CUSTOM PLANETS OR MOVE OVER SLARTIBARTFAST!

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Planets come naturally in a variety of unappealing forms and must be customised to clients' needs. This may involve modest landscape gardening (carving fjords, for instance) or simple climate change (using such obvious techniques as illumination from space by mirrors, shifting the planet's orbit or creating a nearby supernova). Sometimes a change of air may be required. Sometimes the starting material is so unpromising (such as gas-giants) that its easier to start over with a new surface a few thousand klicks up. Prompt delivery is essential.

The most popular models are ordinary terraformed planets or earthlike habitats, suitable for hunting lodges and retirement homes. But we can also cater for more exotic desires, like low-gravity worlds rented out as theme parks. Then there are ocean worlds, always popular with deep-sea fishermen. Desert worlds, for the sort of people who like desert worlds. And black hole planets for people who really want to get away from it all.

However, such bijou curiosities as diamond worlds (7.5 x 10^{28} carats) and planets of gold (1.5 x 10^{25} troy ounces) are only expected to become available (to the very rich and rather stupid) after the neutron star mines have reached full production.

1. INTRODUCTION

In this lecture we'll travel much further — and use more radical technologies — than in previous lectures. Even so, I see it as an extremely conservative approach to the future, drastically under estimating what we'll actually be able to do.

First we'll look at terraforming, asking what it is, why we should do it, how we can do it, and what other things we could do instead. You'll have heard most of this before, but from a different perspective; you'll find that I'm in marked disagreement with almost everybody else — especially over time scales and economics. We'll look at the rapid terraforming of planets like Mars and Venus, but since there aren't all that many suitable planets in the Solar System we'll also look at space habitats and artificial planets. Some of these will be far larger than any natural planet.

Other solar systems may contain terraformable planets too; we'll look at a selection of generic terraforming techniques, useably throughout the galaxy. Then we'll consider a possible scenario for the next few hundred years. Notice that I'm already talking about time scales very much smaller than most terraforming pundits would accept.

2. WHY TERRAFORM?

2.1 What is Terraforming?

Terraforming is the art of making new Earths or transforming hostile planets into life-bearing ones. There are several types. First, the unpronounceable ecopoesis. This means that only plants can live there, and a pretty dismal sort of terraforming it is too. Better is a habitable terraform which means that human beings can live there too. Best of all is a planetological terraform, which is stable over geological epochs. For the most part we'll be looking at habitable terraforms.

2.2 What are the Motives for Terraforming?

Motives for terraforming fall into a variety of categories, such as:

Ideological — By and large, advocates of ecopoesis are concerned with the preservation and dissemination of Life with a capital 'L', whereas those of us who spell it with a little 'l' are usually more interested in taming the universe for mankind.

Scientific — Scientists want to learn about planets and how planetary ecosystems can work. Experiments one would hardly risk doing on Earth can safely be carried out on other planets.

Economic — The economic approach considers terraforming in terms of industrial growth and capital accumulation – every new piece of real estate can be sold for profit; and every new habitat can develop its own economy and industry, adding further to the Gross Human Product.

Aesthetic — The aesthete looks at terraforming as a means of enhancing the human environment. It increases options. And terraformed worlds can be fun: fun to make, fun to live on, fun for films, fun for holidays.

Self-preservation — Terraformed worlds are safety nets: if another dinosaur-killer strikes the Earth, if war takes out the space colonies, or civilisation collapses, the human race will not become extinct.

2.3 What are the Terraforming Options?

Many terraforming scenarios take things very slowly, over thousands or millions of years. I don't believe humans have the patience for this. I haven't, anyhow. Furthermore, slow terraforming would be quite uneconomic. I am strongly of the opinion that any terraforming we do has to be done fast — preferably within a human lifetime.

Life-bombing is the "natural" way to terraform. This can mean something as simple as dropping a few bacteria, going away for a few billion years, and hoping that when you come back you'll find a pretty place — with a diverse earthlike ecosystem. Apart from being slow, it's not too likely to succeed, the more likely outcome is a planet of greenish, slime.

Bombing with a succession of tailored bacteria and plants, Followed by or interspersed with the introduction of carefully chosen animal species, may be more effective; however, it may be hard to maintain sufficient interest in the project over the centuries.

Alternatively, we can terraform "artificially" with high-tech methods, which are usually faster.

We won't take on the highest of high-tech in this lecture; that would involve nanotechnology, self-replicating systems or molecular copiers, and would let us do essentially anything we liked in about seven days! We won't be doing anything that fast today; instead we'll be taking from a few decades to a century.

