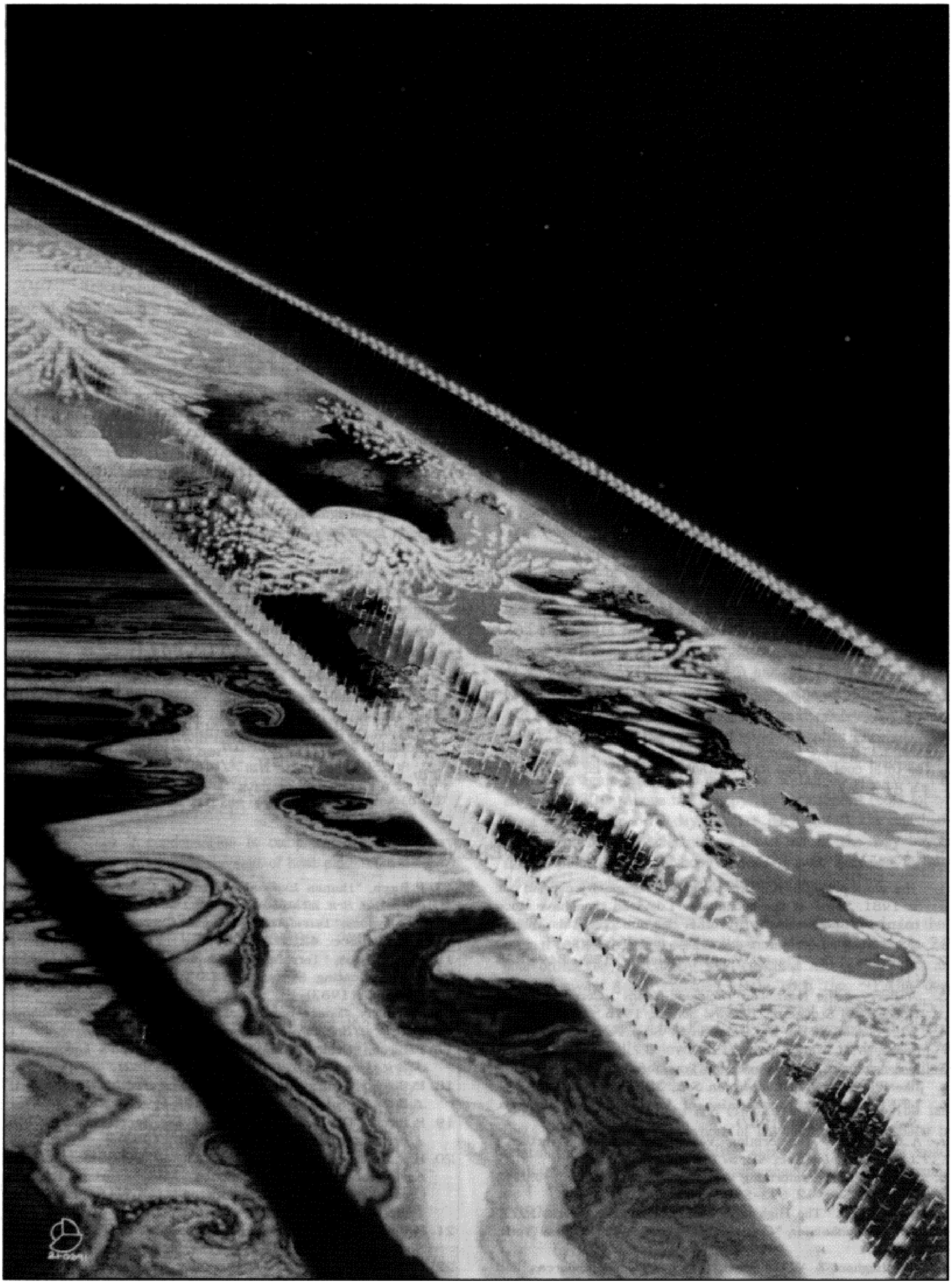

Suprajupiter in construction. Stage one: the strip habitat.

(Artist: Ron Brocklehurst)

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SUPRAMUNDANE PLANETS

PAUL BIRCH
48, Cliff Road, Cowes, IOW, PO31 8BN, England

Conventional space colony designs are toroidal or cylindrical and spun to simulate gravity. Such habitats cannot easily be made as large as a planet unless materials stronger than diamond are available in bulk. Successful imitation of planetary horizons and weather patterns may not be simple. It is shown that habitats of planetary size may be constructed by englobing any sufficiently large planet with a new landscaped surface, which can be supported by Orbital Rings or Dynamic Compression Members. These artificial *supramundane* planets can sustain natural horizons and natural weather. Even larger habitats may be constructed by englobing stars or black holes. It is shown that supramundane habitats and planets can be built progressively in affordable stages. A scenario is presented suggesting that in a few centuries supramundane planets may house a large fraction of the human race.

1. INTRODUCTION

The concept of habitats dynamically supported by orbital rings [1-3] or dynamic compression members [4] was introduced in an earlier paper [3]. It has also been mentioned in my paper on terraforming Venus, in this issue [5]. Here we go into more detail.

First, some definitions. A habitat supported above a planet, star or other massive heavenly body we call a *supramundane habitat* (from the Latin *supra*, above, and *mundus*, world). If the habitat is a globe completely surrounding the gravitating body we call it a *supramundane planet*. An artificial planet englobing a gas-giant is then a *suprajovian planet*. And a structure englobing a star, also known as a Dyson sphere, is a *suprastellar planet* [6]. Suffices representing other astronomical bodies—*eg supraplanetary, suprahole*—can also be used.

The *underplanet* or *underbody* is the underlying planet or other heavenly body, which generates the supramundane planet's gravity. The apt term *underworld* may be less suitable for technical use.

The foundation of a habitat is the *toposphere* (a neologism from the Greek *topos*, place, and *sphaira*, sphere, region), comprising the structural components whose arrangement determines the topology and overall shape. In this paper we shall be considering not only the construction of the toposphere, but also the provision of an atmosphere, a biosphere, a geosphere and a luminosphere.

The *atmosphere* (Greek *atmos*, air) of a habitat includes the air we breathe and its weather; the upper atmosphere may also include ozone layers, ionospheres and magnetospheres. The *biosphere* (Greek *bios*, life) includes all the living organisms in the habitat. *Geosphere* (Greek *ge*, earth) is a neologism for the earth, soil, rocks and waters of a habitat, and could also be applied to the crust of a natural planet. *Luminosphere* (Latin *lumen*, light, and *sphaera*, sphere) is a neologism for the sky, and the illumination of the habitat by day and night (a clumsy word, but the Greek form photosphere has been pre-empted for the light-giving part of the Sun).

In conventional space colony designs [7-9] gravity is simulated by spinning the structure. The overall shape is toroidal or cylindrical. The toposphere is in tension, a suspension bridge without end. It must use strong materials; the maximum radius of such a habitat is determined by the strength to weight ratio of the tension members. A toposphere of fused quartz could have a radius up to about 200 km, of diamond perhaps 2500 km. These figures can be improved upon if the habitat alone (and not the tension structure) is made to spin; but it is apparent that constructing space settlements of planetary size by these methods will be difficult without exceptionally strong materials. By contrast, dynamic support techniques are not dependent on material strength [1-4].

In a rotating space colony "centrifugal force" replaces gravity. The geosphere is therefore flat along the axial direction, and curves *upwards* to spinward and anti-spinward. Consequently, except for the effects of relief, no natural horizon exists. In a large enough colony fractal relief [10] will help generate horizons, but unless we take care the terrain to spinward and anti-spinward may still dominate the sky.

The Coriolis force, which controls planetary weather patterns, is oriented axially in a rotating space colony. It will tend to promote vertical vortices rather than the horizontal vortices obtaining on Earth; this will affect atmospheric circulation and may lead to different weather-patterns.

The disadvantages of the conventional space colony are not serious. They will be pleasant places to live, large enough to contain whole countries and convenient for space travel. It is probable that within a century or so most of the human race will reside in such space settlements. It is unlikely that natural planets will then ever again accomodate more than a small fraction of the total population.

Nevertheless, planetary-sized habitats, with natural weather and natural horizons, will assuredly be attractive to many people, especially if their climate, geography, seasons, flora and fauna are pleasantly Earthlike. If they can be constructed at a reasonable cost per unit area, they will compete effectively with smaller rotating space colonies, though they are unlikely to replace them altogether.

This paper shows how planetary-sized habitats can be established around any sufficiently large astronomical body, by constructing a new surface, supported by orbital rings or dynamic compression members, at the radius at which the acceleration due to gravity is one Earth gravity ($9.81\,ms^{-2}$). These artificial planets will have all the outward characteristics of natural planets. Gravity will be directed inward. The geosphere will curve down to the horizon in all directions. If the planet rotates daily on its axis the Coriolis force will give rise to natural weather, and night and day will progress naturally around the globe.

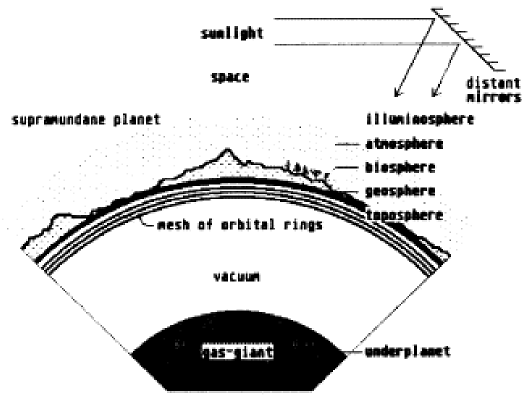

Fig. 1. A supramundane planet.

A supramundane planet will have its sky fully open to the heavens, but an incomplete habitat will need sidewalls to retain its atmosphere.

The cost of the atmosphere, geosphere, biosphere and luminosphere of supramundane and rotating habitats are roughly the same. The cost and thickness of the high-strength toposphere of a rotating habitat is proportional to its radius; but the toposphere of a supramundane habitat does not need to be made of strong materials [1-4] and its cost is only weakly dependent on its size, its areal mass density being of the same order as that of the supported habitat and independent of its radius. It is apparent that the cost of a supramundane habitat should be competitive with the cost of conventional space colonies.

By contrast with most scenarios for the terraforming of natural planets, the construction of supramundane habitats can progress quickly. If the market were sufficiently buoyant a large artificial planet could be constructed in only a few years; but if demand is less strong, construction can proceed more slowly and by small stages, successive portions of the planet being occupied as they are completed.

2. SUPRAMUNDANE PLANETS

An Earthlike supramundane planet for human habitation (Fig. 1), with a surface gravity approximately equal to that of the Earth, can be constructed if the underlying heavenly body itself has a surface gravity not less than this amount. If the mass of the underbody is M, then the surface area of the supramundane planet is given simply by:

$$A = A_{\oplus} M / M_{\oplus}$$

Suprajupiter, for example, would have an area some 316 times that of the Earth, and a radius $\sim 1.1 \times 10^8$m $\sim 1.6\,R_{♃}$. Similarly, Saturn, Uranus and Neptune would provide 95, 15 and 17 times the Earth's surface area respectively. By the same token, a single suprastellar planet would have an area $\sim 3 \times 10^5 A_{\oplus}$.

It is immediately apparent that supramundane planets can provide orders of magnitude more living space than natural planets, a property they share with other forms of artificially constructed space habitat.

The diagram shows the basic features of supramundane planets: the underlying planet; the support or foundation of orbital rings and dynamic compression members; the foamed or hollow core moulded to the desired topography; the crust or shell of rock, soil and water; the atmosphere, open to space; the distant sunshades and mirrors for illumination. In the following sections we examine these components in more detail.

