Alternatives to Earth

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INTRODUCTION

As an astronomer I am sometimes asked if I look on the vastness of the Universe with optimism for future solutions of Man's territorial and resource problems. Can we see our future living space in the enormous reaches of the Milky Way? Can we look forward to relieving our growing global claustrophobia by expanding Man's domain outwards towards the stars?

Our TV screens in the late 1960's and early 1970's carried inspiring images of Moonwalkers taking their 'great leaps for Mankind' with accompanying commentary on how Man was achieving his dreamed-of greatness as a truly cosmic being. Less conspicuously, but rather more seriously, NASA writers have authored articles arguing the worth of 'space' for Mankind - always a worth to be realised in the future, with surprisingly little detail on what forerunner benefits are being realised now. Representatives of aerospace-oriented industry argue that we must look to space as the ultimate solution for terrestrial ills (e.g. K.A. Ehricke in 'The Extraterrestrial Imperative').

I shall attempt to demonstrate that the rich harvest of speculation about the utility of the planets for Man has been severely blighted by the discoveries of the last few years. I shall emphasise the view that dreams of exploiting the resources of the Solar System planets, or of using them as living-space for an overgrown population, *are* merely dreams. Although it may be uplifting for Man to dream of a future among the stars, such dreams are so far removed from our present technological competence that it would be dangerous nonsense to expend an appreciable fraction of our problem-solving effort in pursuit of alternatives to Earth.

I shall describe briefly the variety of physical environments provided by the Solar System planets, and summarise present thinking on how their diversity may have evolved amongst material with a common pre-planetary origin. Given our questionable competence for managing the present environment of Earth, it will be evident that the other Solar System planets provide no short-term solutions for any of the issues that will be raised by later lecturers.

I shall then look farther afield to assess the possibility that other stars in the Milky Way have planets which could support Earthlike biospheres. While there *are* observations encouraging us to believe that there are many 'other Earths' throughout the Milky Way, my purpose will not be to suggest that their exploitation by Man will be an important factor in dealing with the problems of an expanding population. Rather, I shall suggest that dreams of 'cosmic Man' will be realised only if we first evolve more successfully in our present role as 'planetary Man'.

INGREDIENTS OF AN ALTERNATIVE TO EARTH

The basic physical process of all life on Earth may be described as one in which small amounts of solar energy are borrowed by complex molecules arranged in the particularly sophisticated structures we call organisms. The molecules manipulate the borrowed energy in such a way as to preserve their structural arrangements and temporarily ward off the overall tendency to increasing molecular chaos in the Universe. Thermodynamics tells us that in any closed system the total *entropy*, or degree of disorder, must increase as time passes. Highly organised molecular systems like ourselves must work hard to buy time against the natural tendency to disorder. To do this, we require an energy supply (if we are closed off from a suitable supply, disorder sets in and we die), and our supply derives ultimately from the hydrogen-fusing reactions inside the Sun.

In addition to an energy supply, we require specific physical and chemical conditions to obtain in our environment, in order to allow the molecular machinery for the preservation of our low entropy to function.

While the demand for energy is probably fundamental to all life forms, on Earth or elsewhere, the specific physicochemical needs of terrestrial life are undoubtedly a product of its particular course of biochemical evolution.

All organisms on Earth consist of large carbon-based molecules dispersed in an aqueous medium. They all depend on the presence of heavy chemical elements and of liquid water. Living organisms are particularly adept at acquiring liquid water; in desert regions they may contain most of the available supply. The processes of life also flourish at the boundaries between liquids, solids and gases and therefore require a definite range of temperatures and pressures in the environment. Furthermore, essentially toxic materials must be absent.

The detailed requirements for support of life as we know it will be taken up more fully later in the course. For the moment, I shall adopt the summary of requirements listed in Table 1, and examine briefly the environments provided by the nearby bodies of the Solar System.

