetic diurnal cycle

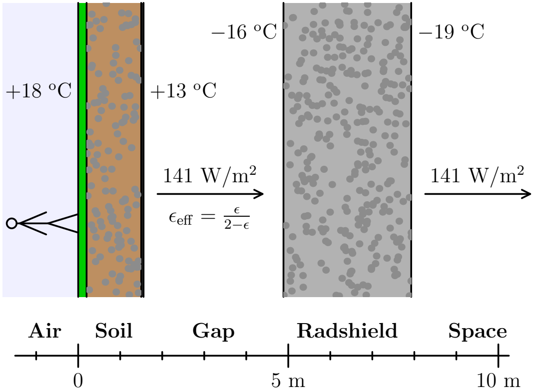
- 3 timezones, ± 8 h time differences
- Light channel has adjustably sloped ceiling to create the wanted light level in each zone
- Sum over zones is constant: no light is lost





Thermal design

- Vacuum gap between rotating and non-rotating parts
- Soil and radshield use internal liquid heat transfer, because soil is rather pool thermal conductor
  - In soil, heat transfer fluid can be water
  - In radshield, e.g. light hydrocarbon, e.g. heptane
- If needed, vacuum gap walls can be zigzagged to increase cooling by increased radiation transfer area



Interconnectivity

Fast and easy travel is necessary, and it must be propellantless to be sustainable

- The straightforward way:
  - Travel vehicles (cars/trains/elevators...) operate in zero gravity tunnels
  - Entry and exit at cylinder axes
  - Passengers experience weightlessness during trip
- The Anti-Vomit way (can coexist with the straightforward way):
  - Entry and exit at cylinder's rotating perimeter
  - Vehicles move at constant speed i.e. the rotation speed
  - Tracks/roads are spiralled to create gravity also during trip
  - Passengers do not experience weightlessness
- Vacuum or atmosphere design options
  - If vacuum, vehicles move through airlocks, or passengers do it and wear spacesuits
  - If atmosphere, noise might be an issue – power consumption is not
- Radshielding of the tunnels is likely unnecesary, because time spent is short

Mass budget

For 2000 m^2/person

Stationary radshield walls	Ceres soil	6712 t/person	69 %
Soil and biosphere	From Ceres soil	2482 t/person	25 %
Tensile structural parts	Piano wire (Fe)	484 t/person	5 %
Air	N_2, O_2	97 t/person	1 %
Reflectors, structures ...			< 1 %
Total	$\sim$	10,000 t/person	100 %

- 94 % of mass is radshield+soil+biosphere, which do not need much processing
- The main energy goes into production of tensile material
  - Baseline is piano wire (99 % Fe)
  - Other possibilities: dyneema, carbon fibre, glass/basalt fibre, ...
- No need to abandon any Ceres material: radshields are our trashbin (as long as $\gtrsim 0.75$ % of Ceres material is nitrogen, for the atmosphere)

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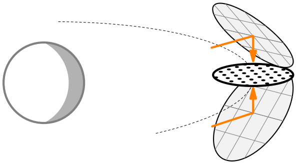
Resource limits

- Mass 5000 kg/m^2 per living area, 10^7 kg/person
- Production energy 5 GJ/m^2 per living area, 10^{13} J/person
- For example, 10^{18} kg megasat for 10^{11} people needs 0.1 % of Ceres mass and 3 % of its angular momentum
  - Living area 200 million km^2 – larger than Earth's continents
- If power system doubling time is 4 months, bootstrapping time is 10 years
  - 30 doublings from kW to TW power level
  - The elevator is no bottleneck, it lifts material quickly
  - Physics would not preclude rapid bootstrapping
- After bootstrapping, growth is limited by Ceres surface area, but the limit is high:
  - If one covers 20 % of Ceres by solar panels $\Rightarrow$ 300 million new people per year
  - For comparison, present population growth is 80 million per year

Conclusions



- Interconnected megasatellite world in Ceres orbit
- Land with 1.5 m of soil, natural sunlight, 24 h day/night cycle
- Population density of 500 people/km^2, like Netherlands
- Economical, because can lift Ceres materials by space elevator
- Long-term sustainable, all atoms circulate
- Growable to at least beyond 10^{11} people

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