3. TOPOSPHERE

3.1 Support Energy

A supramundane planet is supported and upheld by the flow of momentum in a web of orbital rings or dynamic compression members in its toposphere. There is a simple relation between the amount of kinetic energy required of the mass-streams and the gross weight supported. The kinetic energy is the product of the gross weight and the radius, independent of the detailed arrangement. Let the radius, gross areal density and surface gravity of the supramundane planet be R, ρ_{ag} and g. Then the gross weight supported and the total kinetic energy required are:

$$W = A\,\rho_{ag}\,g = 4\pi R^2 \rho_{ag}\,g$$

$$E = \tfrac{1}{2} W R$$

It should come as no surprise that the kinetic energy required is just the amount that would be needed to place the entire mass of the supramundane planet into a circular orbit at that same height.

This is quite a general non-relativistic law, known elsewhere as the Virial Theorem. It is true if the planet is supported by circumferential orbital rings, or by compression members down to the centre, or a criss-crossing lattice of struts, or by the pressure of a monatomic gas. If the support medium is relativistic—such as light, electromagnetic radiation or electron beams—the amount of energy is doubled.

Some caution is needed in applying this formula, however. First, the weight of the orbital rings or support medium must be included in the total. Second, if the mass of the supramundane planet—including the support structure—is distributed over a range of radius, the kinetic energy is to be summed over all components. Third, if any of the weight is taken by a solid planetary surface, the length of those supporting mass-streams that reach the surface, and thus their kinetic energy, is reduced accordingly.

We note that the toposphere possesses global stability, for if the supramundane planet should start to collapse inwards, work would be done against the toposphere, increasing the energy stored in the orbital rings and hence the outwards pressure. Ensuring full local stability is more difficult, but suitable lattice-works of orbital rings and compression members can be devised.

Although the kinetic energy of the orbital rings is well-specified, the choice of their mass seems fairly arbitrary. Two extreme possibilities exist: the mass of the orbital rings can be a vanishingly small fraction of the total mass if their velocity is greatly in excess of the orbital velocity; or the mass of the orbital rings can dominate if their velocity is only slightly higher than the orbital velocity. Excessively massive orbital rings would be costly, but if the toposphere is too light it may be unable to balance the angular momentum of the supramundane planet's diurnal rotation (section 3.3). The stability of the system (section 3.4) may also be enhanced by a modest toposphere mass. An orbital-ring mass-fraction in the range 20–50% may therefore be chosen.

Supramundane habitats can reduce their support energy requirements, if the underplanet is not too far below, by raising the habitats above a base floating in the underplanet's atmosphere. If the gravity of the underplanet is about $1g$ the habitat itself can float in the atmosphere. Such aerial colonies could be aggregated into an artificial planetary surface, a supramundane planet without orbital rings [5].

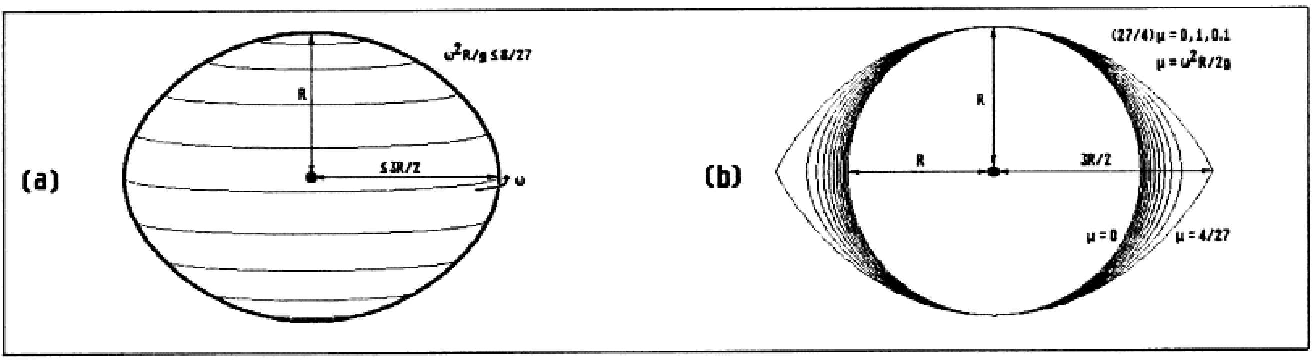

Fig. 2. Geometry of rotating supramundane planets (a) Equatorial bulge (b) Family of shapes over range of the rotation parameter.

3.2 Geometry of Rotating Supramundane Planets

The toposphere of an Earthlike supramundane planet is basically spherical. The shape is that of the equipotential surfaces of the gravitational field—which for a point source are of course spherical. If the toposphere did not follow an equipotential then some parts of the planet would be 'lower' than others, and the waters and atmosphere would flow down to them, leaving the rest uninhabitable. Thus deviations from the equipotentials should not normally exceed a few kilometres at most.

Now suppose that we cause the supramundane planet to rotate. The equipotentials, in what is now a non-central field of force [1], take the approximate form of oblate spheroids (Fig. 2). If the angular velocity is ω, the polar radius and surface gravity are R and g, the radius at a zenithal angle ϑ is r, and we define parametric variables $\rho = r/R$ and $\mu = \omega^2 R/2g$, then the shape of the supramundane planet's surface is described by the equation:

$$1 - \rho + \mu \rho^3 \cos^2\vartheta = 0$$

We note that the limiting case of rapid rotation occurs when $\mu = 4/27$, at which angular velocity there is a cusp on the equator, where the radius achieves its maximum value of $3R/2$ and the surface gravity falls to zero. Greater values of the rotation parameter do not lead to possible planetary surfaces.

If we choose a 24-hour rotation period and a one-gee polar gravity, the maximum value of the polar radius is then $8g/27\omega^2 \approx 5.5\times10^8$m $\approx 86R_\oplus$. This corresponds to an underplanet mass of $7400M_\oplus \approx 24M_♃ \approx M_\odot/40$.

Physical rotation of all suprajovian planets should therefore be practicable, up to and including those encompassing substellar bodies or brown dwarfs. These will be illuminated from without, and thus diurnal rotation will be of value. Larger versions will be considered as superstellar planets, which we expect to illuminate using power from the star itself—from inside the planet. Diurnal rotation would no longer be useful. Thus we see that the rotation limit falls conveniently around the boundary between suprajovian and suprastellar planets, between external illumination and internal illumination.

The above analysis has assumed a point source model for the gravitational field. If the underbody itself is oblate—due to its own rotation—it will induce oblateness in the supramundane planet. This effect will be significant only when the underplanet is only slightly smaller than the supramundane planet—as with the outer planets Saturn, Uranus and Neptune. Sub-stellar bodies, although much more massive than Jupiter, are actually smaller, so their oblateness will not noticeably modify the shape of the supramundane planet.

Although the gas-giants in our solar system are only slightly oblate, it is possible that others elsewhere may rotate so fast that they are almost disk-like, with an equatorial radius up to 12/7 the polar radius. A fictional—but scientifically remarkably sound—account of life on such a rapidly spinning heavy-gravity planet can be found in Ref 11. Such scenarios can be simulated with a rapidly rotating supramundane planet, which will have a substantially lower gravity at the equator than at the poles—taken to extremes, the equatorial gravity will drop almost to zero.

Tides may be simulated by allowing the shape of the planet to vary from the equipotential in a periodic fashion. Only a very slight vertical movement ~1m would normally be used—although tides of any magnitude could be generated. Very complex tidal patterns with any combination of periods are possible.

3.3 Counter-rotation of Toposphere

A rotating supramundane planet will have a large angular momentum which will tend to keep its rotation axis aligned in a particular direction—like a gyroscope or a natural planet. On Earth, the rotation axis is inclined at ~23½° to its orbit, a feature to which we owe our seasons. Axial tilt of a supramundane planet would give seasons there too, but with a 'year' equal to the orbital period of the planet around the Sun. To provide Earthlike seasons and a standard year, the rotation axis should be made to precess with a suitable period ~1 year.

Precession of the rotation axis can be accomplished without difficulty if the *net* angular momentum is zero. To this end we may cause the inner toposphere and the mass of the supporting orbital rings to counter-rotate. That is, they are given a net angular momentum equal and opposite to that of the upper toposphere and the surface of the supramundane planet.

Now the axis can be precessed to any direction by the application of an orthogonal couple [1-3]. Since the rotational energy is always less than the orbital energy, and since the precession period is much greater than the rotation period, the precessing force is very much less than the weight and can therefore be made available at minimal cost.

It is therefore apparent that the rotation axis of a supramundane planet can be manipulated to give seasonal variations as we wish. Other effects could be produced, such as the night and day pattern of the terraformed Venus in Ref. 5—though this would be achieved more easily with mirrors, as described.

The rotation axis of some planets—like Uranus—may be highly inclined to the planet's orbital plane and the rotation axis of the supramundane planet. This will induce a breathing motion in the triaxial spheroid. The toposphere and geosphere may need extra suppleness in shear to follow this pulsation.

It should also be noted that the physical rotation of the supramundane planet gives rise to the Coriolis forces that help to drive our weather (section 6).

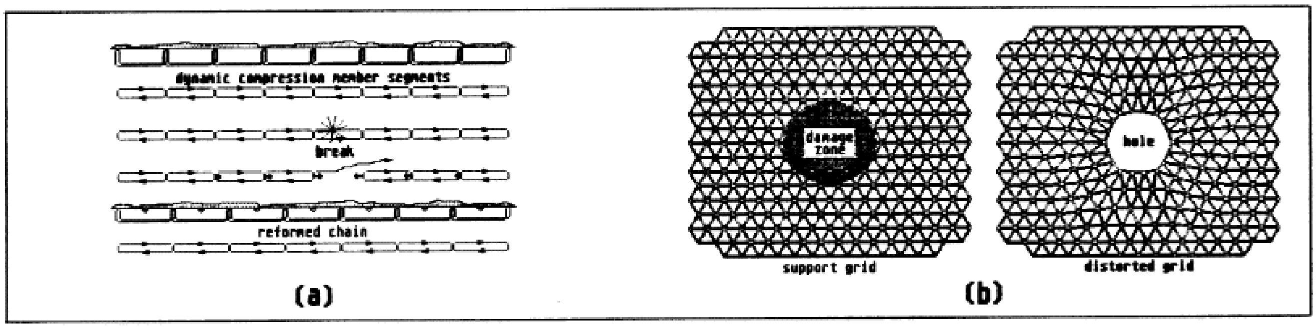

Fig. 3 Damage limitation (a) Reforming of compression chain after link failure (b) Adaption of support grid to a circular excision.

3.4 Support Grid Arrangement

The orbital rings and dynamic compression members can be arranged in a variety of ways. Many details and analyses of the mechanisms have been presented elsewhere [1-4]. They will not be repeated here. In Ref. 3 supramundane planets were described as supported by an arrangement of three orthogonal layers, each composed of coaxial orbital rings. There may, however, be disadvantages to this simple arrangement from the point of view of stability, redundancy and habitat extension.

A support grid containing many separate momentum loops and dynamic compression members as well as complete orbital rings is likely to be least susceptible to the destruction or failure of one or more of its components.

The property of *damage limitation* (Fig. 3) is the crucial requirement in the design of the topospheres of supramundane planets. Of all the orbital rings and support mechanisms in the assembly, some are bound to fail. If the failure of such a component could ever lead to the progressive failure of other members, the results would be catastrophic. That is, in all circumstances the failure of a given link must lead on average to the destruction of less than one further link. Chain reactions must at all costs be prevented. This is vital.

