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HOW TO MOVE A PLANET

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The orbits of planets like Venus and Mars may render them unsuitable for terraforming without the use of soletta mirrors. This paper describes how to move a planet to the right distance from the Sun. Dynamic compression members, formed from high-velocity mass-streams, thrust against the planet, effecting the desired orbital shift and transferring angular momentum. Energy is supplied by a light-sail windmill in solar orbit, allowing the procedure to be completed within a period of ~ 30 years.

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1. INTRODUCTION

Although Venus has long been thought of as Earth's sister planet, it receives twice as much sunlight, and, in consequence, is very hot. Bombarding the planet with ice-moons or asteroids [1,2] could modify its orbit, but scarcely by any significant amount. It may also result in serious loss of atmosphere to space.

Moving a planet with antimatter or fusion rocket engines has been considered by other authors [1,3,4,5] but the level of power required, and the difficulty of operating through an atmosphere, seem to make this technique slow and costly at best.

One interesting proposal [6,7] is to establish an accelèrating force by means of solar sails, gravitationally bound to the planet. Unfortunately, the timescales are prohibitive; even if the whole region of space between the Sun-Venus Lagrange points is filled with heavily ballasted sails ($\sim 3 \times 10^{18}$ m^2 at ~ 250 g/m^2, yielding a force $\sim 2.5 \times 10^{13}$N), it would take ~ 40 Myr to move Venus out to Earth's orbit.

Rapid-terraforming proposals [8,9] by the present author suggest that planetary insolation be controlled by the cheap and immediate technique of deploying large mirrors in space. However, some degree of continued maintenance would be required; and there is a school of thought which claims that terraforming ought to leave planets in a stable state, persisting over geological time without further manipulation.

This paper presents a concept for moving planets in a short time - say 30 years - at a modest cost. It should be read in conjunction with Refs. 8-14, where the basic techniques and assumptions are more fully described, and in parallel with Ref. 15, where a similar method is considered for modifying planetary rotation rates.

For definiteness, we shall stick with the problem of moving Venus out to the distance of the Earth's orbit, but it will be apparent that the same technique could be used for other planets and other purposes.

2. MOVING VENUS

Figures 1 and 2 show two ways of moving a planet with dynamic compression members [14], transferring momentum and energy to the planet *via* high-velocity mass-streams.

The first method is almost identical to that suggested for speeding up the rotation of Venus [15]; here orbital angular momentum is obtained by slowing the rotation of the Sun.

Moving the planet away from the Sun also demands extra kinetic energy, which may be generated by a solar-orbiting light-sail windmill [13], then transferred to a high-velocity mass-stream ($v \gg 300$ kms^{-1}) *via* a co-circular electromagnetic travelling wave accelerator [15].

The accelerated mass-stream, having looped around the Sun on the accelerator's circular track, is projected on a course for the planet's limb. There it is captured and swung back towards the Sun along an equatorial track.

Although the track is fixed relative to the planet's surface, the mass-stream pick-up points circle backwards to match the planet's rotation.

Similar tracking of the pick-ups occurs at the Sun's limb, to which reversal loops on the accelerator track return the mass-streams after making up any loss in energy.

One difficulty is how to couple the reversal loops to the non-rigid Sun below the track. At present, the solar magnetic field is much too weak; but it would appear that flux trapped between the (superconducting) tracks can be "wound up" by the reversal loops to a sufficient strength (~0.1T) within $\sim 2 \times 10^7$s. Alternatively, one might try attaching ram-scoops to the reversal loops, thereby mining the Sun at the same time [10].

Planetary orbits can be modified by this technique without reference to any other body in the solar system and without any loss of material. However, very much larger forces and higher energy expenditures are required than for increasing planetary rotation rates alone.

We calculate as follows. Moving Venus out to Earth's orbit requires $\sim 8.4 \times 10^{32}$ J, corresponding to ~ 0.2% of the solar luminosity over thirty years. Fortunately, only a fraction of this need be supplied by light-sail windmills, since in this scheme up to $\sim 7.4 \times 10^{33}$ J is available from the Sun's rotational energy. Up to $\sim 7 \times 10^{22}$ kg of solar material could be mined with the excess.

Over thirty years, the force required is initially $\sim 3.7 \times 10^{21}$ N, rising to $\sim 6.0 \times 10^{21}$ N as the planet spirals out towards Earth, while the force to weight ratio goes from 6.6% to 21%.