TABLE 1: HUMAN ENVIRONMENTAL REQUIREMENTS FOR PERMANENT HABITATION (adapted from Dole, *Habitable Planets for Man*)

Temperature	Seasonal mean daily minimum - 10°C maximum 40°C			
	Mean annual minimum 0°C maximum 30°C			
	Extremes depend on exposure time and other factors			
Light Input	0.02 to 50 lumens per sq. cm.			
Gravity	Near zero to about 2g			
Atmospheric Composition	Constituent	Tolerable Range of Inspired Partial Pressures (mm of Hg)[a]		
	Oxygen	50	to	400
	Carbon dioxide	0		7
	Helium	0		61,000?
	Neon	0		3,900?
	Nitrogen	10?		2,330
	Argon	0		1,220
	Krypton	0		350
	Xenon	0		160
	Water vapour	near zero		25
	Toxic gases	trace amounts only		
Other Characteristics	Liquid water Indigenous life forms Tolerable wind velocities dust levels natural radioactivity meteorite infall rate volcanic activity electrical activity			

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[a] 1 Earth atmosphere at sea level corresponds to about 760 mm of Hg pressure.

THE SOLAR SYSTEM

Briefly, the known Solar System consists of four large and five small planets, thirty-two satellites of planets, and a host of minor planets, comets and miscellaneous interplanetary junk, all in gravitational orbit around the Sun. The orbits of all the massive pieces of extra-solar material in the system lie within a few degrees of a common plane. The orbital motions of planets around the Sun, and those of most satellites around their planets, share a common directional sense. This sense is also shared by the rotations of most of the planets on their own axes (excepting those of Venus and Uranus), and by the rotation of the Sun. The mean plane of the Solar System lies in the equatorial plane of the Sun. These regularities in the kinematics of the Solar System strongly suggest that most of the material in it had a common origin, rather than consisting of a collection of random cosmic debris swept up by the Sun in its travels around the centre of the Galaxy.

There is also a strange numerical law, known as the Titius-Bode relation, connecting the mean distances of the planets from the Sun: these distances, relative to that of the Earth, form a series defined by

$$d_n = \frac{A + B.2^n}{10} ,$$

where $A = 4$ and $B = 3$. To obtain the mean distances of the planets from the Sun, n must take successively the values $-\infty$, 0, 1, 2, 4, 5, 6. The value $n = 7$ gives only a poor fit to the mean distance of Neptune, but a passable fit to that of Pluto; the latter's orbit is so eccentric that this is not an impressive coincidence however. The 'missing' value $n = 3$ corresponds not to a planet, but to the mean distance of the minor planet (or 'asteroid') belt between Mars and Jupiter. The explanation of numerical coincidence is still a matter for some controversy.

Table 2 summarizes some relevant physical data about the planets. All of them receive some part of the Sun's radiated electromagnetic energy, in particular the heat and light which nourish and sustain life on Earth. What promise is there that within this well-organized assembly of minor objects clustered around the Sun there are environments potentially utilisable by Man?

TABLE 2: SOLAR SYSTEM DATA

Planet	Semimajor axis of orbit around sun A.U.[b]	 Titius-Bode	Orbital Period[c]	Rotation Period[c]	Diameter (Earth=1)	Mass (Earth=1)	Mean Density (gm/cm^3)	Mean Density Corrected for Effect of Gravity[d]	Surface Gravity (Earth=1)
Mercury	0.3871	0.4	87.97d	59d	0.38	0.056	5.1	5.1	0.39
Venus	0.7233	0.7	224.70d	242.9d	0.95	0.82	5.3	4.8	0.89
Earth	1.0000	1.0	365.26d	23h56m04s	1.00	1.00	5.52	4.4	1.00
Mars	1.5237	1.6	1.88y	24h37m23s	0.53	0.108	3.94	3.7	0.38
Ceres[a]	2.7673	2.8	4.60y						
Jupiter	5.2028	5.2	11.86y	9h50m to 9h55m	11.19	318.0	1.33		2.35
Saturn	9.5388	10.0	29.46y	10h14m to 10h38m	9.47	95.2	0.69		0.93
Uranus	19.182	19.6	84.01y	10h45m	3.69	14.6	1.56		0.99
Neptune	30.058		164.79y	16h?	3.50	17.3	2.27		1.38
Pluto	39.439	38.8	247.69y	6.4d	<0.47	0.06?	?		?