Fig. 3a outlines a process of damage limitation in a chain of dynamic compression members, whereby after loss of a link, the remaining units close ranks. Note that, because the chain is in compression, the unbalanced forces at the break naturally tend to push the links inward and reform the chain. For this purpose the links should be capable of significant elongation, which may sometimes be more than the elasticity of the loop material will permit. A number of techniques for providing this extensibility are described in Refs 1 & 2. A further technique, utilising additional loops of material, is indicated in the diagram. Here the extension of the chain is balanced by the fall of the supported load—note that as drawn there must be similar chains or other links below to balance the forces.

Fig. 3b shows some serious damage to a hexagonal support grid—a large circular hole has been punched through the middle, perhaps by a meteorite. The grid is distorted, but adapts its shape to divert the load around the hole. The hole shrinks by about 10% (exaggerated in the diagram). The shortening of the links around the hole increases their kinetic energy and the compressive force, while other links are lengthened and correspondingly weakened. The adiabatic extension or contraction of a non-relativistic dynamic compression member of length d modifies the energy stored in proportion to d^{-2} and the compressive force in proportion to d^{-3}, corresponding to a polytropic index $\gamma = 3$.

The design of the toposphere is improved if the orbital rings are not confined to a thin layer, but are spread out over a significant fraction of the supramundane planet's radius. Both stability and damage limitation are thereby enhanced.

Now an assemblage of pseudo-randomly oriented dynamic compression members filling the interior of the supramundane planet would behave as a hot monotonic gas, polytropic index $\gamma = 5/3$. This has the usual property that the pressure increases with depth, due to the weight of material above. Local stability is thereby imparted, in that if an area of the planet—*at constant areal density*—should move downwards, it would enter a region of higher pressure and be pushed back up, provided that the mass density of the 'gas' falls off with height at least as fast as $1/r$, when the toposphere mass-fraction is just 50%. This stability can be achieved with a lower mass-fraction if the pressure is anisotropic, that is, if the dynamic compression members are preferentially oriented towards the vertical. This in turn leads to the conclusion that orbital rings and dynamic compression members should criss-cross the interior of the supramundane planet, meeting the geosphere at steep angles, not simply following the circumference.

A potential cause of serious instability is the flow of air and water down towards a dip in the geosphere surface, or away from a rise. This must be actively avoided by maintaining the base of the geosphere strictly along the correct equipotentials. This can be achieved be supporting the geosphere base on an array of dynamic compression members which react to any increase in weight by *increasing* their length. That is, they are given a slightly *negative* reciprocal Young's Modulus [4].

Very low filling factors in the toposphere are advantageous for another reason. The kinetic energy of the toposphere elements is more than enough to vaporise the entire supramundane planet. It is therefore vital that if any of the mass-streams get loose and plough into other elements, the energy released must be dissipated without destroying yet more components or allowing further mass-streams to break free.

Where the mass-streams are widely spaced, jets of plasma from a failure zone will spread out widely before being intercepted. The energy flux will then be insufficient to damage the neighbouring mass-streams.

In the lattice of mass-streams, the sudden vaporisation of a given stream will release a kinetic energy of order gR per unit mass. Of this, a fraction proportional to the square root of the filling factor will be intercepted by the neighbouring mass-streams, which will receive an energy input per unit mass $\sim g\sqrt{(Rt)}/2\pi$, where t is the effective solid thickness of the geosphere ($\sim$10m or $\sim 2\times10^4\,\mathrm{kgm^{-2}}/2\times10^3\,\mathrm{kgm^{-3}}$). For Suprajupiter, the result is only $\sim 5\times10^4\,\mathrm{Jkg^{-1}}$. Not until we come to the heavy multi-layer suprastellar planets does this effect become large.

We may ensure that any mass-stream breaking loose is immediately vaporised by surrounding each stream or bundle of streams with a stationary sheath. Plasma and errant mass-streams could also be *deflected* away from vulnerable areas, such as the orbital-ring junctions and end-stations, by strong magnetic fields.

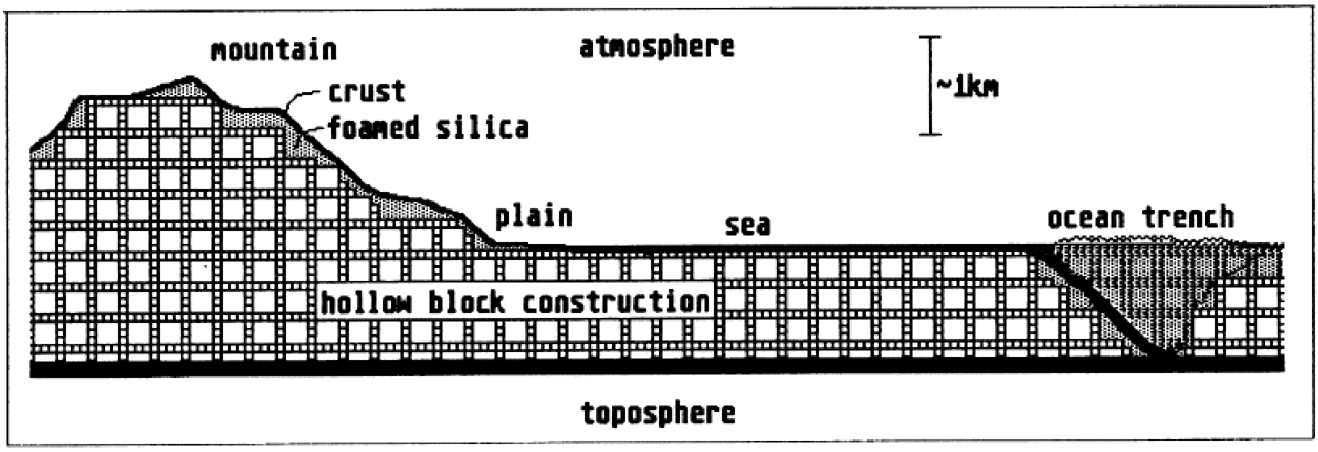

Fig. 4. General layout of geosphere and the provision of landscaped surface relief.

4. GEOSPHERE

The geosphere of a supramundane planet (Fig. 4), like that of a conventional rotating space habitat, is supported by the toposphere and is contoured to the desired shape.

Here we see that the toposphere forms a level foundation, upon which the irregular planetary surface is built up. The crust consists of a layer of rock and soil about five metres deep on average, landscaped in conformity with the fractal relief. Seas and lakes can have about ten metres depth of water instead.

Most of the volume below the surface is a foam or honeycomb of empty chambers. The mean density could be as low as $\sim 2\,kg\,m^{-3}$ to support the crust, but a figure of $\sim 10\,kgm^{-3}$ is more probable. The construction is based on slotted blocks of fused rock, built up into a fractal sponge [10].

In the simplest form, a flat fractal carpet (Fig. 5a) is projected upwards into a honeycomb of tubes or chimneys. The fractal dimension of the carpet is $D = \log 7/\log 4 = 1.4037$ and of the honeycomb therefore $D = \log 28/\log 4 = 2.4037$. Over a range of scale of $4^7 = 1.6\times10^4$ (say from 0.25m to 4km) the solid filling factor of building blocks of the structure is about 0.3% by volume. This is a convenient filling factor, but the deep chimneys are not very useful, and the structure has little strength in shear.

In a three-dimensional foam, cubic holes or chambers are cut out from the lattice. The fractal dimension of the base-4 structure is $D = \log 37/\log 4 = 2.6047$. Over a 4^7 range the filling factor is about 2% by volume. Although this is quite small, it is much denser than we require. The cubical "rooms" are convenient, but do not interconnect.

A ramified fractal sponge results if the trema or cut-out is a three-dimensional cross, obtained by cutting away the walls, floor and ceiling of the cubical room, leaving only the skeletal framework. The fractal dimension is $D = \log 10/\log 4 = 1.6610$. Over a 4^7 range the filling factor is only $\sim 2\times10^{-6}$, which is far too small. Thus we cannot sustain such a degree of ramification over the whole range of scales. Nor would we wish to. A variant in which floor and ceiling are left has a dimension $D = \log 19/\log 4 = 2.1240$ and a corresponding filling factor of $\sim 2\times10^{-4}$. Corresponding base-3 examples have dimensions $D = \log 7/\log 3 = 1.7712$ and $D = \log 11/\log 3 = 2.1827$ respectively.

A disadvantage of the foam or sponge is that the measure of the structure carrying the through load is less than the fractal dimension of the structure. In other words, as a load carrier, the structure is progressively less and less efficient. For example, in the base-4 fractal foam, the dimension of the through-load carrying structure is $D = \log 28/\log 4 = 2.4037$, and so over a 4^7 range only $(28/37)^7 = 0.1421$ of the structure carries the load.

Some inefficiency in carrying the vertical load is not serious. The ability to distribute loads sideways is more important, in order to allow for uneven or variable loading, and to prevent collapse in case of limited failure of the dynamic support of the toposphere. This suggests that ramifying structures in the geosphere base should retain floors and ceilings more than sidewalls—a convenient exigency.

The fractal honeycomb ($D = 2.4037$) is an efficient vertical-load carrier. If we superimpose three such honeycombs, aligned on orthogonal axes, we have a structure of the same fractal dimension which is efficient at carrying through-loads from any direction. It is also strong in shear. Ignoring overlap—it is no longer strictly self-similar—it is three times as massive as the unidirectional honeycomb.

The geosphere base is then constructed as a compromise combination of ramified fractal lattices. The basic structure is the set of orthogonal honeycombs. The vertical chimneys are sub-divided with fractal floors, as in the fractal foam; this adds mass. The horizontal tunnels are made ramifying, as in the fractal sponge, and so to a lesser extent are the cubical rooms or chambers; this subtracts mass.

The fractal construction is based on a cubical room nominally 3m on a side (internally 2.85m). The walls, ceiling and floor are constructed from 0.15m thick blocks. The 1m deep hollow floor has two skins and is partitioned every metre. Ramifying corridors, running around the room and 0.85m wide internally, are formed by omitting the vertical and horizontal partitions from the hollow sidewalls.

The geosphere base thus provides an enormous amount of room for storage, accomodation, shops, industry, hydroponics, transport—anything that doesn't need to go on the surface. The precise layout will of course be modified for these purposes as convenient. Transport networks (section 11) in particular may prefer a hexagonal arrangement of tunnels.

The mean density, for a mean height $\sim 1\,km$, is $\sim 10\,kgm^{-3}$, giving an areal density $\sim 10^4\,kgm^{-3}$, the same as the crust. Including the atmosphere the toposphere must therefore support $\sim 3\times10^4\,kg\,m^{-2}$, leading to a gross habitat mass $\sim 4\times10^4\,kgm^{-2}$.