2.4 What is the Competition?

In the future people will live in all kinds of habitat — both natural and artificial. Each will have to compete for inhabitants in terms of cost, availability, security, and quality of life. Terraformed planets will be only one option among many.

Naturally habitable planets have the disadvantage of being rare: so far we only know of one. It is doubtful whether there are more than a handful of planets in the galaxy on which a man could live without a space suit. Furthermore, extraterrestrial life forms, if they exist on these planets, may pose an unknown and potentially catastrophic threat.

When it comes to man-made habitats we find that, by planetary standards, rotating space colonies will mostly be rather small; they also come inside out. And although artificial planets can be very large, they may be considered less robust than a well-terraformed world.

To be economically viable a project may need to be completed (or at least begin generating adequate returns) within thirty years or less; otherwise the interest charges become astronomical. Hence any terraforming must be rapid.

3 ECONOMICS

My economic assumptions are as follows (Fig 3.1) . People will still be people; there will be no little green men no extraterrestrial, and no von Neumann machines or molecular copiers. If I'm wrong, all bets are off. I assume that existing trends, such as industrial growth and increasing personal wealth, will continue. For convenience, I use a population growth rate of 2.4% per annum, with an industrial growth rate of 4.8%.

The growth of industry and population is what makes terraforming and space colonisation possible. If you haven't the industry, you haven't the wherewithal to build extensive habitats; if you haven't enough people, you can't populate them. It works the other way round too — the construction of space habitats, and the terraforming of other worlds, will both encourage and enable further economic and population growth.

We can demonstrate long-term progress by means of empirical trend lines. Consider the human population in space since the start of the space age (Fig 3.2). Over the last thirty years it has increased at around 25% per annum. Even with the post-Apollo cutbacks it has continued to grow. At present rates, the population in space will exceed that of the Earth in less than a hundred years.

In the scenario used in this lecture the growth of space habitats soon outstrips growth on Earth (Fig 3.3); indeed, it is not long before the population of the Solar System is itself vastly exceeded by the population of the colonisation wave sweeping out through the galaxy.

In the earliest stages of space colonisation we have very small colonies, at very high population densities — perhaps as little as ten square metres of ''land' per person. With time, however, habitats get bigger and population densities fall. By the time we get around to terraforming Venus, habitat areas are up around 100,000 m^2 per person (the same as the current figure for Earth). In the era of artificial planets and suprastellar habitats, even more room is available to the ever richer population.

It is hard to guess how long the demand for ever more extensive estates is likely to persist. I have assumed, quite arbitrarily, that demand levels off at 2500 km^2 per person. This is only an average, of course; many estates will be very much larger yet.

4 LUNAR AND ASTEROIDAL SETTLEMENTS

The closest world beyond our own is the Moon. Unfortunately, it's not particularly good for colonisation. The sort of habitat we might build there is a sort of subsurface ellipsoidal cavern, artificially illuminated from within (Fig 4.1). Digging the hole is easy enough but finding enough nitrogen to fill it may be a problem; we may have to make do with imported nitrogen — as little as possible — eked out with oddments of helium, neon or argon.

On the Moon, the gravity is far too weak for earthlike habitats; whilst on the asteroids it is both too weak and inconveniently strong (it's easier to build rotating habitats in zero gee). The rotation periods are all wrong — nowhere near twenty-four hours — and surface temperatures are extreme. All in all, less than ideal for settlement.

However, both the Moon and the asteroids are excellent sources of raw materials. They can provide any amount of fused rock and soil for the construction of space habitats. They can be mined for metals like titanium and aluminium. There are carbonaceous asteroids rich in volatiles, and nickel-iron asteroids yielding not only an excellent steel but also gold and platinum by the billions of tonnes. Perhaps not enough to make the planet of gold, but it's early days yet!

5 RAPID TERRAFORMING

5.1 Mars

Even without terraforming, Mars is easy to colonise. In a way, that's a problem; the presence of colonists in their dome cities could prove a nuisance.

What do we have to do? First, warm the planet to ~290K, about the same as Earth. Second, increase the atmospheric density to 300 mbar or so, providing ~240 mbar of breathable oxygen Third find sufficient liquid water to fill the Martian seas.

We'd also like to increase the gravity to 1 g, but no one's worked out how to do that yet — not over the whole planet, anyhow!

Mars has abundant water and carbon dioxide, we think, but nitrogen seems to be under-supplied perhaps 100 mbars' worth in all, perhaps even less. We're not sure. One of the first things we need is a full geological survey of the planet. Till then, we're guessing.

If the planet turns out to be as short of nitrogen as some people think, we may be stuck with para-terraforming, which can get by with just enough to fill the space below the roof. Or we could import extra supplies from Venus or Titan — an expensive business on a planetary scale.