[a] Typical minor planet (asteroid)

[b] 1 A.U. (astronomical unit) = 92,956,000 miles

[c] y=years, d=days, h=hours, m=minutes, s=seconds

[d] Planetary interiors are compressed by gravity. This column gives estimates of mean densities with this effect removed.

Mercury

The planet nearest to the Sun was once thought to provide both the hottest and coldest environment in the Solar System. Slim evidence provided by the Italian astronomer Schiaparelli suggested that Mercury's rotation and orbital periods coincided, so that it kept one face permanently presented to the Sun. Exotic schemes, such as using ice and frozen oxygen from the 'dark' side, allegedly at about -240°C, were put forward for maintaining a habitable zone in the 'twilight' region between it and the sunlit side.

Such slender straws could no longer be clutched at when it was shown from radar reflection studies in the mid-1960's that the rotation period is 59 days, whereas the orbital period is 88. There is no permanently sunlit or permanently dark side. All regions of the planet are turned towards the Sun every few weeks, and their temperatures raised to about 340°C.

Mercury's small mass can retain vanishingly little water or gaseous atmosphere at such a temperature, and this cyclic furnace would be a most inhospitable environment for life as we know it.

Venus

Speculation on the habitability of Venus was rife until the 1960's, for its surface is perpetually hidden from our view by a dense cloud layer. Venus is in some respects almost a twin of the Earth: the mean diameter is 7800 miles (compare 7900 for the Earth) and the mass is 0.82 that of the Earth. Venus thus has essentially the same capability to retain an atmosphere as does the Earth under similar thermal conditions. Venus, being closer to the Sun, receives almost twice as much solar radiation as the Earth, but its cloudy atmosphere reflects more: the intensity of solar radiation reaching through its clouds might be therefore comparable to that of the terrestrial environment. The recent U.S. and Soviet space probes revealed however an environment very different from ours: an atmosphere of 90 % carbon dioxide, 7 % nitrogen, only 1 % oxygen, and less than 1 % water vapour. The surface temperature is over 300 °C, the surface atmospheric pressure exceeds 100 Earth atmospheres, and there is little or no magnetic field. The absence of magnetic field means that energetic solar particles and cosmic rays can penetrate the atmosphere quite freely, without becoming trapped in regions analogous to the terrestrial van Allen belts. Altogether, the planet appears quite inhospitable to terrestrial life-forms, except perhaps in its upper atmosphere.

The Moon

As early as the 2nd Century A.D., Lucian of Samosata, a Greek satirist, wrote of a Moon populated by beings who were at war with others in the Solar System over the right to colonize Venus; as late as 1901, H.G. Wells visualised a Moon carpeted with plants. His moonmen were, however, forced to comply with terrestrial telescopic data by living underground. The Moon, with only 10^{-15} of the Earth's atmosphere, a day-night temperature variation of 100 $^{\circ}$C to -150°C, and an essentially zero magnetic field, provides none of the requirements for the maintenance of life.

You may object that human life has already been maintained on the Moon for short periods during the Apollo program. The NASA astronauts, however, take with them a terrestrial environment-substitute capable of providing short term life-support under purely exploratory conditions. To support five men in similar fashion, with shelter, supplies, a modest amount of research equipment and a return vehicle, would require landing at least 150,000 pounds of material on the lunar surface. The cost per pound of payload delivered to the lunar surface using Apollo-related technology is around $70,000. Support of five men on the Moon for a year, Apollo-style, would therefore cost around ten billion dollars. It is difficult at present to conceive of a way in which those five man-years could be so well spent as to justify such cost.