At the Sun, the cost of the $\sim 1.5 \times 10^{19}$ kg counterweight may be excessive (~ 15,000 T£ compared with only ~ 5 T£ to spin up Venus to 1 rev/day [15]). This is because only the component of force along the planet's spiralling orbit does useful work: the

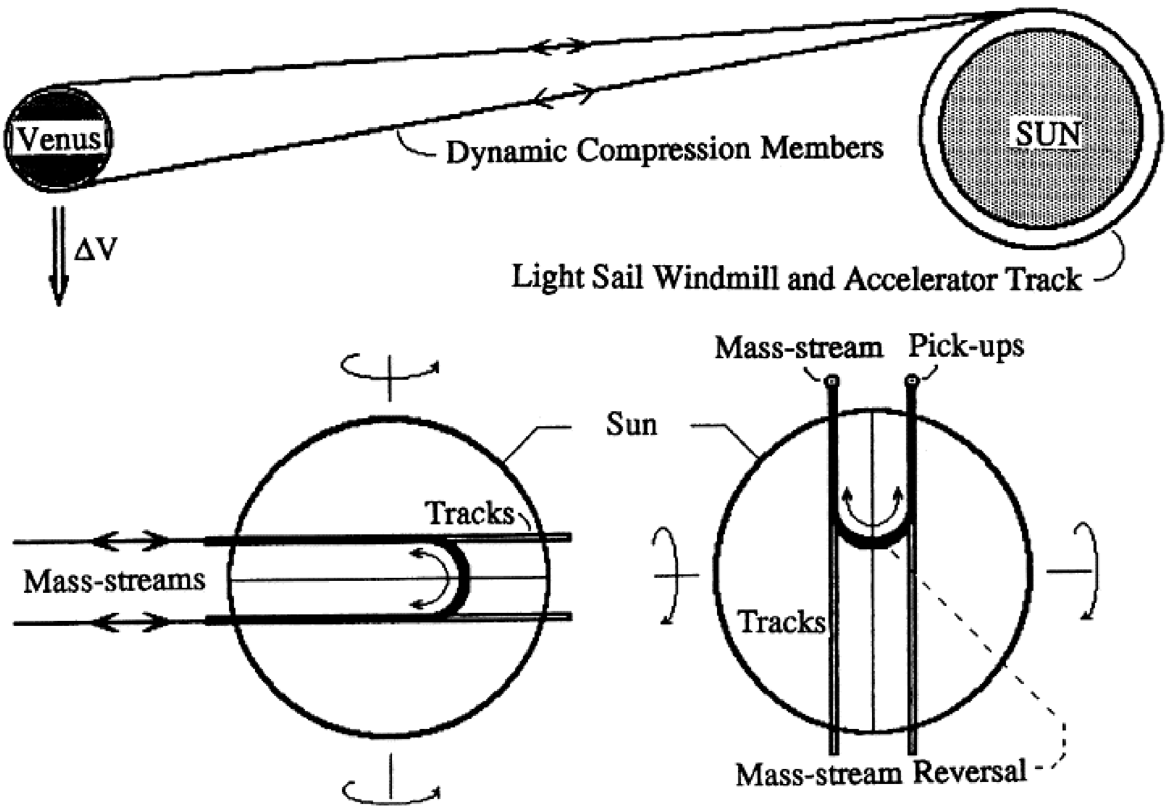

Fig. 1 Moving Venus with dynamic compression members.

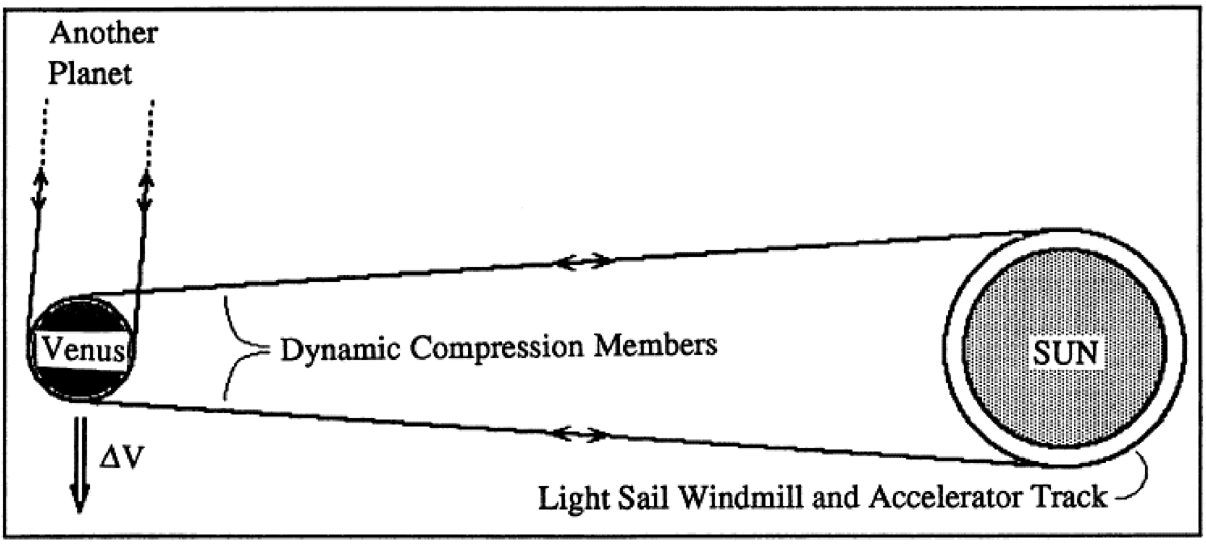

Fig 2. Transferring angular momentum to other planets.

small fraction $R_{Sun}/D_{Venus} \sim 0.006$.