Otherwise, we have to make do with the nitrogen available and accept a lower atmospheric density than on Earth. It turns out that we don't actually need as much nitrogen as on Earth because low gravity is quite effective at damping down the spread of fire.

The strength of the convection currents feeding the fire is directly proportional to the gravity, so that 240 mbar of oxygen on Mars becomes equivalent to only 100 mbar on Earth. We're probably okay.

To terraform Mars we proceed as follows: —

First, we start warming the planet by means of a soletta, a rather complicated mirror positioned in space between Mars and the Sun (Fig 5.1). The sunlight comes in, bounces between tile slats and narrows down onto the planet. The soletta actually works like a condensing lens, but because it's only a thin aluminised film, like a solar sail, it's very light; even though the mirror is wider than the planet its mass is a modest 50 million tonnes. The soletta goes some 100,000 kilometres out from Mars — still within the planet's gravitational influence. The pressure of sunlight reflected from the annular mirror onto the back of the soletta is what stops it failing down.

Mars can thus be illuminated with sufficient sunlight to warm it to Earthlike conditions. Exactly how much sunlight it needs is not completely clear, but the value lies somewhere between 1.3 and 2 times the present insolation. We can play tricks with this by filtering out the stuff we don't need — the infrared and ultraviolet — and increasing the amount of visible light to compensate. This allows us to match (or even exceed) the intensity of visible light on Earth.

Unfortunately, simply warming the planet won't release enough volatiles. For one thing, it takes a million years or so for the heat to sink down through the deep crust. For another, a lot of the volatiles are locked up chemically in the regolith (we believe).

We're going to have to get drastic.

Let's nuke the place. Even better, lets burn holes in it (Fig 5.2). Sunlight, coming in from the magnifying soletta, converges onto another solar-sail lens. This aerial lens is very light and floats very high up in the Martian atmosphere — at a height of ~400 km.

It acts like a burning glass, concentrating all the sunlight that would otherwise fall over the whole planet down into a spot some 80 km across. The rock melts and vaporises. The rock-vapour flows away under the lens, condensing out to form glassy hills on either side of the melt. Volatiles — like oxygen, nitrogen, carbon dioxide and water vapour — are freed.

Now it is likely that when the ancient Martian seas disappeared they left behind evaporate deposits of nitrates and nitrites. Strongly heated, such deposits would release copious amounts of nitrogen and oxygen. If we can find pure nitrate deposits in sufficient quantity we should be able to make a breathable atmosphere in as little as ten years, which of course is jolly fast.

Naturally, we choose to melt out the regolith preferentially in those regions containing the best deposits.

Carbon dioxide is also released by regolith vaporisation (from carbonates) and photosynthesis can turn as much of this into extra oxygen as we need.

In the meantime, colonists and terraformers can live in dome cities: say, 1 km domes with a full Earth atmosphere pressure inside and the ambient Martian atmosphere outside (Fig 5-3). Because of the low gravity it is probably a good idea to have a few surface centrifuges (Fig 5.4); like space colonies rotating about a vertical axis, they provide a full Earth gravity towards the periphery of the habitat. That's the main problem with living on Mars: the low gravity may not be at all good for one's health. If nothing else, it won't make going to the toilet any easier (the Moon, of course, is even worse).

After terraforming we have a pretty-looking Mars with old-fashioned canals (Fig 5.5). Water drains from the uplands and the polar ice caps into the valleys, cascading through chains of broad lakes and sweeping falls into canals like narrow seas, and thence into the broad equatorial canal. Away from the canals lie the high deserts, the tablelands, the mountains.

In the *handramits* (the canal valleys, if you know your C. S. Lewis), the climate is pleasant — temperate or tropical according to latitude. Fertile lowlands, on either side of the deep water, give way to forest slopes and gaunt hills of glass. The *harandra* (the uplands, the old surface) is wild and lonely. Its climate is harsh and continental, arctic tundra to and desert; freezing by night, sweltering by day. Shallow seas in the old basins moderate these temperature extremes, producing a subtropical or Mediterranean climate.

Earthlike — and yet not like Earth — a world familiar enough to be pleasant and different enough to be interesting. The New Mars. Think of it as a planetary "Disney World".

5.2 Venus

For really living we want Venus.

Venus is practically a twin of the Earth. Or it could be, once we've cooled it down to 290K from its present molten-lead heat; removed the excess CO_2 (it has around 100 atmospheres at present — and practically all of it must go); provided breathable oxygen, reduced the day to something like 24 hours (because the Venusian day lasts about 120 Earthly days — and that's a bit too long to stay out of bed, and provided upwards of 100 metres of water over the whole parched planet.