Mars

The Mariner spacecraft have provided a wealth of detailed information about the Martian atmosphere and surface, laying to rest some notorious speculations and observational uncertainties. The surface is well cratered, superficially resembling that of the Moon, but showing much more evidence of atmospheric erosion. The atmospheric pressure is about one hundredth that of the Earth, and the atmosphere contains occasional clouds and hazy patches, rarely obscuring more than a small fraction of the surface from view. The chemical composition of the atmosphere is still in considerable doubt, but it appears to be mostly carbon dioxide, with less than 20 % nitrogen, about 1 % oxygen, and less than one billionth of the terrestrial proportion of water vapour. Summer daytime temperatures rise to around +30°C, but fall to -75°C at night.

Speculations concerning the habitability of Mercury, Venus and the Moon were mainly the work of fiction writers or of astronomers in exceedingly whimsical moods. In contrast, serious attention has long been given to the possibility that earthlike life might survive with minimal assistance on Mars: why is this?

In 1877, Schiaparelli (again!) reported observations of 'channels' or 'canals' on Mars, linear features of considerable extent crossing the surface of the planet. These features were studied further by many competent observers, including Camille Flammarion in France and Percival Lowell in the U.S.A. Lowell in particular made extensive charts of over 600 links in the 'canal system', which he interpreted as evidence for an advanced form of planet-wide technology. The seasonal growth and recession of the prominent white polar caps of the planet, together with conspicuous colour changes in the surface features during the Martian springtime when the appropriate cap is receding, suggested to some that the canals might be an irrigation system on a world with an acute water shortage. The reddish colour of much of the surface, suggestive of a sandy desert, reinforced these notions.

Unfortunately the canals appear not to exist. The Mariner photography shows some crater chains and broad valleys which might be linked into apparently linear features on visual inspection of a telescopic image near the limit of resolution, but the main systems described by Lowell seem to have been pure illusions. It is also unlikely that the polar caps are water ice, although this is a controversial point: frozen carbon dioxide (dry ice) appears more plausible. In any event, their rate of recession in springtime gives an indication of their thickness, knowing the solar heat supply. The best estimate is a thickness of only half an inch or so; there is hardly enough material in them, even if distributed by sublimation rather than in canals, to significantly influence the balance of existence elsewhere on the planet. The seasonal colour changes in some of the dark areas, which could be due to the growth of vegetation, have also been attributed to movement of light-coloured dust over a darker base by seasonal planet-wide storms, of which the dust storm that greeted Mariner IX in 1971 was an extreme example.

For Man, Mars is hardly an attractive prospect. Unaided by the life-support apparatus of an Apollo flight, he would asphyxiate before he froze; the environment has been compared with that of the Sahara desert raised to the altitude of the terrestrial stratosphere. The planet's magnetic field is less than a thousandth of the Earth's, so the surface is regularly bombarded by energetic charged particles produced in solar flares; the lack of oxygen in the atmosphere also means there can be no ozone 'blanket' to screen out solar ultraviolet radiation, as there is on Earth. Lab experiments have shown that some simple terrestrial organisms can survive in, and possibly adapt to, Martian conditions, but for Man on a large scale the red planet seems scarcely much more hospitable than the Moon.

Asteroids

The asteroids, or minor planets, are chunks of rock mostly less than a few miles across. Although little is known of the details of their chemistry or surfaces, it is certain that their gravitation would be too feeble to retain any atmosphere or water. They need not concern us further here.