Using the applied force more effectively would reduce costs. Although a periodically varying force acting radially from the primary can be highly effective at pumping up the eccentricity of a planet's orbit, eventually pushing it to escape velocity and ejecting it from the system, circularisation of the enlarged orbit would require the presence of a third body.

The geometry of fig. 2 allows dynamic compression members to push against both the Sun and another planet. Then, nearly the whole of the thrust of the Venus-planet leg is utilised in pushing Venus along its orbit. Although any given pair of planets will be suitably aligned for less than half of the time, one can always swap to another pair for the remainder.

The required force can thus be reduced by a factor ~ 150 to ~ 2.5×10^{19} N, cutting the cost of the solar counterweight to ~ 100 T£, no longer outrageously high for terraforming.

Most of the energy could be obtained from the orbital motion of the other planets; it takes four bodies (including the primary) to balance both energy and angular momentum.

Which planets shall we push against? Jupiter and Saturn are the most massive and have ample orbital angular momentum but in the absence of a solid surface one of the larger moons would have to be pressed into service as a counterweight. Mercury and Mars are closer, but their angular momentum is insufficient. The best arrangement is probably a combination.

Let Mercury supply the bulk of the energy and Jupiter or Saturn the angular momentum. Mars, moving inwards from 1.52 AU to 1.33 AU (the distance at which Earth-like conditions would obtain for this low-gravity planet [8]), supplies 3% of the energy and 7% of the angular momentum needed to move Venus from 0.72 AU to 1.0 AU. Mercury, moving inwards from 0.390 AU to 0.125 AU, supplies 92-95% of the energy and 12% of the angular momentum. Then Jupiter, moving inwards by 0.0014AU from 5.20 AU, supplies the remaining 81% of the angular momentum and 5% of the energy. Alternatively, Saturn moves inwards by 0.0063 AU from 9.54 AU to supply 81% of the angular momentum and 2% of the energy.

At Jupiter, the thrust of the dynamic compression member can be taken up by one of the moons, probably Europa, whose weight in Jupiter's gravitational field is ~ 500 times the desired force.

At Saturn, the counterweight could be the moon Tethys, moved into a halo orbit ~ 17 R_{Saturn} behind the planet and afterwards sent to Venus to provide ~ 1 km of water.

The energy stored in the dynamic compression members [14] will be ~ 1.0 x 10^{31}J, some 1.2% of the total required. However, if the mass-stream is initially given a low velocity ~ 300 km/s, the light-sail windmill need only provide ~ 10^{27}J (~ 50 G£ at ~ 5 x 10^{-17} £/J). The speed builds up to β~0.1 over ~3 yr as the mass-stream bounces between Venus and Mercury.

The mass of the pellet stream [14] comes to ~ 2 x 10^{16}kg (~ 20 T£), but on the Venus-Sun leg the thrust need not exceed ~ 2.5 x 10^{14} N or the solar counterweight ~ 10^{12} kg. Using this scheme, the planet can be spun up to 1 rev/day concurrently at no extra cost.

Another route may be to utilise similar techniques to eject a large outer-planet moon (such as Io, Europa, Ganymede, Callisto, Titan or Triton) from its orbit, at an energy cost of only ~ 3 x 10^{30} J, before directing it into gravity-assist passes of Venus and the outer planets [9].

Either way, the *complete* terraforming of Venus may be achieved at an additional expenditure, which because of the very strong bootstrapping effect of fortuitous energy production is not easy to estimate, but which is likely to be of order 20 T£ or less, well within the value of the terraformed planet [9]. The simultaneous completion of the terraforming of Mars [8] could be seen as a bonus.

Stars are much more massive than planets, but could be moved around in much the same way. For a galactic civilisation the way stars wander about randomly may be an irritation. Can we lock them into position?

The Sun and α-Centauri are moving closer at 22 km/s, a figure typical of stellar motions. Now consider eliminating this radial velocity by means of a dynamic compression member between them, power by the full output of the two stars ~8 x 10^{26}W. After time t the energy stored is ~ 2 x $10^{10}t$ J/m and the force ~ 4 x $10^{10}t$ N at either ends. Each star decelerates at ~ 2 x $10^{-20}t$ m/s^2, giving a velocity change ~ $10^{-20}t^2$ m/s, reaching the required 10^4m/s in ~ 10^{12} s or 30,000 years. A thousandfold increase in power brings it down to ~ 1000 years.

If energy extracted from the relative motion of the stars is used instead, the timescale remains ~ Δv/D ~ 10^{12}s. We can do somewhat better with multiple star systems and globular clusters, where the stars are close and fast. Indeed, shrinking all multiple systems to contact binaries could release enough orbital energy to straightjacket the galaxy within ~ 30 years.

It would appear that moving stars, though clearly practicable on astronomical timescales, is not generally attractive on engineering timescales - not until sufficient energy has been turned into an accessible form.

3. CONCLUSIONS

We conclude that through the use of high-velocity dynamic compression member to apply forces efficiently, planetary orbits can be modified on convenient engineering timescales ~ 30 years, that the cost of such operations is not excessive in conjunction with terraforming or artificial-planet-building projects; that energy can be converted to and from orbital energy with little loss; and that the technique may also apply to the regularisation of stellar motions.

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