We could proceed as follows.

First we cool the planet with a sunshade (Fig 5.6), quite similar to the Mars soletta. It's a little more complicated than a simple shade — sunlight is deflected sideways just enough to miss the planet — but this way we eliminate most of the light pressure, making it easier to hold the shade in place with light from the annular support mirror.

At a later stage, when we want to occupy the planet, we can orbit another soletta in a 24-hour polar orbit; the sun will then appear in the sky 90 degrees away from its true position Venus is now in shadow and starts to cool down Unfortunately, because the atmosphere is so very think, it contains an enormous amount of heat and thus takes a long time to cool down — something like 200 years. Not so long to a planetologist, but to an engineer it's ridiculous. So we look for ways of speeding things up. There are several possibilities.

One way is to construct gigantic heat pipes connecting the hot dense lower atmosphere and the cool thin atmosphere around the 1 bar level (Fig 5.7). This keeps the upper atmosphere radiating as high a temperature as possible. Such heat pipes, although tens of kilometres high, are entirely feasible with fused rock construction. The way they work is this: at the bottom of the pipe the working fluid (water, to begin with) boils, flashing into steam through an expansion nozzle; at the top, the steam jet spreads out, cools and condenses; water drains back clown to the bottom and closes the loop. As the temperature falls, water is progressively replaced by ammonia. With heat pipes the cooling period can be cut to about 90 years.

Ninety years is still rather a long time, so recently I came up with a better scheme: heatballs (Fig -5.8).

Heatballs are hollow spheres containing a small amount of water. Down at the Venusian surface, they get hot: the water inside them evaporates. Now fling them up into space from the north pole. Out in space, they cool; the water recondenses. Wandering along magnetic field lines, they find their way back to the south pole and plunge towards the surface.

Guided now through evacuated conduits deep in the atmosphere back to the north pole, they heat up once more before swinging back out into space.

The heat balls are electrically charged, and follow magnetic field lines at orbital speeds without loss of kinetic energy. The required magnetic field can be generated by a pair of solenoids, one at either pole; the field strengths are quite small, so the amount of energy stored in the magnetic field is not enormous.

Because the heatballs can spread over a considerably wider expanse than that of the planet's surface alone, they can radiate from a much greater total area, and consequently radiate a correspondingly greater amount of heat. If the heatballs swing out to, say, three planetary radii cooling rates can thus be increased by a factor ~10, bringing cooling times down to as little as a decade,

The total mass of the heatballs is surprisingly low (equivalent to only ~16 mm of water over Venus) because the water (which has a high latent heat of vaporisation) is effectively reused every orbit, say every 10,000 seconds.

As Venus cools, carbon dioxide rains out of the atmosphere, forming oceans in the low-lying regions. I don't know whether dry ice is denser or lighter than the liquid CO_2, so I'm not sure whether those oceans freeze over; however, any water ice will naturally float on top of the CO_2. Now because we don't really want oceans of liquid carbon dioxide we can cover them over with a floating platform of lightweight hollow blocks (Fig 5.9). The water ocean goes on top.

To get that water ocean we have to find some water. Where from? The icy moons of Saturn are the best bet — Enceladus, for example, could provide enough water to cover Venus to a depth of ~140m.

A steam-powered rocket drives the iceman out of its orbit, bouncing it off the gravity fields of other satellites, flinging it away from Saturn and into the inner Solar System. Eventually it approaches Venus, where we break it in half, one half swings round one side of Venus, the other half round the other (Fig 5.10). Now divide each half further into, say, 100 moonlets. These moonlets orbit the Sun with the same period as Venus; every half orbit then, that is, every 112 days, they return to the vicinity of Venus, where they collide, a pair at a time, just, short of the planet. Water vapour from the vaporised moonlets falls onto the planet and cools to become rain.

During icefall, it's a good idea to protect the surface from the heat and flash. We use a sky canopy, not unlike a para-terraforming roof, but a good deal thinner (we're not trying to hold in an atmosphere, just providing a sort of lightweight tent around the globe).

You can live on the surface during icefall; simply cover your colony with a transparent tent (Fig 5.1 1); the atmosphere inside is soon made breathable, but the pressure inside and outside is the same (this makes it much easier than para-terraforming on Mars). Enlarging the colony is easy; just make the tent bigger.

In the early stages of terraforming, the construction of aerial colonies (Fig 5.12), floating like enormous dirigible balloons high in Venus' atmosphere — at around the 1 bar level, where the temperature is not excessive — would enable us to move colonists in straight away providing useful economic returns early on.