The great outer planets

The 'four major planets' referred to earlier come next in distance from the Sun: Jupiter, Saturn, Uranus and Neptune. We have yet to visit these planets with our space probes, but much is known of them through spectroscopy of the sunlight they reflect and through microwave radiometry, which indicates their atmospheric temperatures. Jupiter, the largest of them, is fairly typical, and I shall concentrate on describing it. Its mean distance from the Sun is 483 million miles, the orbit being traversed once every 12 years. The planet rotates once every 9.8 hours, leading to a shape that is visibly very flattened at the poles. Its mean diameter is 89,000 miles, while its mass is 318 times that of the Earth; its mean density is thus only 1.3 times that of water, while that of the Earth as a whole is 5.5 times that of water. This alone suggests that Jupiter is composed mostly of very light material. Spectroscopy of its atmosphere confirms that this is mostly hydrogen and helium with smaller amounts of very hydrogenous molecules, such as ammonia and methane. The temperature in the visible clouds is about -100°C. There may be no well-defined surface. In such an atmosphere, the gas pressure would steadily increase with depth until a sort of 'slush' of frozen methane and ammonia was encountered. Still deeper conditions may be such that the hydrogen is in a pseudo-metallic form.

Such a hydrogen-rich atmosphere is quite inhospitable to terrestrial organisms in their present form, although it is interesting that it provides conditions similar to those in which primitive life is thought to have evolved on Earth billions of years ago. Today's terrestrial organisms are adapted to a changed environment that they have helped to create, as later lectures will discuss. Although the atmosphere of Jupiter would be toxic to modern terrestrial life, it is not inconceivable that our primeval predecessors could be evolving there today.

The other outer planets (excluding Pluto, about which we have essentially zero information) seem chemically similar to Jupiter, but their atmospheres are still colder, due to their greater distances from the Sun. The promise for environments readily adaptable to our form of life decreases still further with increasing separation from the Sun.

THE EVOLUTION OF THE SOLAR SYSTEM

Having found such diversity, it is appropriate to re-examine the idea proposed earlier that the planets may have had a common origin.

Proto-stellar material collapses out of the turbulent inter-stellar gas in a rotating galaxy, thereby acquiring some angular momentum. As the gas condenses to form a star, its rotation rate increases. There seem to be two alternative courses in the evolution of a rotating protostar, both involving fragmentation.

One is fission of the protostar into two comparable fragments, the total angular momentum being taken up by their subsequent mutual gravitational orbits. The two fragments each form stars, and the result is a 'double star'. About half the known stars in the Milky Way are members of such systems.

The other alternative can be inferred from observation of our own Solar System. The total mass of all the planets is about 1/700 of the solar mass, yet 98 % of the angular momentum of the Solar System about the Sun's rotation axis is vested in the orbital motions of the planets. (Sixty per cent of the total is contributed by the orbital motion of Jupiter alone.) The total angular momentum of the Solar System about the central axis is not very different from that of many double star systems about axes through their centres of mass.

Numerous studies of single-star formation by gravity from interstellar clouds suggest that the collapsing material will flatten into a disc. The Swedish physicist Hannes Alfven and the British cosmologist Fred Hoyle have shown that the angular momentum of a collapsing central 'protostar' could be transferred outwards to a small amount of material in a circumstellar disc by winding up the protostellar magnetic field. The process would not continue indefinitely, but the result would be a relatively slowly-rotating magnetised star surrounded by a small amount of material possessed of a large amount of orbital angular momentum.

The material surrounding the central object would condense into planets. As the individual planets were assembled by gravitational accretion of surrounding matter, they would never reach the stage in the development of a star where nuclear reactions begin in the interior. Their gravitation could not compress them enough to raise the internal temperature to the 20 million degrees or so required to begin hydrogen fusion. Jupiter, the most massive planet in the Solar System, has about one-tenth to one-thirtieth of the <u>minimum</u> mass for star formation.

The point must now be re-emphasised that the initial protoplanetary material would have been interstellar gas containing mostly hydrogen, with only the small 'primeval' proportion of helium and the traces of heavier elements added by the explosive phases of earlier 'first-generation' stars (first lecture). In fact, the chemical composition of that material must have resembled the mixture we see today in the surface of the Sun (Table 3). In this scenario, the hydrogenous planets may seem more reasonable than our own Earth, but consider now the effect of 'turning on' the Sun as a star.