The building blocks for the construction of the geosphere—and for all manner of buildings and edifices in and around the habitat—are composed of fused rock. The compressive and tensile strengths of silica SiO_2 are $\sim 3\times10^9\,Nm^{-2}$. Other components of silicaceous rock, such as alumina and aluminium silicate, and various glasses, have similar strengths. Thus the common dirt of moons and asteroids—even the slag of metal refining in space [12]—will provide constructional material of

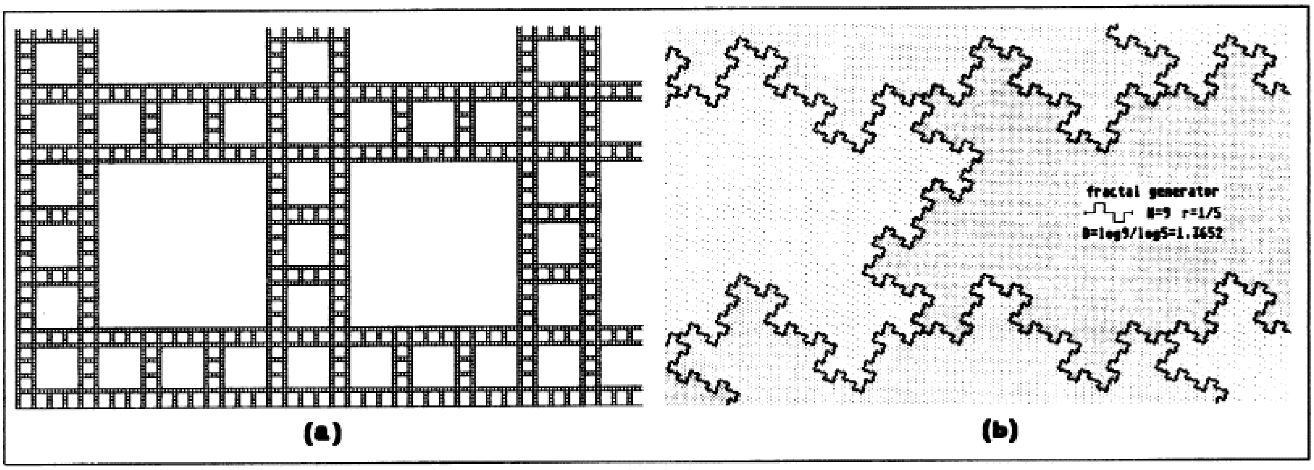

Fig. 5. Geosphere construction (a) Fractal architecture of geosphere base (b) Fractal slotted building blocks of fused rock.

great strength and low cost. Where carbon-rich minerals abound, exceptionally strong blocks of diamond are also feasible.

Ordinary masonry construction has little strength in tension, a limitation which can be overcome if the blocks are suitably keyed and slotted together. A simple splayed mortise-and-tenon joint, thus— —as used in carpentry, will work, but can only give a tensile strength up to one third of the intrinsic strength of the material.

Fractal keying (Fig. 5b) can improve on this, fitting the blocks together so intimately that nearly the full intrinsic strength can be achieved. Surprisingly, an array of fractal tiles can be effectively *stronger* than a uniform slab, because it is resistant to the effects of stress concentration. Microscopic cracks, originating along the joins, will usually propagate only a tiny distance before they intersect the fractal surface again and terminate, causing only a tiny loss of strength. The fractal structure of the surface, finer than the critical Griffiths length, also increases the effective surface energy of fracture.

No attempt has been made to prove that the fractal generator used is the best possible generator. Several other possible generators are worth considering, including and .

The basic shape of the block shown—the initiator—is a rectangle two units long and one unit high, so the pattern occurs twice along the long side. A less indented and more convenient shape results if the pattern is halved in size to occur twice on the short side, four times on the long side. Since the fractal tile on a unit square is pertiling, all blocks based on rectangles with integer sides are also pertiling.

Thus we may choose a basic building block of size 30cm × 15cm × 15cm. At a density of $\sim$2200kgm^{-3} each block has a mass of $\sim$15kg.

The blocks could be fabricated with compressive surface layers by spraying a mist of molten droplets onto a cooled form, or by vapour deposition. The energy required to do this is $\sim 2\times10^6$ Jkg^{-1}, small compared to the kinetic energy to be stored in the orbital rings.

The cost of heat energy from coal is only $\sim$£2/GJ, so even on Earth the cost of the energy would be only $\sim$£4/m^3. Solar mirrors in space will push the price of heat down by orders of magnitude. The raw materials may be available at $\sim$£1/m^3, somewhat more expensive than air or water. It is estimated that manual assembly of the blocks could proceed at up to 5m^3/manhour (it is more like Lego than bricklaying). Putting all this together, we obtain a cost for the geosphere base $\sim$10£m^{-2}.

Of course, this geosphere design applies equally to conventional rotating space colonies, in which the toposphere—under tension—can also be constructed from similar fractal building blocks.

The geosphere base may extend several kilometres beneath sea level. The deeper it is, the stiffer the geosphere and the greater the lateral distance uneven loads can be carried.

A deep base also permits the incorporation of occasional deep ocean trenches. Such trenches would be very massive and the concentrated weight would need special support—a trench $\sim$1km deep and $\sim$2km wide would use up the geosphere mass quota for $\sim$50km on either side. However, a trench or slot $\sim$10m high sloping under the land would be much lighter; its vast underwater chambers, bound together by rows of columns in tension, would make an ideal zoo for deep-sea life.

The crust or surface of the geosphere will be very varied. The fine detail of the relief is moulded in foamed rock, whose rough and irregular surface grips the sand and soil and loose rocks spread upon it—especially on slopes. But where a cave, a cliff, a crag, a rocky outcropping is required, the rock itself is fused to the foundation, or formed by deposition upon that foundation. Minerals like quartz, granite or sandstone are easy to produce or simulate—others, such as chalk or limestone, may be more difficult.

I do not attempt to detail the geology and mineralogy of these artificial landscapes; but much effort will doubtless be spent, in the design of successive space colonies, to obtain ever more faithful replicas of the natural landscape and to imitate the diverse scenery of Earth. The use of fractals to generate computer landscapes is already well-advanced [10].

Weathering should soon improve the appearance of many features and formations, giving a much more natural look, and on a well-designed habitat will not thereafter be a serious problem. Nevertheless, attention should be paid to the continuing upkeep of these habitats. From time to time rivers and seas may need to be dredged and soil erosion made good. Cliff faces may sometimes need repair. But with care the total cost and effort of maintainance should be less than on a natural planet.

Both lighter and heavier geospheres could also be constructed. The geosphere base of the outermost layer of a multi-layer suprastellar planet might usefully be hundreds of kilometres thick, and the solid crust perhaps ten kilometres thick. At the same time, many of the inner layers could be very light with $\lesssim$1km of air between layers. Indeed, we could imagine levels of flat grassland, shallow lakes or seas and a low sky, with a total areal density under 10^3kgm^{-2}.

5. BIOSPHERE

The biosphere of a supramundane planet can be Earthlike, varying from place to place with the climate and geography. All forms of life can be represented—microscopic life, plantlife, animal life, birds, fishes, insects. And people too, of course.

Thus there will be grasslands, forests, meadows, moorlands, jungle, marshes, scrubland, parks and gardens—even deserts if we choose. Then there will be the life of streams, ponds, rivers, lakes, estuaries, seas and oceans—even sulphur pools if we want. There will be the life of high mountains, alpine uplands, hills, downs, plains, valleys, dead valleys—even of caves and subterranean caverns. There will be life from the tropics, the temperate zones, the arctic. Life from continents, maritime coasts and islands.

In short, the lot.

Important functions of the biosphere are the maintainance of a breathable atmosphere through photosynthesis of CO_2 and the provision of food. An even more important function is to furnish the inhabitants with a pleasant environment.

Seeding and planting out new colonies will be a considerable task, and a major industry will grow up around it—like the nurseries, landscape gardeners and breeders we are familiar with on Earth, but on a much grander scale. It is not necessary to go into great detail here, but a few points can be made.

Plants, seeds and animals can be raised in dedicated nurseries located in the geosphere base of existing habitats, or in specialised space habitats.

Most plants, and some animal life, can be sown as seeds on the new land, or mixed in with the last layer of soil to be deposited. This topsoil will consist of crushed rock and a humus of finely-chopped vegetable matter and compost, including trace elements and a nitrogenous fertiliser. Since most seed-grown plants come to maturity in a few years or less, this easily-automated process should generate most of the biosphere cheaply and quickly.

Trees, and some of the larger shrubs, may need to be grown in hydroponic nurseries and transplanted to their permanent locations, where the topsoil can be poured in place around them. In the specialised environment of hydroponic nurseries, arboriculture can be much faster than in the open. Growth rate factors include continuous illumination (×3), optimisation of the light spectrun to infra-red-free moderately-narrow-band red light (×3), optimisation of the CO_2 level to $\gtrsim 2\%$ (×3), optimisation of temperature (no winter), continuous optimised supply of water and nutrients, absence of pests and predators. Even on a highly conservative estimate, large mature trees should not normally need more than ~10 years to grow.

Coral reefs are perhaps the natural environment slowest to mature. However, artificial reefs of foamed rock may become encrusted with sufficient coral for a mature ecology within a decade or so—*vide* the overgrowth of World War II wrecks in the Pacific.

Animals can be released into the wild as soon as the plant life can support them—within less than a season in most cases. Many species may be installed only in isolated reserves or safari parks—we don't *want* wild boars in our back gardens.

A niche for every Earthly species could be provided somewhere on a supramundane planet, but we need not take them all if we do not choose to, and there is certainly no obligation to maintain anything like the same balance of numbers and habitats. Few people will wish to live in swamps or jungles, so it is unlikely that we shall create much more than token areas of such environments. The general rule here is that we will provide such environments as enough people like *and are prepared to pay for.*

A simple estimate of the biosphere costs, based upon existing nursery practices and gardening costs, is $\sim 10\,£\,m^{-2}$. On a large scale, big trees may be planted on a spacing of ~10m in a wood and cost ~£1000 each. Smaller shrubs may be spaced only 1 m apart and cost ~£10 each. These costs are perhaps appropriate to densely-populated regions, to parks and gardens. But on a supramundane planet there will be vast areas of sparsely-populated countryside, grassland, moorlands and seas, where the biosphere cost will be greatly reduced. Even in the great forests there will be less need for instant maturity. An average biosphere cost of $\sim 1\,£\,m^{-2}$ or less is therefore probable.

6. ATMOSPHERE

The atmosphere of a supramundane planet should consist of $\sim 10^4\,kg\,m^{-2}$ of $\sim 25\%O_2/75\%N_2$. Suggestions have been made that helium could be used as the primary diluent, since it is more abundant in the universe than nitrogen, but its unfortunate effect on the voice render it unacceptable for general use. However, nitrogen is sufficiently common among the outer planets and could be mined from the atmospheres of Titan or the gas-giants. Oxygen could be obtained from water ice, rock or CO_2.

Photosynthetic transformation of a CO_2/N_2 atmosphere might take ~25 years [5]. Exotic forms of photosynthesis, extracting oxygen from rock or water, may also be considered. Dissociation of CO_2 or mineral oxides could be faster, using energy supplied by pellet-stream from a solar-orbit light-sail windmill [3] or by dumping material from nearby moons onto a gas-giant planet by orbital ring [3].

As on Earth, the atmosphere will be open to space, the scale-height will be ~8km and its total effective depth will be ~100km, with space satellites orbiting safely at altitudes down to ~300km. It will rapidly eliminate any radiation belts intersecting the supraplanetary surface, and protect the surface from cosmic rays and any UV not absorbed by the solettas.

The only major difference from Earth is in connection with the climate. If the rotation period is 24 hours, as on Earth, then the Coriolis velocity shear will be the same—$73\,mm\,s^{-1}/km$ at the poles. But the maximum scale of weather patterns will be increased in proportion to the supraplanetary radius. This leads to the likelihood of longer-lasting and more severe weather systems. Mean wind speeds are likely to be higher.

The potentially fiercesome weather could be tamed in several ways: we could control the surface insolation via the soletta mirror in space, thereby manipulating the temperature, humidity and flow-patterns of the atmosphere; we could warm or cool the environment via the geosphere; we could control ocean currents by movements of the toposphere.

However, a simple passive technique should suffice. Since oceans sixteen times as wide as the Pacific are neither necessary nor especially desirable, the sizes of the greatest continents and oceans do not need to be scaled in proportion to the supraplanetary radius. Instead fractal relief can be cut-off on a terrestrial scale, thus breaking up the weather patterns and checking their growth.