After terraforming, we have a planet very like the Earth, with both land and seas, and a sun crossing the sky once every twenty-four hours. However because day and night is produced by an orbiting soletta, instead of by the planet's spin, the sun's path across the sky is peculiar Fig 5.13). This feature is likely to lead to climate patterns more even than on Earth; nowhere as persistently cold as the Arctic and Antarctic, nor as persistently hot as the equator.

5.3 Suitable Planets are Few

The snag is: there are only two readily terraformable planets in the Solar System — Mars, and Venus. We might be able to do something with oddments like Ganymede or Titan but even so, the potential of terraforming is limited to a total additional surface area less than twice that of the Earth. For more, we must turn to artificial planets, space colonies, or other solar systems.

6. SPACE COLONIES

Space colonies, indeed most forms of human habitat, will comprise (Fig 6.1):

The *luminosphere* provides the habitat with light and heat from the sun or some other source of energy. The *atmosphere* provides breathable air and is important in weather. The *biosphere* includes all life forms but not their non-living environment (in the literature, biosphere is sometimes given the wider meaning of an ecosystem). The *geosphere* is the landscaped surface of soil, rock and water, over a contoured base. The geosphere base is likely to be of a lightweight fractal honeycomb construction Below the base is the *toposphere*, supporting the whole habitat.

These are generic descriptions applicable to most forms of habitat, including natural planets like the Earth (where the geosphere is mostly solid rock, and the toposphere is the mantle and core).

6.1 Rotating Space Habitats

Suitable locations for space colonies include orbits around the Earth-Moon Lagrange points. Consider a large fat cylinder rotating on its axis (Fig 6.2); a landscape of seas, plains and mountains girdles it within, while sunlight, reflected from external mirrors, enters through the end caps.

The total mass of the habitat works out at around 40 tonnes per square metre of habitable land, more or less equally divided amongst atmosphere, crust, geosphere base and toposphere (Fig 6.3).

The geosphere base uses a low-density fractal architecture to keep the structural mass low, slotted together out of strong but readily available fractal blocks of fused rock (Fig 6.4). This is a constructional technique equally suitable for supramundane planets and rotating space habitats; it provides strength in tension as well as compression whereas normal masonry construction only has strength in compression.

The maximum size of conventional rotating space colonies is determined largely by the strength of available structural materials. The limit is about 250 km radius for quartz, 1000 km for sapphire, and 2500 km for diamond. That last case is actually pretty big, a colony equalling the land area of the Earth. Even so, most conventional space colonies will be considerably smaller than natural planets.

To some extent we can get around the size limit by making colonies longer, because the constraint is on the radius not the length. An extreme example is the macaroni habitat (Fig 6.5), an ultra-long habitat with a sunshine tube down the middle, if we loop it all the way round a star the total habitable area may be around 2000 times that of the Earth. And if we stretch a macaroni tube along tramlines between one star and another, the habitat area becomes something like 100 million Earths. There is sufficient material in the solar system to construct macaroni habitats thousands of light years long.

Even the largest diamond colony or the longest macaroni habitat is not a planet, though, because planets have horizons and you live on the outside, whereas space colonies have the outside on the inside!

6.2 Supramundane Habitats

Now we come to artificial planets.

A supramundane planet is a kind of ultimate space colony, an artificial planet with the outside properly on the outside, with natural horizons and natural weather, with night and day naturally chasing each other round the spinning globe.

A supramundane planet (Fig 6.6) is built around a massive heavenly body, such as a jovian planet. The habitable surface is supported dynamically above the underbody by orbital rings or dynamic compression members; the details of its landscaping, geosphere, geosphere base, biosphere and atmosphere are similar to those of other space habitats. It is illuminated from above with mirrors. Below is the toposphere (the support mechanism and orbital rings) in the otherwise empty space above the underbody.

Supporting the habitat with orbital rings avoids any requirement for ultra-strong materials: we no longer need to manufacture diamond in gigatonne lots.

The underbody could be a planet, a star, even a black hole; however, its gravity has to exceed 1 g because that's the gravity we want for the habitable surface. Then the area of the supramundane planet in Earth areas is simply equal to the underbody mass in Earth masses. The more mass you have the bigger your supramundane planet.

Rotating supramundane planets take up a shape like an oblate spheroid (Fig 6.7); a twenty-four hour period is easily provided for habitats above any size of underbody, up to the heaviest super-jovian on the verge of becoming a brown dwarf star.