As the Sun acquired its own source of energy through nuclear fusion, its radiation kept the nearer planetary condensations at higher temperatures than the outer ones. The lightest molecules in their atmospheres acquired the greatest mean velocities of random motion (all molecular species acquire the same mean <u>kinetic energy</u> in a gas raised to a given temperature). Thus the light molecular species could move at velocities comparable with the velocity of escape from the gravitational attraction of many of the condensing planets; hydrogen and helium could be evaporated off more readily than the heavier molecules. The flow of radiation from the newly-born star

TABLE 3: ATOMIC ABUNDANCES IN THE SUN[a]
The quantity tabulated is $\log_{10}(N_x/N_H)+12$, where N_x is the abundance of element X, and H is hydrogen.

Atomic Number	Element	$\log_{10}(N_x/N_H)+12$
1	H	12.00
2	He	11.10
3	Li	0.96
4	Be	2.36
6	C	8.72
7	N	7.98
8	O	8.96
11	Na	6.30
12	Mg	7.40
13	Al	6.20
14	Si	7.50
15	P	5.34
16	S	7.30
19	K	4.70
20	Ca	6.15
21	Sc	2.82
22	Ti	4.68
23	V	3.70
24	Cr	5.36
25	Mn	4.90
26	Fe	6.57
27	Co	4.64
28	Ni	5.91
29	Cu	5.04
30	Zn	4.40
31	Ga	2.36
32	Ge	3.29
37	Rb	2.48
38	Sr	2.60
39	Y	2.25
40	Zr	2.23
41	Nb	1.95
42	Mo	1.90
44	Ru	1.43
45	Rh	0.78
46	Pd	1.21
47	Ag	0.14
48	Cd	1.46
49	In	1.16
50	Sn	1.54
51	Sb	1.94
56	Ba	2.10
70	Yb	1.53
82	Pb	1.33

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[a] Goldberg, L., Muller, E.A. and Aller, L.H., *Astrophysical Journal Supplements*, vol. 5, p.1 (1960).
Unlisted elements are of dubious abundance.

thus increased the proportional concentration of the heavy elements in the innermost planets; the eventual equilibrium of each planetary atmosphere represents a balance between the molecular motions induced by the stellar radiation and the gravitational pull of the remaining matter.

This accounts for the higher relative abundance of hydrogen in the outer planets, and for the run of the mean densities of the solar system planets with increasing distance from the Sun (Table 2). It seems likely that the condensations which formed Mercury, Venus, the Earth and Mars lost most of their original gaseous atmospheres at an early stage of their development, and that the atmospheres of the last three today are secondary phenomena produced by subsequent outgassing of their interiors.

This brings us to a further question. Why are the atmospheres of Venus and Mars so dominated by carbon dioxide, of which the Earth's atmosphere has relatively very little? The difference between Earth and Venus, otherwise so similar in their gross physical properties, seems particularly intriguing.

If the Earth's atmosphere today had the composition of present-day volcanic exhalations it too would have nearly 100 times more carbon dioxide than nitrogen and other gases. So the proper question seems to be not "where did Mars and Venus get all their carbon dioxide from?" but "where did all the Earth's carbon dioxide go?"

The carbon on the Earth's surface is mostly locked up in carbonate rocks and in living organisms. This possibly provides the clue we need to understand the Earth-Venus differences. Suppose that the volcanic exhalations of both planets, condensed from essentially similar preplanetary material, provided them both with primeval atmospheres rich in carbon dioxide.

The first difference between the two planets was probably a difference in the rates of weathering of the surface silicate rocks through processes such as:

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$$

These weathering processes are slowed down if the temperature is increased and would therefore have proceeded more readily in the somewhat milder environment of the primeval Earth than in that of primeval Venus. Even a small initial temperature difference would eventually result in more of the atmospheric carbon dioxide ending up in carbonate rocks on Earth than on Venus. The divergence between the two environments would then have been increased by the 'greenhouse effect'.