For aesthetic reasons, the fractal dimension of coastlines and islands is likely to be chosen to be somewhat higher than the value of $D\sim1.2$ typical of Earth. Now higher values of the fractal dimension tend to produce greater fragmentation. It may therefore be appropriate to choose a high value approaching $D\sim2$ on the scale of the supraplanetary circumference, dropping to $D\sim1.5$ at $\sim R_\oplus$, and down to $D\sim1.2$ at ~1 km scale. This will not only keep the weather in check, but also provide long expanses of coastline and a multiplicity of islands.

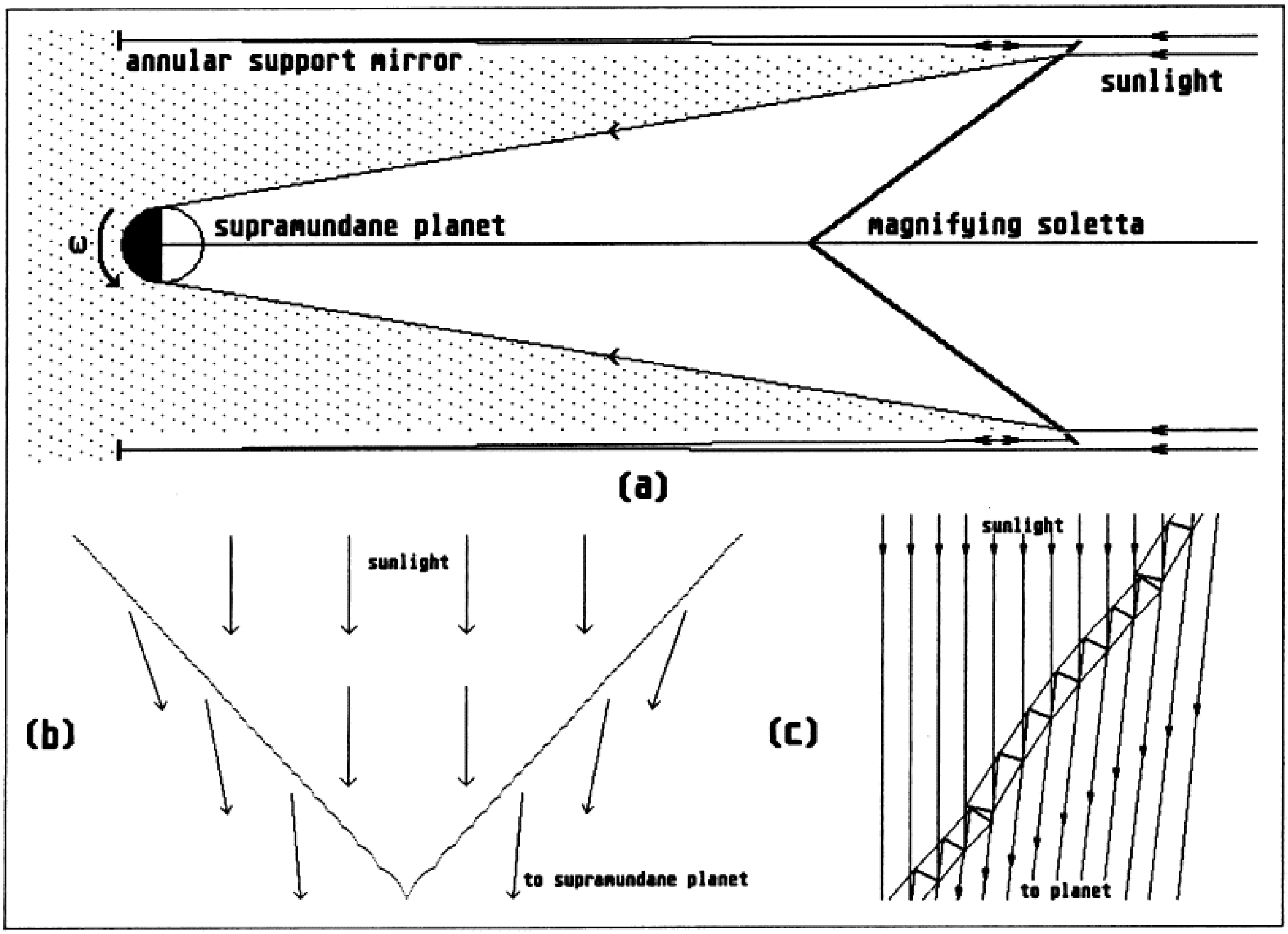

Fig. 6. Illumination of supramundane planet (a) Layout (b) Soletta geometry (c) Light paths through enlarged section of soletta.

7. ILLUMINOSPHERE

A supramundane planet rotating with a 24-hour period can be illuminated by a soletta placed near the Lagrangian point L1 of the underplanet-sun system (Fig. 6). The soletta is constructed of solar sail material, reflective on both sides, and its component mirrors are arranged to form a magnifying "lens". It can be supported by a *dynamic compression member* [4], utilising light directed from an annular mirror orbiting on the opposite side of the planet.

The light paths through the soletta (Fig. 6c) are quite subtle. Each successive strip of mirror is angled slightly more steeply than the previous one, diverting the sunlight inwards through an angle of twice the increment. We start at an angle ~15°, progressing through steps ~0.06° to ~30°, where we stop and start over again. Since the deflection angle decreases linearly from ~5mrad at the outer edge to zero at the centre, the number of steps per cycle will increase in inverse proportion as the centre is approached (Fig. 6b). The gross mirror area of the soletta is then ~1.08 times the frontal area. A small fraction ~1% of the sunlight leaks through without being deflected inwards, so the shadow is not totally black.

If the supramundane planet, radius R, lies at a distance D from the Sun, the radius of the soletta is set at $RD/D_\bullet$ to provide an insolation the same as Earth's. Although the soletta may be far larger than the supramundane planet itself, its areal density will be smaller by a factor ~10^8; thus the mass of the soletta will not dominate if the planet no further from the Sun than ~20 000AU ~1/3 light-year. Indeed, even in interstellar space starlight could fully illuminate an Earthlike habitat.

The soletta must be placed sufficiently close to the planet that it subtends at least as much as the Sun seen from Earth (~0.01 radians). That is, the soletta distance S obeys:

$$S \leq RD/R_\odot = M^{\frac{1}{2}} D R_\bullet / R_\odot M_\bullet^{\frac{1}{2}}$$

Now the distance to the L1 point is $D(\frac{1}{3}M/M_\odot)^{1/3}$, so the ratio of these distances σ obeys:

$$\sigma \leq M^{1/6} M_\bullet^{-1/2} (3M_\odot)^{1/3} R_\bullet / R_\odot = (0.59 M/M_\bullet)^{1/6}$$

Thus if the underplanet is at least two Earth-masses the soletta can be placed beyond the L1 point and will not need the annular support mirror to counteract the effect of gravity and the residual photon thrust. Further analysis of the photon thrust problem and light support may be found in Refs. 5 & 13. Suprajovians within the solar system may not need support mirrors, but elsewhere in the universe they will sometimes be necessary.

If the planet is orbiting another star, of luminosity L_*, then the soletta radius becomes $RDL_\odot^{\frac{1}{2}}/D_\bullet L_*^{\frac{1}{2}}$. The constraint on σ becomes:

$$\sigma \leq (0.59 M/M_\bullet)^{1/6} (M_*/M_\odot)^{1/3} / (R_*/R_\odot)$$

For main sequence stars we find that $M_*/M_\odot \sim (L_*/L_\odot)^{.29}$ and $R_*/R_\odot \sim (M_*/M_\odot)^{.75}$, and then $\sigma \leq (0.59 (L_\odot/L_*)(M/M_\bullet))^{1/6}$. Less-massive planets of luminous early-type stars (W, O, B, A) and red-giants may therefore require solettas positioned closer than their L1 points.

Now the net weight of the soletta in the vicinity of the L1 point is about $9GM_{\bullet}\rho_a(S-S_{L1})/D^2$ per unit area, and the photon pressure is about $f\,(L_{\bullet}/4\pi D^2)$ with $f\sim10\%$. The ratio, which is unity if the two are in balance, is independent of D, but the balance point lies further beyond L1 for stars of higher luminosity. We find that, within the constraint on σ, passive balance may only be achievable if the soletta is heavily ballasted ($\rho_a \gg 3\times10^{-4}\,\mathrm{kg\,m^{-2}}$)—the use of a support mirror may then be preferable.

Magnified by the distant soletta, the orb of the Sun in the sky of the supramundane planet will look much the same as on Earth. Its angular diameter may be about 5% greater, to allow for the imperfect reflectivity of the mirrors, but it is unlikely that this would be noticeable.

If the supramundane planet rotates once every 24 hours, with an axial tilt of $26\frac{1}{2}^{\circ}$ precessing once a year, then the cycle of day and night, the progression of the seasons, and the division of the planet into tropical, temperate and arctic zones will be fully Earthlike.

If we should choose not to rotate the supramundane planet it is still possible to provide a 24-hour day, utilising a soletta in a 24-hour orbit in the geometry proposed in Ref. 5 for the terraformed planet Venus. That soletta could be illuminated directly by the Sun, or indirectly via the magnifying soletta.

The illumination of suprastellar planets is a rather different affair. Energy must be distributed amongst the layers and shine as visible light from the habitat skies. The energy could be carried as electricity or in the motion of mass-streams, or by incandescant plasma and magnetic fields. Or light could be directed by mirrors. Detailed discussion of suprastellar planet design is unfortunately beyond the scope of this paper. It is hoped to rectify this omission at a later date.

However, mention should be made of the cooling problem for multi-layer planets. In general, radiating surfaces roughly equal in area to the combined surface area of the layered planets must be provided. The habitats can be illuminated with an average of $\sim100\,\mathrm{Wm^{-2}}$ of *visible* light—the infra-red component would only increase the cooling load and may be filtered out. A 10^4 layer suprasol planet would then need to radiate from a sphere $\sim1\,\mathrm{AU}$ in radius at $\sim290\mathrm{K}$. Waste heat could be transported from Suprasol to the radiating zone as thermal radiation at a higher temperature $\sim3000\mathrm{K}$ or as follows.

Sealed quartz spheres of water vapour at $\sim.01$ bar, perhaps $\sim100\mathrm{m}$ in diameter, stream along at close to escape velocity $\sim250\,\mathrm{km\,s^{-1}}$ through the toposphere beneath each layer, covering the sky of the layer below. They absorb the excess heat radiated from the habitat surface. They press upwards at $1g$ and help to support the planet. After circling for perhaps $\sim10^5$–$10^6\mathrm{s}$, they are deflected upwards to the outermost surface and thence up into space, reaching a distance of $\sim1\,\mathrm{AU}$ before falling back, in a period of $\sim2^{-3/2}\,\mathrm{years}\approx10^7\mathrm{s}$. On their way they radiate heat; the water vapour condenses, releasing $\sim2\times10^6\,\mathrm{Jkg^{-1}}$. Entering the planet once again at $\sim270\mathrm{K}$, they are warmed and the water is re-evaporated. At a cooling rate of $\sim0.2\,\mathrm{Wkg^{-1}}$ we need $\sim500\,\mathrm{kgm^{-2}}$ of water—less than the habitat mass—to cool a habitat receiving a net $100\,\mathrm{Wm^{-2}}$. The flow rate is $\sim5\times10^{-5}\,\mathrm{kg\,s^{-1}m^{-2}}$ or $\sim5\times10^{-3}\,\mathrm{m^3s^{-1}m^{-2}}$. At $\sim250\,\mathrm{km\,s^{-1}}$ the fraction of the outermost surface required for the incoming and outgoing cooling flows is thus $\sim4\times10^{-4}$. The spheres have a mass $\sim25\%$ that of the water they carry.