A rotating supramundane planet is illuminated by means of a magnifying soletta (Fig 6.8), supported by the pressure of light from an annular support mirror, the rather complex shape is for stability. It turns out that wherever the planet is situated – even far- into interstellar space – it's possible to gather enough sunlight to enable earthlike conditions to be maintained.

Damage limitation is a bit of a problem (Fig 6.9). If someone sets off a nuclear explosion or drops an asteroid onto the habitat, we don't want the whole artificial planet collapsing on us. Observe how the support grid, even with a big chunk knocked out, of it, has to redistribute itself into a distorted grid that nevertheless continues to support the planet. This is probably the trickiest part of the whole affair: to make certain that the supramundane planet cannot possibly fall down under any limited number of failures.

There is enough energy in the system to vaporise the whole planet, so we must make absolutely sure it can't get loose.

We don't have to complete a supramundane planet in one go (Fig 6.10); we can start off with smaller units, such as a strip habitat in a ring around the planet, or a plate habitat at the junction of several strips. We then simply extend those strips sideways as we need. We don't have to find the money for the whole planet at once — only for the next habitat extension.

Where does the material for these artificial planets come from (Fig 6.11)? There's plenty in the underbody planets and their moons. We don't even have to spend any energy; with a bit of cunning we can carry mass simultaneously inwards from the moons and up from the planet, balancing both angular momentum and energy. Another possible source of material is the Sun (Fig 6.12), which could be mined using a ramscoop to collect gases from the stellar atmosphere and separate out the metals.

7. GENERIC TERRAFORMING TECHNIQUES

7.1 Extrasolar Planets

Well, that's more or less it for the Solar System. But are there planets in other solar systems? Probably there are. However, in all those billions of other solar systems there are probably very few genuinely habitable planets, planets where you could jump out of your ship without a space suit and start farming. Nevertheless, many extrasolar planets will be suitable for terraforming.

The most valuable planets will be like the Earth before life arose. Others will be like Mars or Venus. At the most, there may be a handful per solar system. Their combined areas will therefore be small compared to the potential habitable area of fabricated space colonies and supramundane planets. Nevertheless, such planets will have a not inconsiderable value as robust reservoirs of life; once created, a terraformed planet is much harder to knock out than a space habitat.

Our strategy should therefore be to terraform each planet quickly (so that settlers can move in), then proceed to a full planetological terraform over a longer period, so that the system becomes adequately stable without drastic maintenance over geological time.

7.2 Mirrors for Planetary Warming/Cooling

Among cheap and cheerful generic techniques, lightweight mirrors in space must take pride of place. With soletta mirrors it is easy to warm a planet, or cool it, or to adjust the temperature distribution across its surface almost any way we like.

On excessively hot worlds like Venus, temperatures can be moderated by means of a light-supported sunshade. This is practicable surprisingly close to the central star — even to within a few stellar radii. Thin atmospheres will cool quickly; thicker ones may call for heatpipes or heatballs to speed things up.

On icy worlds like Mars, temperatures can be raised by means of a magnifying soletta. This is practicable even to distances of about a third of a light year from the central star (depending upon stellar type). Indeed even in interstellar space, enough starlight could be collected to illuminate and warm an earthlike habitat or terraformed planet The thin atmospheres of such worlds will warm quickly.

A problem arises with low-gravity worlds, like Mars. the greater depth of their atmospheres enhances the greenhouse effect (water vapour, by the way, is by far the most important, greenhouse gas in the atmospheres of habitable planets), which tends to destabilise the climate. Icehouse and hothouse runaway may then only be avoided by active control of the insolation to maintain temperatures within the desired range. This degree of control of the soletta is not at all onerous; the requirement does however mean that the full planetological terraform may not be achieved.

7.3 Energy Intensive Engineering of Crust

Regoliths can take for ever to thaw, but with regolith vaporisation we can release volatiles and mould the surface topography quickly. Options for regolith vaporisation include the use of thermonuclear explosives, the impact of comets, the projection of pellet streams from space, or the focusing of sunlight by solettas and aerial lenses.

Since interstellar flight also demands powerful energy sources (such as relativistic pellet streams) the same energy sources are likely to be available to colonists for terraforming extrasolar planets on arrival.

7.4 Photosynthesis for Atmosphere Modification

Photosynthesis is clearly an integral feature of the ecosystems of habitable worlds, but in most terraforming scenarios is also used to generate a breathable atmosphere in the first place.

Initially, photosynthesis should be much faster than on Earth as higher levels of CO^2 and an abundance of water, nitrates and other nutrients encourage rapid and efficient plant growth. An immature surface, without pervasive drainage channels, leads to extensive eutrophic lakes. The climate is controlled. There are few decay organisms or animals. Only the most productive strains of algae, grasses, reeds and other luxuriant species are employed.