A carbon dioxide atmosphere is relatively transparent to the arriving solar radiation, which is absorbed only at or near the planetary surface. The arriving energy warms the surface, which reradiates mainly in the infrared. Carbon dioxide is opaque in the infrared however, and on Venus this reradiated energy does not escape into space but is 'trapped' in the atmosphere, keeping its temperature high. The Earth would gradually have escaped from this effect as the rock-weathering removed the carbon dioxide here. The lower temperature resulting from the reduced greenhouse effect further accelerated the rock-weathering on Earth so the conditions on the two planets would have diverged at an increasing rate.

A further important difference may have been the appearance of life on Earth. The fossil record shows that the early terrestrial life was plant life, which breathed in carbon dioxide and breathed out oxygen. The appearance of life would have helped remove more carbon dioxide from the Earth's atmosphere, replacing it with oxygen.

The oxygen on Earth could then contribute further to its difference from Venus. Oxygen and its triatomic form (ozone) effectively absorb the ultraviolet part of the solar radiation in the upper levels of the Earth's atmosphere, preventing this radiation from reaching the surface. This screening of the lower atmosphere from the solar ultraviolet helps to prevent much dissociation of water vapour in the lower levels into hydrogen and oxygen. This may have further affected the final equilibrium on Earth; if the water is dissociated, the hydrogen can escape from the Earth's atmosphere, but once this process is suppressed the planet would have tended towards a cooler watery environment that favoured the proliferation of life and the further removal of carbon dioxide.

All of these considerations indicate that the detailed balance between the chemistry of an atmosphere, its heat input, and the chemical conversions possible at its surface through plant and animal respiration and by abiological processes, may be a delicate one. The combination of a number of small differences, each of which accentuates the effects of another, may over billions of years have left Venus still with its primeval carbon dioxide in a hot 'super-greenhouse' atmosphere and Earth with a carpet of green plants, weathered rocks, oceans, and an atmospheric ultraviolet filter. The difference between a suffocating inferno and our 'good Earth' may rest on a very sensitive balance on the cosmic time-scale. There may be much to be learned about the long-term stability of planetay environments by comparative studies of the planets in the Solar System.

ALTERNATIVES TO THE SOLAR SYSTEM

Our immediate planetary neighbours are uninviting environments for Man. I feel that there can be little hope that any of the Earth's *impending* problems of resource depletion or overpopulation could be alleviated at all significantly by utilisation of these planets. It will take much longer to develop the technology to travel to the planets economically, or to reorganise them for human occupation, than to find less fantastic solutions to terrestrial problems. Even if we do acquire a massive ability for planetary re-engineering, it will make more sense to apply that ability here on Earth than elsewhere in the Solar System.

It is interesting however to look further afield than the Solar System for environments that might be hospitable to our form of life. Let us recall the requirements. First - an energy supply: this suggests that a suitable planetary environment would be located near a star. Secondly - there must be some quantities of the heavier elements: the star and its planetary system must have condensed from second-generation matter, that is interstellar gas some part of which has already been through the process of stellar element synthesis. Thirdly - liquid water and a gaseous atmosphere: the planet must not be too close to, nor too far from, the star. Finally - long-term stability: the star must not be of a type which undergoes violent variations, and should preferably be in the stable phase of hydrogen-to-helium conversion.

We can immediately rule out the neighbourhoods of all the first-generation stars in the Galaxy, of all the stars which have passed through their hydrogen-to-helium conversion phase, and probably of most of the double stars (around which it is difficult to obtain stable planetary orbits; the formation of double stars may anyway preclude the formation of planets in the same system).

Studies of stellar rotation have shown that most stars with surfaces appreciably hotter than that of the Sun are in rapid rotation - the mechanism for the formation of planets and outward transfer of angular momentum may have failed in these cases. Stars with surfaces appreciably cooler than that of the Sun will however be poor hosts for life-supporting planets.

