Sterile Spheres:
small rovers with planet-wide range

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ABSTRACT

Small unmanned vehicles deployed from a single landing point can comprehensively explore Mars in a few months. Each vehicle comprises a hermetically sealed transparent container, an ellipsoidal shell of low-expansion glass whose surface has been totally sterilised by flash heating to temperature sufficient to decompose all organic chemicals. An inner shell contains gas at Earth-standard temperature and pressure. All moving parts are housed within this inner shell, so off-the-shelf motors, bearings and lubricants with robustly verified working lifetimes can be used, minimizing development cost and ensuring circumplanetary range. A vacuum gap between the inner and outer shells provides thermal insulation and contains solar cells and cameras.

A substantial part of the vehicle's mass is mounted within the inner shell, connected to a central axle about which it can be turned so as to cause the vehicle to roll forward. This mass can also be displaced sideways so that the vehicle turns as it rolls.

Continuous thrust produced in this way is at most about one-third of the vehicle's weight. However a second propulsion method can extract the vehicle from almost any pit, slippery sand area or other potential trap. A flywheel, normally stationary, is spun up to high speed then braked suddenly. The resulting large torque causes the vehicle to turn end-over-end. Thus it can climb a steep slope, move across soft sand with a scooping effect like a paddle wheel, or leap up a small cliff or across a crevasse with a pole-vault style takeoff.

The vehicle can navigate autonomously for long periods. Several methods by which it can harvest information about its immediate environment, and periodically return large volumes of data, are described.

Progress in the capabilities of planetary landers and rovers has been modest for many decades. The distance driven record set on the Moon by Lunokhod 2 in 1973, 39 km, was not exceeded until 2014, on Mars{1}. The present Curiosity rover masses only slightly more than the Lunokhod, and its instruments do not include even a modest-power optical microscope. It and all other recent Mars surface missions are sterilised to a poorer standard than the Viking landers of the 1970s, and therefore cannot be sent to Mars's most interesting regions.

Rolling-ball vehicles are not a new concept, including for use in space exploration{2}. This paper describes a novel design: a small but capable vehicle with circumplanetary range, which can be developed quickly and cheaply using commercially available components and processes, and which can be sterilised to a perfect standard.

A preferred implementation of the vehicle is shown in Figures 1-4. Minor diameter might be anywhere in the range 10-40 cm, with long axis ~25% greater.

The outer shell is low-expansion glass. Possible choices range from borosilicate glass commonly used for kitchenware and laboratory glassware, through proprietary formulations such as Zerodur and Cornell's ultra-low-expansion glass range. In this context however, fused quartz is ideal as it can withstand being flash-heated to well over 1000°C to completely sterilize it{3}. This temperature is sufficient to destroy any information-carrying organic chemical, including viruses and prions: DNA nucleotides separate at 190°C{4}. The outer surface cools before damaging heat can penetrate to the equipment within.

Equipment for shaping glass for space telescope mirrors creates paraboloids whose convex surface has raised ridges to add stiffness, for example in a honeycomb pattern. A similar pattern of ridges can optionally add stiffness and strength to the rover's outer shell: the ridges will also act as grousers to increase ground traction. Six approximately square tiles, or twelve approximately pentagonal tiles, can be fused together to make the shell.

The vehicle can easily withstand the most extreme Martian conditions, including a surface whose temperature varies tens of degrees over short distances. Unlike Curiosity's aluminium wheels, the shell can roll without damage over extremely sharp rocks: only diamond could scratch it.

We will assume an ellipsoidal shell of major diameter 50cm, minor diameter 40cm, thickness 3 mm: surface area 6000 cm^2, glass volume 2000 cm^3 with density 2.2, shell mass 4.4 kg. Total vehicle mass will be set twice the mass of the shell, 9 kg.