All in all, photosynthesis can probably provide a breathable atmosphere in decades rather than millennia. Most people would probably disagree with me on that, and that is almost certainly because they are basing their ideas upon the natural ecology of the Earth. However, I would claim that terraforming is an engineering problem not a question of natural ecology. The quasi-equilibrium state of Earth has tittle in common with the purposeful, radical and rapid transformation of a planet during the process of terraforming.

7.5 Import/Export of Volatiles

The import and export of volatiles can be expensive in planetary quantities. Perhaps that can be turned to an advantage — volatiles can be traded. By exporting excess volatiles we don't need we can pay (both in money and energy) for the import of other volatiles — for example, swapping carbon dioxide or nitrogen for water.

Crashing comets — or moonlets of water or ammonia ice — onto planets to be terraformed is likely to be considerably cheaper. The supply is limited, but likely to prove adequate for the similarly limited number of terraformable planets.

If we consider the elemental abundances obtaining throughout the universe we see that adequate quantities of the elements needed for terraforming and habitat construction should be available in all parts of the galaxy. Some of these elements may not be in the best places — some we may have to seek in the stars themselves — but we can get at them; no overall shortages are to be expected. We must therefore conclude that the terraforming of extrasolar planets is indeed feasible.

7.6 Pellet Streams for Orbit Modification

It would obviously be tidier if we could shift each terraformed planet into a suitable stable orbit, where earthlike conditions could be obtained without having to mess around with solettas and sunshades.

Within our solar system Venus is too close to the Sun and too hot. We could move it out to the orbit of Earth in as little as thirty years, pushing off hard against the other planets (Fig 7.1). The near-relativistic pellet streams of the dynamic compression members generate enormous forces, even though their total mass is modest.

The energy required comes partly from light sail windmills round the Sun, but mainly from the orbital energy of the planets. There's a sort of free-lunch effect here: once we start pushing against, say, Mercury, orbital energy from Mercury's motion boosts the kinetic energy of the mass-streams; energy is then transferred into the orbital motion of Venus with high efficiency. Just pushing against the Sun (Fig 7.2) would be much less effective, because the angle through which the compression member acts would be very small.

Even if we decide not, to use this technique within our own solar system, it should certainly prove useful elsewhere. Its particular merit is that it enables full planetological terraforming to be achieved.

8. SCENARIO — FUTURE HISTORY 2000 - 2200 AD

[Note: written 1993 on *assumption* (not prediction) of projects' immediate commencement; add appropriate number of years for actual start date.]

2000 Space Hotel constructed in Low Earth Orbit. Soon caters for 100,000 people a week.

2010 First settlements on Mars. Surveys performed. Lunar City, Lunar mining. Colonies at L4 and L5.

2020 Terraforming of Mars begins. Construction of mirrors in Mars orbit. Asteroid mining. Cylindrical colonies at L5. First starship departs for a-Centauri.

2021 Mars soletta and aerial lens deployed Regolith vaporisation commences.

2022 Selected plant life distributed over Mars. Photosynthetic transformation of air begins.

2030 Little Switzerland built — radius 80 km. Missions to e-Eridani and other stars.

2040 Terraforming of Venus begin Heat pipes emplaced in Venusian atmosphere. PDL built — radius 160 km.

2050 First aerial colonies on Venus. Sunshade deployed Supra-uranian strip habitat commenced

2060 Carbon dioxide rain reaches Venusian surface. Archipelago built — radius 320 km. Suprajupiter strip habitat commenced

2070 Devolatilisation of Martian regolith completed. Suprasaturn strip habitat commenced Extrasolar habitats built by colonists.

2080 Terraforming of Mars completed Sapphire colony of radius 640 km. Rapid transit in-system at continuous one gee.

2100 First ground stations established on Venus. Lage scale mining of outer planets.

2130 First tent colonies established on Venus. Rupture of Enceladus commences. Diamondia built — radius 2560 km.

2160 Carbon dioxide oceans on Venus now covered. Sky-canopy deployed. Icefall commences. Photosynthesis of atmosphere proceeds Supra-Uranus is now 2000 km wide.

2190 End of Icefall. Canopies dismantled. Terraforming of Venus completed

>2200 Interstellar colonisation continues. Terraforming of extrasolar planets.

9. BLUE SKIES

That's more or less it for custom planets. Except for those planets of gold I mentioned.

Unfortunately, there's not enough gold in the asteroids, the cores of gas giants, or even the atmospheres of stars. To satisfy our lust we must seek out, the neutron stars, where mass transmutation of the elements goes on. Neutron stars are the philosophers' stone of the universe.