Similar spheres, utilising the latent heat of vaporisation of aluminium or silicon and made of carbon, could transport energy from the innermost surface (where relativistic light-sail windmills convert the Sun's light with $\sim66\%$ efficiency, leaving a cavity temperature $\sim2000\mathrm{K}$) to the habitat skies, to radiate visible light through selective filters.

8. UNDERPLANETS AND UNDERBODIES

Supraterrestrial planets, although easily constructed, may not be especially valuable or worth the bother of building them. Small planets, such as Mars, have too low a surface gravity. Larger terrestrial planets, such as Earth or Venus, can be used in their natural or terraformed state. Supramundane habitats of limited area may however be constructed above such planets for specialised purposes. Supraterrestrial habitats above the polar regions, for example, would intercept sunlight otherwise missing the planet and give ready access to space.

Gas-giants of all sizes will make excellent underbodies for suprajovian planets larger than the Earth. At the top end of the scale massive gas-giants merge into sub-stellar bodies and brown dwarfs of a few percent of a solar mass. Throughout this range diurnal rotation and an open sky beneath the Sun allow Earthlike and attractive suprajovian planets.

At the next level up we come to suprastellar planets, where the underbody is a star, providing energy as well as gravity. Such underbodies range from red dwarfs upwards; any main sequence star or white dwarf is suitable. And although the envelopes of red giants, such as Betelguese, are so extended that the surface gravity is less than $1g$, 'suprastellar' habitats could still be built there *beneath* the stellar surface. *Intrastellar habitats* could even be built inside the Sun.

The end-products of stellar evolution, such as neutron stars and black holes, are of course also suitable. Black holes may come in very large sizes, as the result of condensations in the core of globular clusters or galaxies. A black hole of $\sim3\times10^{12}M_{\odot}$ may eventually result from the collapse of a large cluster-dominant elliptical galaxy. Its event horizon would have a radius of ~1 light year and a surface gravity $\sim10\,\mathrm{m\,s^{-2}}$. This is then about the largest black hole which could be used for a simple $1g$ suprahole planet.

Stepping back a pace, consider the possibilities of smaller black holes, which may be discovered or manufactured. Suprahole planets could be constructed without difficulty around small black holes down to about $M_{\bullet}$. With even smaller holes, $1g$ habitats could still be constructed, but below around $M_{♂}$ it becomes necessary to roof them over, since the escape velocity is no longer enough to hold an atmosphere. With still smaller holes, the Hawking radiation must be considered. A black hole of mass $\sim3\times10^{14}\mathrm{kg}$ would pour $\sim400\,\mathrm{Wm^{-2}}$ of high-energy radiation onto a suprahole 'planet' of radius $45\,\mathrm{m}$. This is perhaps about as small as we could expect to manage.

Suprahole planets smaller than Mars would not need dynamic support. More conventional construction with strong materials would be possible. For even smaller suprahole habitats it becomes doubtful whether there is any point in using black holes, instead of spinning the habitat for gravity, unless they are required primarily for some other purpose.

Multi-layer supramundane planets are possible with all kinds of underbody. They will be appropriate where the underbody provides energy as well as gravity, and where its luminosity exceeds that which can be used by a single layer. For a star like the Sun, $\sim10^4$ concentric layers might be employed—or even more if the waste heat is radiated at less than $\sim290\mathrm{K}$. But suprajovians distant from their suns, deploying vast mirrors to maintain an adequate illumination, are less likely at first to utilise multiple layers.

Most of the larger bodies we see in the universe are thus potential sites of supramundane planets, most of the smaller bodies potential sources of mass, most of the luminous bodies potential sources of energy, most of the energy sources potential luminaries. The potential habitable area of the visible universe to the Hubble radius is thus $\gtrsim10^{32}$ times that of the Earth.

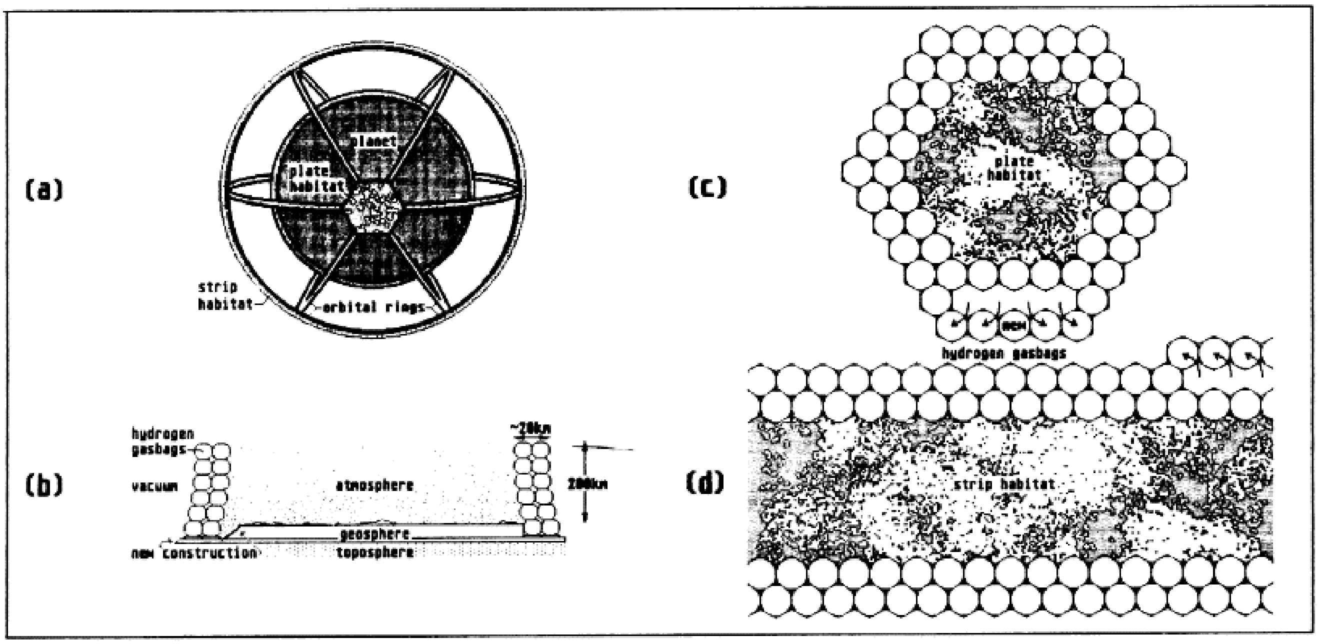

Fig. 7. Construction and extension of supramundane habitats (a) Support (b) Atmosphere retention (c) Plate habitat (d) Strip habitat.

9. SUPRAMUNDANE HABITAT CONSTRUCTION

The construction of supramundane planets would be a daunting task, if they could not be inhabited before completion of the entire globe, for there is a factor ~100 in size between the larger rotating space colonies and the smaller supramundane planets. Fortunately, smaller supramundane habitats, covering only a fraction of the area of the whole planet, can readily be constructed and occupied first (Fig. 7).

Supramundane habitats are divided into two main classes: plate habitats, supported at the junction of orbital rings or by compression members from below; and strip habitats, supported along their length. Aerial colonies, and those not far above the underplanet's surface, can conveniently be in plate form, but strip habitats are probably more convenient for orbital rings. Equatorial strip habitats can be rotated with a 24-hour cycle most conveniently.

Supramundane habitats will have the same basis of toposphere, geosphere and atmosphere as the complete planets, except for one thing: the atmosphere must be prevented from pouring over the side by ~200km high retaining walls. At the bottom they must resist the full atmosphere, but the pressure falls exponentially with height and is negligible at the top.

The walls may be constructed of gasbags filled with gas-giant atmosphere (Fig. 7b), inflated to ~2 bar at the base. The scale height of the walls can be up to $1/(2\rho/Yg + m/kTg) \sim 40$km for quartz, Kevlar or carbon-fibre ($Y \sim 3$GNm^{-2}), considerably greater than the atmospheric scale height (~8km). With a scale height of 20km (safety factor ~3) the pressure in the topmost gasbag is ~0.1mbar, contained by a ~100gm^{-2} film. At the base the wall thickness is then ~1m, suitable for construction from linked blocks.

The gasbag columns are shown resting on hexagonal bases on the edge of the toposphere. When inflated, they will be squashed together and form an airtight seal.

The cost of these walls will perhaps be slightly less than that of the equivalent area of habitat. Thus once the habitat is more than ~100km across, the extra cost of the walls will be small. Note that the number of gasbag columns is proportional to the radius of a plate habitat and independent of the width of a strip habitat.

Extension of the habitat is facilitated by the double wall (which also provides redundancy) and proceeds as follows. First the toposphere is extended beyond the wall. Gasbag columns from the outer row are partially deflated or laced in to release them from the press, and are slid out to their new locations (Fig. 7c & d). New columns are added as required (Fig. 7c) and the row re-inflated. The inner row is then moved in the same way. The geosphere base is then built up and landscaped at the edge of the habitat *inside* the wall. A temporary shallow lip will prevent the sea cascading down the exposed base.

It is apparent that supramundane habitats can be habitable at a very early stage—even when only ~100km^2 has yet been built—and that most new construction can take place from the existing habitats. Large rotating space colonies could also be constructed in this economical fashion, by the sideways extension of a cylindrical strip habitat.

The same technique could be used in reverse to repair major damage to a supramundane planet, if large sections should be destroyed by accident or war. Holes, cordoned off with gasbag columns, would be mended from the edge inwards and the progressively redundant gasbags stored for future emergency use.

Illumination of these habitats may be a little awkward before completion of the magnifying soletta. An incomplete soletta may have to be placed closer to the planet—necessitating the provision of an annular support mirror—to narrow its focus down to the habitat size. Alternatively, small orbital solettas may be used [5], particularly where it would be inconvenient to give the habitats a diurnal rotation.

If the CO_2 level in a supramundane habitat is kept moderately high, rapid photosynthesis could be encouraged by illumination with twice the normal amount of light; oxygen could then be released fast enough to keep up with the enlargement of the habitat. For heat balance, the long wavelength end of the spectrum could be eliminated (infra-red is no use for photosynthesis). Filters transmitting only visible light can readily be devised—such as a solar sail material consisting mostly of hexagonal holes spaced ~350nm apart ($\lambda/2$ for red light), which will reflect back the infra-red and let through most of the visible and ultra-violet. Similar techniques can eliminate ultra-violet.

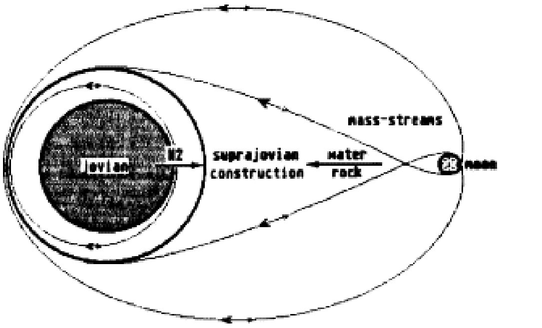

Fig. 8. Mining jovian moons and planets for suprajovian.