With its small ratio of mass to wheel diameter, average rolling resistance 0.04 is a conservative assumption: measured terrestrial figures are .04–.08 for car tires on gravel, soil or sand{5} or .04–.07 for a stage coach on a dirt road{6}. Mars gravity is 3.7 m/s^2, rolling drag 1.33 N, so work of 1.33 W can propel the vehicle at 1 m/s. If we want to maintain this average speed by day and night, allowing for losses and some additional power for electronics, 4 W daytime electric output from solar cells is needed.

Mars top-of-atmosphere insolation is 587 W/m2, and space-rated GaAs solar cells of efficiency 30% are available: allowing 10% for reflection at the inner and outer surfaces of the glass shell, sunward-facing cells nominally produce 16 mW/cm^2 ignoring atmospheric effects, implying 250 cm^2 sun-facing area. A sphere has surface area four times its crosssection, so for omnidirectionality 1000 cm^2 cell area is needed. Power will be boosted in practice by additional sunlight reflected and scattered from the adjacent Martian surface: average albedo is 0.17. Curiously, the effect of atmospheric dust will usually further increase the solar harvest: except in extreme dust storms, scattering is several times greater than absorption{7}, and will produce extra power from the non-sunward-facing cells. Cells tiling 1000 cm^2, one-sixth the shell's surface area, will generate ample power.

Solar cell mass is 100g. The flywheels for high-torque extractions can spin at rim speed as high as 1 km/s if made from carbon-carbon, if the inner shell is filled with hydrogen so the local speed of sound >1 km/s: many terrestrial electric motor/generators are designed to operate in hydrogen gas, due to its better thermal conductivity compared to air. Flywheel mass is ~1% of vehicle mass, 100g. The vehicle's central axle is a hollow tube, and the pressure-containing inner shell essentially a balloon whose thickness can be a fraction of a millimetre. Most of the remaining mass, including motors, batteries, electronics and their radiation shielding can, form part of a ballast of 1.5 kg. The heaviest single item will be the battery: 100 kJ storage is required, implying ~200g lithium-ion battery. If the ballast's centre of mass is 15 cm from the central axis, continuous torque can be generated sufficient to keep the vehicle moving at constant speed against rolling resistance .12 on the flat, or up a smooth slope of inclination 7°. These values may occasionally be exceeded, but it is almost impossible for the vehicle to become trapped: to climb a steep or slippery slope, or escape from a hole or sand trap, a much larger torque can be generated by the flywheel manoeuvre described below.

With the inner container and the reverse sides of the solar cells silvered, and/or with additional layers of silvered Mylar in the gap, the inner shell has thermos-style insulation: with emissivity of inner and outer surface 0.03 heat leakage is 0.015 x black-body = 4.5 W/m2 from interior at 0°C to exterior at 0 K: 2 W, exactly matching the average solar cell output over one diel. As the environment is always above 0 K, the interior will remain above freezing point. Exceptionally, during a planetary dust storm, the temperature may fall to that of the outside environment for a prolonged period, but no movement will be attempted during this time.

The end space between the inner and outer shells contains cameras, including multispectral and microscope types. The vehicle can store gigabytes of data, including for example photographs with patterns which might represent microfossils, and spectra which might indicate the presence of chlorophyll or analogous biochemicals harvesting energy from sunlight. Other instruments could include a magnetometer and a depth-sounding radar. It would optionally be possible to include biopsy-style samplers, hollow titanium or Inconel tubes embedded in the outer shell near the vehicle's axis of rotation. These would initially be sterilized as thoroughly as the rest of the exterior. Coming into contact with the surface only as the result of an extreme and deliberate manoeuvre, they could acquire soil samples for further investigation.

Solar cell area is less than one-fifth the outer shell's area, and power generated need not be constant as the vehicle rolls: a small capacitor can smooth the output. A substantial part of the shell can therefore be ridged and silvered on its inner surface to act as a Fresnel mirror. With the vehicle in an appropriate position and orientation, which can be altered as the sun moves across the sky, solar energy can be focused to heat a patch of adjacent soil, allowing detection of water ice up to several centimetres below the surface as it rapidly evaporates. In a low-lying location such as a planitia basin, a pool of liquid water can be formed.