To mine a neutron star (Fig 9.1) we use the powerful magnetic fields of the star itself and an energy beam spearing down to the magnetic pole. Now we can guide the near-relativistic jet of neutron star material through a clever mass spectrometer arrangement to yield streams of pure elements. By tuning the beam, we can obtain any element we want. it becomes as easy to build a planet of gold as a planet of muck. And if you want a miniaturised personalised, private star — just assemble a moon of uranium and stand back!

Star-mining lets us build even bigger supramundane planets. Around ordinary stars we build multi-layered suprastellar planets (Fig 9.2). With some 10,000 layers the total area is around three billion Earths — that's for a G3 star like the Sun. Even larger are suprahole planets, powered by material falling into a black hole of a few solar masses up to galactic masses. There may be a 3 x 10^8 solar mass black hole at the centre of our own galaxy, which we could use as the underbody for planets 10^{14} times the size of the Earth. Even greater masses may be found in the core of cluster-dominant elliptical galaxies.

Eventually, in this sequence of ever larger supramundane planets, we come to Supraself (Fig 9.3), which has no underbody, for its gravity is generated by its own mass; each shell is dynamically supported within the gravity of the shells beneath. Supraself has a mass of about 2 x 10^{12} solar-masses, as massive as the largest galaxies. The outer shell is about 1.2 light years in radius, and 14 square light years in area, which is quite a lot of land to find in one chunk. And of course that's only the first layer; there's another 30 million shells below that. The total habitat area is thus about 2 x 10^{23} Earths. I guess even Americans, would take a fortnight or more to "do" Supraself!

At this size we have to be careful to avoid gravitational collapse, as some of the layers lie very close to their event horizons. Considerable space-time distortions occur around Supraself — it takes General Relativity to describe the geometry and analyse the physics. Thus time in the heart of Supraself is running 2500 times slower than in the universe at large, and even on the outer shell the stars in the sky are strongly blue-shifted.

Well, that's about the biggest planet in the current catalogue, and all I have for you today. Perhaps the next stage should be the Custom Universe, or, Move over Gods!

* * *

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FIGURE CAPTIONS

Section 3

Fig. 3.1 Economics

Fig. 3.2 Population in space — doubling time is ~3 years and population growth rate ~25% per annum.

Fig. 3.3 Scenario predictions for population and habitat area.

Fig. 3.4 Lunar City/Base in subsurface cavern.

Section 5

Fig. 5.1 Mars Mirror system — Soletta Geometry and Light Paths (source "Terraforming Mars Quickly", *JBIS*, **45**, 331-340 (1992) (fig.1))

Fig. 5.2 Aerial Mirror Lens and Regolith Melt (source "Terraforming Mars Quickly", *JBIS*, **45**, 331-340 (1992) (fig.2))

Fig. 5.3 Domed City Colony on Mars (source "Terraforming Mars Quickly", *JBIS*, **45**, 331-340 (1992) (fig.3))

Fig. 5.4 Surface Centrifuge within Domed City (source "Terraforming Mars Quickly", *JBIS*, **45**, 331-340 (1992) (fig.4))

Fig. 5.5 Mars After Terraforming (source "Terraforming Mars Quickly", *JBIS*, **45**, 331-340 (1992) (fig.5))

Fig. 5.6 Venus Mirror System (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.7))

Fig. 5.7 Cooling by Shading and the use of Heat-Pipes (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (combined figure from figs 1 & 2))

Fig. 5.8 Cooling Venus with Heat-Balls

Fig 5.9 Thermally Insulating for Carbon Dioxide Oceans (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.4))

Fig. 5.10 Ice-Moon Trajectories Near Venus (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.3))

Fig. 5.11 Colony on Venus after Cooling (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.5))

Fig 5.12 Two kinds of Floating Colony (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.6))

Fig. 5.13 Track of Reflected Sun Across Venus' Sky (source "Terraforming Venus Quickly", *JBIS*, **44**, 157-167 (1991) (fig.8))

Section 6

Fig. 6.1 Parts of Habitat — Generic Descriptions

Fig. 6.2 Large Cylindrical Space Colony

Fig. 6.3 General Layout of Geosphere and the Provision of Landscaped Surface Relief (source "Supramundane Planets", *JBIS*, **44**, 169-182 (1991) (fig.4))

Fig. 6.4 Fractal Architecture and Building Blocks (source "Supramundane Planets", *JBIS*, **44**, 169-182 (1991) (fig.5(b) and (a) i.e. order reversed))

Fig. 6.5 Macaroni Habitats

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