10. RAW MATERIALS

The raw materials for a supramundane planet are $\sim 10\,\mathrm{Mgm^{-2}}$ of air, $\sim 5\,\mathrm{Mgm^{-2}}$ of water and $\sim 25\,\mathrm{Mgm^{-2}}$ of rock. The air should consist of $\sim 25\%$ by weight of oxygen and $\sim 75\%$ of nitrogen; mixtures of noble gases, including helium, neon and argon, can be substituted for some of the nitrogen, provided that the average molecular weight remains about 28. The water will fill the seas (either fresh or salt) to ~ 10m depth over about half the planetary surface. The rock includes material for the orbital rings, the toposphere and the geosphere base, as well as the rock and soil of the crust. Also required are $\sim 10\,\mathrm{kgm^{-2}}$ of carbon ($\sim 1\,\mathrm{kgm^{-2}}$ in the air as CO_2 and $\sim 0.3\,\mathrm{kgm^{-2}}$ for the living biosphere) and trace quantities of phosphorus, magnesium, iron and other minerals.

These raw materials are readily obtainable throughout the solar system and in the vicinity of the outer planets. Consider Suprajupiter: a total of $\sim 4\times10^{21}$kg of rock and $\sim 8\times10^{20}$kg of water is required for its $1.6\times10^{17}\mathrm{m^2}$ surface, equivalent to a rock-moon ~ 1600km in diameter, with 90km thickness of ice on top. This is only $\sim 1\%$ of the mass of the Galilean satellites, which are mostly rock and water ice. Oxygen can be extracted from the rock or water, but nitrogen—in the large quantities needed—would not appear to be available. However, Jupiter itself contains $\sim 0.1\%$ of ammonia in the lower atmosphere.

The process of mining soil on the Moon [12] and transporting it to Earth via Orbital Rings has been analysed in Ref. 3. Mining water and rock on Europa, and transporting it to Suprajupiter, would be very similar (Fig. 8). There is one significant difference, in that the full gravitational escape energy is not released, since the orbital energy at Suprajupiter has to be retained.

There is a net power *output* of $\sim 4.7\times10^{8}\,\mathrm{J\,kg^{-1}}$, sufficient to raise a further ~ 0.38kg/kg up from Jupiter to Suprajupiter. Making allowances for losses, it is apparent that the roller-coaster energy of the rock and water from Europa suffices to bring the nitrogen up from Jupiter. Angular momentum balance is satisfied by the enlargement of shrunken Europa's orbit by $\sim 3\times10^{8}$m, nearly to the orbit of Ganymede.

To estimate the cost of such a procedure we note that the throughput of an orbital ring system is of order its mass divided by a characteristic time, usually the orbital period. In the case of Suprajupiter, a throughput $\sim 10^{-5}\,\mathrm{kgs^{-1}/kg}$ could be achieved. If the specific cost of the orbital rings, which are mostly slag, is set at the enormous figure of $\sim 5\pounds\mathrm{kg^{-1}}$, to include the sleds and power transfer systems, the cost of throughput is $\sim 5\times10^{5}\pounds/\mathrm{kgs^{-1}}$. Over a lifetime of 30 years the cost of mass delivered is only ~ 50p/tonne. What this really implies is that the cost of construction and assembly of the supramundane planet components can be expected to dominate over the cost of supplying the raw materials.

Other suprajovian planets could be supplied similarly.

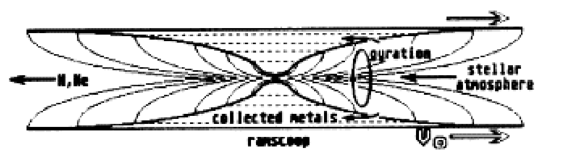

Fig. 9. Ramscoop for mining suns.

10.1 Mining Suns

When more material than can be obtained from the terrestrial and jovian planets is required, we shall be able to mine the great mass of the Sun by means of cooled orbital rings dipping into the atmosphere, or by ramscoop (Fig. 9).

This is roughly how a ramscoop would work. The ramscoop starts in solar orbit with an excess of orbital energy and is directed past the rim of the Sun on a hyperbolic trajectory, just entering the atmosphere.

As the ionised stellar atmosphere enters the mouth of the scoop it is caught by the magnetic field and gyrates. Kinetic energy of forward motion is converted into kinetic energy of rotation with little loss, the plasma remaining 'cool' compared to the orbital energy. The centrifugal effect causes the heavier ions to separate towards the outside. Hydrogen and helium escape through the nozzle and regain their linear momentum through the jet, but the metals—that is, all the rest of the elements—are siphoned off and stored in the body of the ramscoop. The centrifuge also provides fractionation of the elements by mass.

The ramscoop returns to orbit at a diminished speed, heavier in the amount of material mined. Making rendezvous with an orbital ring, it unloads and is reaccelerated for the next pass.

Star-mining (also considered in Ref. 15) opens up to colonisation even those stellar systems devoid of planets or asteroids. The notion that the viability of interstellar colonisation hangs upon the discovery of habitable planets is thus seen to be without merit. We do not *need* any more than we already *know* to be present—the stars themselves.

The energy needed to mine stars is $\sim 2\times10^{11}\,\mathrm{J\,kg^{-1}}$. This could be provided by light sail windmills in solar orbit [3], at a cost [5] over 30 years for a sail $\rho_a = 3\times10^{-4}\,\mathrm{kgm^{-2}}$ at $1\pounds\mathrm{kg^{-1}}$ of $\sim 5\times10^{-17}\pounds\,\mathrm{J^{-1}}$, amounting to ~ 1p/tonne, at a rate up to $\sim 3\times10^{-8}M_\odot$/yr for a power consumption of $L_\odot$. Higher mining rates, desirable for the construction of multi-layer suprastellar planets, are possible if jovian hydrogen and helium is swapped for solar metals, up to a total mass $\sim M_J \sim M_\odot/1000$.

Advanced stellar engineering techniques may enable most of the star's heavy element complement $\sim M_\odot/30$ to be mined within periods of a few centuries or less, corresponding to energy utilisation rates greatly in excess of the luminosity.

By the Virial Theorem, as shown in section 3, the thermal energy of the hot plasma that supports the star internally is itself sufficient to remove initially $\sim 50\%$ of its mass to infinity (collapse of the cooled remnant, releasing more energy, brings this figure to nearly 100%). Adiabatic expansion and cooling of the plasma from $\sim 10^{7}$K down to $\sim 10^{4}$K could supply up to $\sim 1000L_\odot$ with $\sim 1\,L_\odot$ of waste heat radiated from the surface. This would permit the construction of a complete 10^{4}-layer $M_\odot/30$ suprastellar planet in ~ 100 years.

Although much of the metal content will be in the deep interior, rapid mining will lead to enhanced convection, giving access to material from deeper in the star.

The metal content of stars varies with the stellar type, population and age, from a few percent in main sequence stars up to an effective 100% for neutron stars. It is clear that adequate supplies of raw material exist throughout the galaxy.

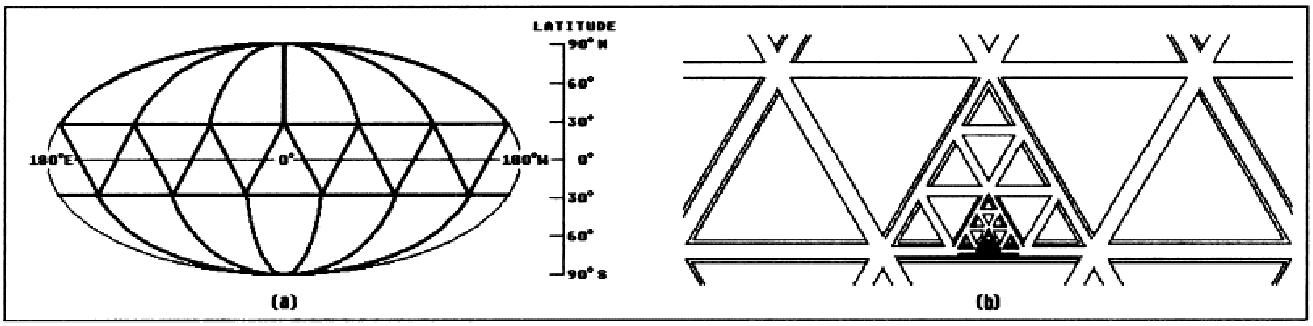

Fig. 10. Planetary transport web (a) Layout of high-level links on globe (b) Sketch of triadic link hierarchy.

11. PLANETARY TRANSPORT WEB

An efficient means of planetary transport upon a supramundane planet can be provided with a hierarchical web of links threading the geosphere and toposphere (Fig. 10). Similar systems can be provided for natural planets and space colonies. Each link conjoins just two points on the lattice—a journey is therefore effected by negotiating a succession of such links.

Let the length of a level n link be d_n . Then the length of a level n+1 link in the triadic hierarchy shown is $3d_n$. Or more generally, $d_n=3^n d_0$. Each link serves an area $(\sqrt{3}/2)d_n^2$, thus the length of link per unit area is $(2/\sqrt{3})/d_n$—which we note *decreases* with n . The total link length per unit area, summed over all levels as $n\rightarrow\infty$, is $\sqrt{3}/d_0$, dominated by the lowest levels.

Travel along the links is executed at a constant acceleration a to the halfway mark followed by a period of deceleration of equal magnitude. If the time taken to traverse a link is t_n then $t_n=3^{n/2}t_0$, where $t_0=2(d_0/a)^{1/2}$. The time taken to traverse a typical sequence of n links up to level n, a distance of $(3/2)d_n$, is $(\sqrt{3/2})(1+\sqrt{3})t_n$, which is $(1+\sqrt{3})/\sqrt{2}\approx1.93$ times as long as it would have taken to do that journey in a single hop. The worst factor in 1-D along a line is ~2.88, in 2-D up to ~3.15, and on average perhaps ~2.5 .

Obtaining the fastest routes through the network for generalised end-points is a surprisingly difficult problem. The choice of direction at each nodal point leads to strong bifurcations—along certain boundaries an infinitesimal change of position can produce a totally different choice of path. The initial choice of direction is determined by the starting position relative to the boundary of a fractal set, which is itself determined by the other end-point. The mathematics are similar to, but more complex than, those of river catchments in fractal landscapes, and are beyond the scope of this paper. We note, however, that efficient nearly-optimal routes are not hard to find.

In the self-similar network shown high-level links comprise only a vanishing fraction of the total length. This implies that many extra high-level links can be supplied without significant extra cost. Indeed, we could connect level n nodes to all the nodes within d_n down to level $n/2$, without increasing the total cost more than ~50%. A lesser degree of connectivity may be adequate in practise. At the lowest levels, some thinning of redundant tracks is also possible.

In a network weighted towards high-level links, the travel time over long distances tends towards that for the direct journey. Most of the journey is accomplished in a single stage in very nearly the right direction. Successive stages are much shorter.

On a supramundane planet, the transport web is not restricted to the surface. Most of the lower levels will lie in tunnels through the geosphere, but high-level links subtending a radian or more may cut across the inside of the planet, significantly reducing the transit time.

A network of roller-coaster links hanging from the underside of the toposphere like cobwebs could provide an efficient transport system, in which cars will swoop through the network under the pull of gravity, following curves known as *brachistochrones*. The disadvantage of this scheme for passengers is the g-force, which varies from zero at the end-points to a maximum of $2g$ in the middle, at a depth of d_n/π.

A network of geodesic links can be very gentle on passengers. Suppose we set the standard acceleration $a=5\,\mathrm{ms}^{-2}$. Because it is orthogonal to the gravitational force, the net perceived gravity is only about $1.1g$. But in 15 minutes a link 1000km long can be traversed. Over longer distances around the globe cars will approach and exceed orbital velocities and higher linear accelerations can be applied.

The transport web will therefore permit rapid and efficient journeys to any point on the supramundane planet in a time only marginally in excess of $(\pi/\sqrt{2})(R/g)^{1/2}$. For Suprajupiter, this corresponds to a travel time ≲2 hours. For a suprastellar planet, the corresponding period is ~12 hours.