Data can be returned at high bandwidth in several ways. A phased array antenna on the inner side of the outer shell can be steered either electronically or by orienting the vehicle, transmitting either via a relay satellite or direct to Earth. For larger volumes of data, the vehicle can closely approach a ground installation such as the lander which deployed it and use it as a relay.

A great circle circumference of Mars is approximately 20,000 km, which the rover can traverse in less than one Earth year. This corresponds to 16 million revolutions, hence the same number of turns of the ballast mass about the central axle. Axial lateral load is only a few newtons. If the ball interior contains Earth air at s.t.p., or hydrogen as used in terrestrial sealed-unit motor/generators, or inert gas, electric motors and bearings with much greater verified working lifetimes than this using their recommended lubricants are readily available off-the-shelf.

To comprehensively check the entire surface of Mars for present or past life, a small number of rovers deployed from a single landing point could drive great circles visiting every type of terrain anywhere on the surface of Mars and report back to the lander in under one Earth year for high bandwidth relay of images they have taken, including microscopic and multispectral, and optionally analysis of physical samples taken by the ‘biopsy’ method. A large number of locations can also be tested for the presence of near-subsurface ice during the drive.

Figures 1-4 illustrate the preferred design performing a variety of manoeuvres. In each case the left view is a frontal view and the right view a side view.

Features are labelled as follows

A	Outer glass shell (light blue)
B	Inner pressure-containing shell
C	Main axle, fixed rigidly to A and B
D	Ballast mass containing motors, batteries, electronics, shielding
E	Flywheels (blue)
F	Flywheel axle (blue)

For clarity, not all lettered features are shown in all views. Items mounted between the inner and outer shells, solar cells and cameras, and on the inner side of the outer shell, Fresnel reflective area and phased array radio transmitter, are not shown.

In Figure 4, the flywheels are accelerated gently clockwise until they are spinning at a high rate. Then they are suddenly braked, causing the vehicle to roll hard right as seen from the front. At all other times than performing an extraction manoeuvre the flywheels remain stationary so as not to affect the normal motion of the vehicle. The outer shell need not necessarily be an ellipsoid, for example a spindle shape with pointed ends might permit more authoritative self-extraction.

Figure 1 Vehicle stationary

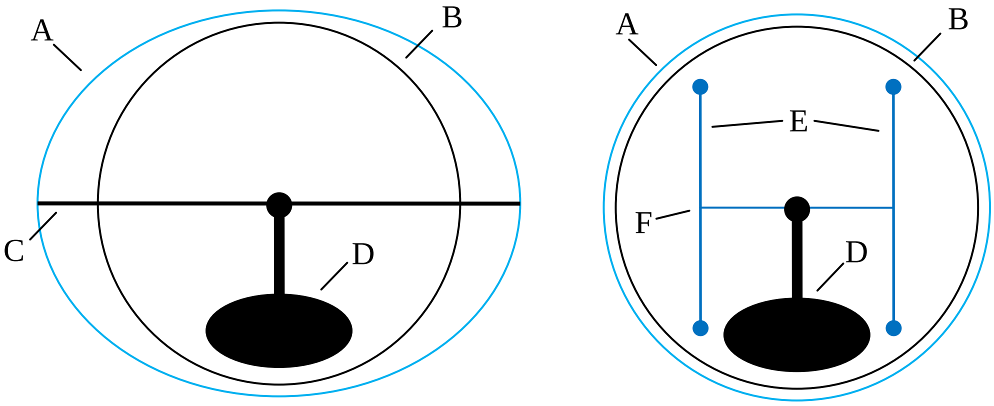


Figure 2 Vehicle moving to left, in straight line

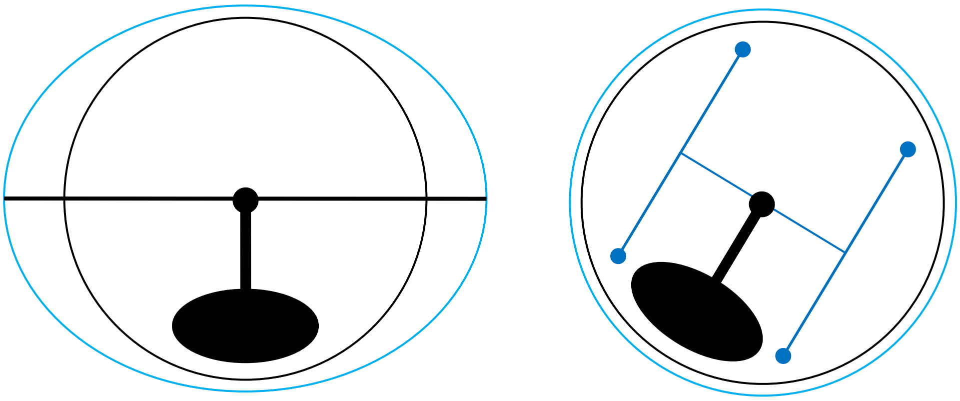


Figure 3 Vehicle moving to left, initiating right turn

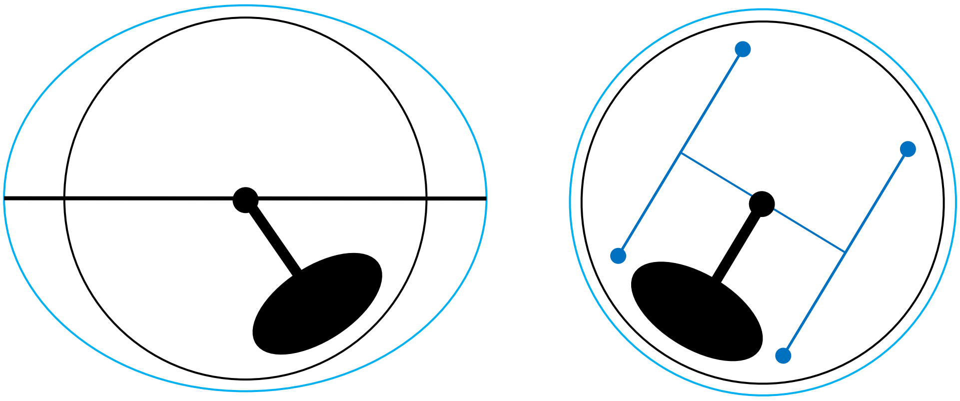
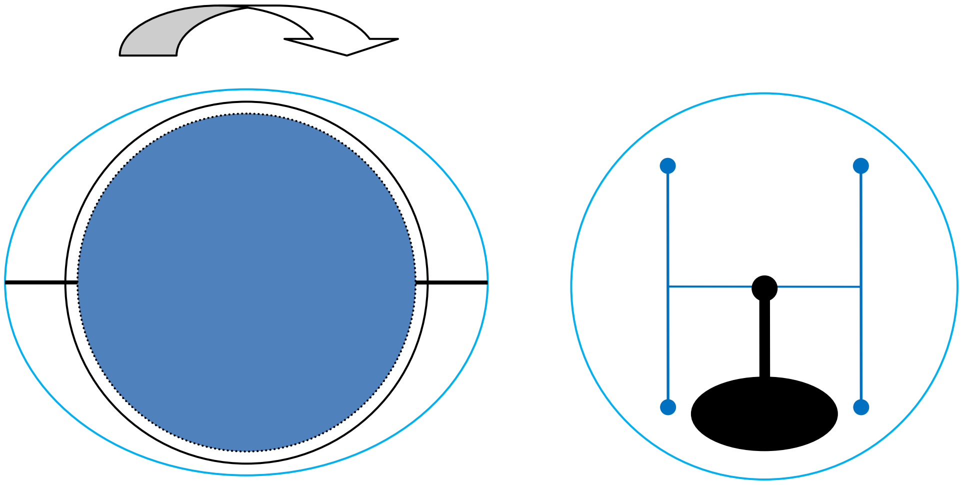


Figure 4 Extraction manoeuvre



ENDNOTE

A UK patent application describing the concept was filed on 29-Sep-2016.

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