Transport links will also extend down to the underplanet, up into orbit and out into space.

The basis of the transport links is a *momentum loop*, a bundle of mass-streams comprising a partial orbital ring or dynamic compression member. Unlike free orbital rings, the bundles can have tension members strong enough to overcome the mass-streams' compression and leave the loop under a net tension. Such a loop is stable [14], but must be supported by the structure of the geosphere or toposphere. Viscous coupling of the mass-streams to the geosphere mass would also damp oscillations and instabilities.

Even a dense transport network of such momentum loops, say d_0~30m, will be very much less massive than the orbital rings supporting the toposphere. Consequently, the cost of a planetary transport web will be only a tiny fraction of the cost of the complete supramundane planet.

Individual cars or capsules will now ride upon the loops, accelerating and decelerating by electromagnetic coupling to the mass-streams. A high efficiency is achieved by bundling a number of cables with a range of speeds. Every passenger will enter a car at his starting-point and tell it his destination. The car will then work out the best route and follow it. There is a great deal of redundancy in the system, so if some of the links go down or become especially busy, average travel times will increase only marginally.

The two arms of the momentum loops will give each link a separate up-line and down-line, on which all vehicles travel in the same direction at the same acceleration between the same two points. The maximum throughput of such links is very great. It is no exaggeration to say that such a transport network can make possible cities as large as a suprajovian planet.

12. SCENARIO

Here is a scenario for the construction of suprajovian and suprastellar planets within the Solar System. It is an optimistic scenario, describing what we *could* do rather than necessarily what we will, and the details are not to be taken too seriously. At the same time it is a conservative scenario, in that it does not include scientific advances as yet undreamt of. Nevertheless, although timescales may be lengthened by human weakness, political expediency or bureaucratic inefficiency—factors already present in my extrapolations from the past—I am confident in my prediction that *something* not unlike this scenario will in due course come to pass.

For convenience, costs are presented nominally in constant 1980 £'s, at amounts that would obtain today if we already possessed a developed space industry turning over $\gtrsim$1T£yr^{-1}. The cost of constructional items is therefore assumed to remain constant. Prices may actually rise or fall if money supply fails to follow industrial growth, but such economic fictions are not important here.

It is assumed that the per capita industrial growth rate will average 2.4% per annum (equivalent to a 30yr doubling time). This is an empirical figure, which has been maintained for at least 200yr. Its validity is perhaps most readily appreciated by examining graphs of the price of coal or copper deflated by wages [16]. Although the growth rate varies from country to country, and fluctuates from time to time, the underlying trend is clear. There is every reason to expect this trend to continue into the future.

Over the past thirty years, space-related expenditure has grown far faster than the average industrial growth rate. Despite major uncertainties caused by political vacillation *average* growth rates of order 15% per annum have probably obtained.

Within the next few decades it is likely that space industrialisation will "take-off", growing at up to ~40% per annum to ~10T£yr^{-1}, the current Gross World Product. My expectation is that space tourism will probably be the trigger for this rapid growth. At present, in vehicles not designed for tourism, launch costs are ~10M£/person, though the energy cost is only ~£20. The potential for rapid cost reduction, coupled with an explosion of demand, is great: costs can be expected to fall roughly as the square root of the cumulative number of passengers carried; and demand can be expected to rise roughly as the inverse square of the ticket price. Once the price is down to ~£300 almost everyone in the developed world can be expected to take a trip; and then large-scale space colonisation will seem a natural progression.

The details of this rapid growth phase—which is principally a redirection of terrestrial industry—are not important to this scenario, but for convenience I define a base level corresponding to ~10T£yr^{-1} at epoch 2000 AD.

Population in space will also rise rapidly. Over the past 30 years its growth has averaged ~25%pa. In another hundred years this growth rate would lead to a space population in excess of Earth's. Introduction of space tourism, and then space colonisation, will lead to an extremely rapid rise in the number of people in space. After this, the growth rate will fall to a long-term average of ~2.4%pa, the same as the per capita industrial growth rate, and thus half of the gross industrial growth rate. A base population of $\sim 10^{10}$ in space and a further $\sim 10^{10}$ on Earth at epoch 2100 AD is assumed.

By ~2100 AD the Gross Human Product $\sim 10^{15}$£yr^{-1} will buy space habitats at ~20£m^{-2} totalling $\sim 5\times 10^{14} m^2$, equal to the surface area of Earth. Both population and population density will then be about the same in space as on Earth. Thereafter, as people get richer, the average population density of new habitats can fall by ~2.4%pa. After ~2500 AD people may own so much territory each that the demand for more may be assumed to fall off progressively, until a plateau is reached at ~2500km^2/person.

In addition, it is assumed that interstellar colonisation, commencing during the next century, grows rapidly until the emigration rates is ~1.2%pa, halving the local population growth rate to ~1.2%pa from a base $\sim 2\times 10^{11}$ at epoch 2200 AD. This emigration rate may well be too high, so long as new colonies may be founded more easily within the Solar System. However, since emigration delays construction of large habitats until the population within the Solar System is large enough, a high emigration rate is now conservative. On this model, the number of other solar systems occupied by $\geq P$ is $\sim P_{tot}/P\ln\Lambda$, where $\Lambda = P_{max}/P_{min} \sim 10^{15}/10^9$, $\ln\Lambda \sim 15$. Those with a high enough population build supramundane habitats and planets of their own.

Although population growth rates in the developed world are currently low ($\lesssim$1%pa), there is reason to anticipate a return to higher growth rates ~2.4%pa through space colonisation. The opening up of new territory has throughout history led to periods of rapid growth. Selection effects also operate. In the perpetually open frontier of space, it is therefore probable that high population growth rates will be maintained.

Because long-term trend lines are empirically determined, they already include all human incompetence, inefficiency, laziness, short-sightedness, political back-stabbing, proxmiring and all the rest. Other trend lines relevant to this scenario include achieved vehicular speed versus epoch [17] and mass of aircraft and spacecraft versus epoch (which may increase by nearly a decade per decade).

The average growth rates and timescales used here may be reliable within about a factor of two. However, the invention of molecular copiers or Von Neumann Machines might speed development enormously.

It is considered that habitats will be constructed to meet the demands of ordinary people, who may be expected to insist upon conservatively designed environments, similar to the more attractive parts of Earth. Appearance will be far more important than efficiency. It is for this reason that I have considered the simulation of tides, seasons, coral reefs; that I have included islands, rivers and ocean deeps; that I have described worlds where life is much like life on Earth.

Since large habitats can be constructed in sections, an investment as small as ~2G£ at a time could suffice. Such amounts will be well within even the *individual* capability of sufficiently rich people—whose numbers can be expected to increase at ~7.2%pa from a base of ~10 at epoch 2100AD. The empirical assumption here is that for wealth W we have $n(>W) \sim P(\bar{W}/W)^2$. Thus by about 2500AD, almost everyone should be rich enough.

It is apparent that vast governmental initiatives are neither necessary nor particularly desirable: I believe that a free-market approach will be the most successful. (That is not to say that governments should not or will not construct colonies themselves, but rather that they must expect to compete for colonists on an open market).

It is anticipated that the construction of large habitats will be contemporaneous with the continued construction of smaller habitats. Thus at any time the largest habitat will contain only a fraction of the total habitat area. I have assumed that roughly equal total habitat areas will be provided in each distinct size range (*ie*, roughly twice as many habitats half the size), except where the completion of a supramundane planet swallows up the smaller constituent habitats.

DATE (AD)	HABITAT AREA Total/$A_\bullet$[1]	p.c./m^2	BIGGEST HABITAT Area/$A_\bullet$	Radius/km	POPULATION Total	System[1]
2040	.005	2×10^4	.0008	160	1×10^{10}	1×10^8
2100	1.0	5×10^4	.05	1280	2×10^{10}	1×10^{10}
2130	3.5	7×10^4	0.2	2560	4×10^{10}	3×10^{10}
2160	13	1×10^5	0.6	2.5×10^4	8×10^{10}	6×10^{10}
2200	50	2×10^5	15	2.5×10^4	2×10^{11}	1×10^{11}
2220	100	4×10^5	17	2.6×10^4	3×10^{11}	1×10^{11}
2260	400	1×10^6	95	6.2×10^4	8×10^{11}	2×10^{11}
2290	1100	3×10^6	316	1.1×10^5	2×10^{12}	3×10^{11}
2500	1×10^6	2×10^8	3×10^5	3.7×10^6	2×10^{14}	3×10^{12}
2600	2×10^7	8×10^8	4×10^6	3.7×10^6	2×10^{15}	1×10^{13}
3000	5×10^9	2×10^9	3×10^9	3.8×10^6	2×10^{19}	1×10^{15}

(1) Population and habitat area in solar system, excluding Earth.

TABLE 1: *Summary of populations and habitats with epoch*

The scenario (Table 1) may run something like this:

2040 Terraforming of Venus [5] may begin. Aerial colonies on Venus [5] may be the first supramundane habitats. Population in space $\sim10^8$ in $\sim2.5\times10^{12}m^2$ of space habitats at $\sim2.5\times10^4$ m^2/person. Biggest habitat $\sim4\times10^{11}m^2$, radius ~160km. (I know this seems highly optimistic, but fifty years is a long time—oh, it might take two or three decades longer to reach this level, but I'll stick my neck out with this prediction).

2100 Strong demand for materials from the outer planets may lead to the construction of the first supramundane habitats there. Some may be of the simple aerial colony design [5], others may be supported by orbital rings.

2130 Biggest habitat is now $\sim10^{14}m^2$, radius ~2560km, about the largest rotating space colony one can build efficiently with a diamond toposphere. Hereafter we shall need to use suprajovians for the larger habitats, commencing at Uranus.

2160 Biggest habitat is now an equatorial strip ~5000km wide around Uranus ($0.6A_\bullet$), widening a strip habitat that may have been commenced as early as 2050.

2200 Supra-uranus ($15A_\bullet$) and Venus terraforming ($1A_\bullet$) completed. Work continues on other suprajovian habitats.

2220 Supraneptune ($17A_\bullet$) completed.

2260 Suprasaturn ($95A_\bullet$) completed.

2290 Suprajupiter ($316A_\bullet$) completed. Emphasis moves towards large multi-layer and macaroni-loop rotating space colonies, then to suprasol habitats.

2500 Suprasol single layer ($3\times10^5A_\bullet$) completed. Large-scale mining of the Sun commences.

2600 Suprasol-12 completed with low mass layers, using mass dumping and solar power for mining. Hereafter we begin to use the Sun's internal heat to increase the mining rates.

3000 Suprasol-10^4 completes the $3\times10^9A_\bullet$ "Dyson Sphere". Habitable area of the fully-tamed Solar System consists of the heavy suprasol planet (~60%); the suprajovians, Earth, Venus and the orbital habitats (~30%); and over 2500 ly of macaroni loop habitats along tramlines to the nearer stars (~10%). In all, there are $\sim10^{18}/P$ solar system with populations $\geq P$ at this epoch of *historical time* [18], down to a cut-off $P\sim10^9$.

>3000 Suprastellar planets are completed in solar systems progressively further out. Radiator sink temperatures are gradually reduced to ~3K, increasing habitat areas by a factor ~100. Taming of the Galaxy continues.

13. CONCLUSIONS

We conclude:

That supramundane planets are an attractive alternative to conventional space colonies and terraformed planets;
That they can be constructed at an acceptable cost and in affordable stages;
That they can be designed to be safe, robust and easily maintained;
That they may be fully Earthlike in gravity, climate and appearance;
That they will be convenient and spacious places to live, work and travel;
And that they may house great populations both in the Solar System and beyond.

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