Relative to a given organism, such as Man, we may consider a star to have a 'habitable zone' surrounding it, whose inner boundary is defined by the distance within which the planet's temperature would be too high, and the outer by the distance beyond which the temperature would be too low. It is easy to see that the size of the 'habitable zone' is smaller for less luminous stars (Appendix #1). Thus the chance that a given star will have a planet lying within the "habitable zone" is smaller the less luminous the star.

All of these considerations taken together lead to a strikingly simple prescription for a search for other planets inhabitable by Man: they will most likely be found around stars similar to our own Sun!

Present observational techniques are poor at discovering planets around other stars. The planets we know of outside the Solar System have been found by their gravitational perturbations of their host stars' motions. They are therefore massive planets, likely to resemble Jupiter in our own System. We know of no individual examples of potentially Earthlike planets.

We can, however, determine the approximate space density of stars like the Sun: the nearest is Tau Ceti, 12.2 light-years away. Then come Sigma Draconis (18.2 light-years), 82 Eridani (20.9 light-years) and Beta Hydri (21.3 light-years) - the mean distance between such stars is about 20 light-years. (Recall that a light-year is about 5,880 billion miles.) If all of these stars had planetary systems, we should expect perhaps one or two of the four named above to have Earthlike planets, from the statistics of our own Solar System. Even then the "Earthlike" planet might be another Venus. Indeed if it were like Earth, rather than Venus, it might well be replete with plant life and thus would have a high probability of being occupied already.

It seems possible that Earthlike planets could occur at roughly 20-light-year intervals throughout the Milky Way. Compared with the range of modern telescopic astronomy, this is a trivial distance and we must say that such planets would be commonplace. There could be about 100 million or more in our Milky Way galaxy alone.

Life on Earth is therefore likely to be but one example of a widespread galactic phenomenon. This has led modern astronomers to consider seriously the possibility of establishing communications with other galactic civilisations (see the volume *Interstellar Communication* edited by A.G.W. Cameron). It is important to realise however that all serious suggestions centre on the viability of projects to send or detect electromagnetic signals. Travel between Earthlike planets, even at 20-light-year intervals, would involve technology beyond our wildest expectations.

Suppose we were to consider sending a manned 10-ton spacecraft to the nearest Earthlike planet, assumed to be about 20 light-years away. To accomplish the journey in a reasonable time, velocities close to that of light would have to be achieved for most of the journey. As it turns out, an acceleration of one 'g' for one year results in a velocity close to that of light, so there is no doubt that human beings could withstand acceleration to such velocities in times that are reasonably short compared with the duration of the voyage. The energetics of the operation are, however, horrendous.

In *Interstellar Communication* Edward Purcell demonstrates that, even using an idealised nuclear fusion propellant, the initial mass of the spacecraft at the launching pad would need to be over a billion times that completing the journey. Nuclear fusion propulsion, which has yet to be developed, would obviously be inadequate. Going still further beyond available technology towards the limit of what we believe to be possible in principle, we could contemplate perfect matter-antimatter annihilation as an energy source. Leaving aside such entirely non-trivial questions as how to manufacture and handle the propellants, we should still need a 400,000-ton fuel supply (half matter and half antimatter) for the craft at launch. To achieve the required acceleration, the rocket would initially produce about 10^{18} watts, mainly as γ-rays. This is rather more power than the Earth presently receives from the Sun as sunshine, so the next problem would be to shield the Earth satisfactorily from the exhaust of the craft .... Such discussions bring the meaning of those 20 light-years into more reasonable perspective.

Even assuming that we could acquire the necessary technological competence, it is important to realise that interstellar expansion of Man's living-space could not allow us to escape the consequences of our present rate of population growth.

Suppose that an advanced human civilisation has succeeded in equipping itself with perfect spacecraft that can travel at the velocity of light. Suppose that this civilisation is growing in population at our present rate of about 2% per year, and that it attempts to achieve a stable population density by going out and colonising all available habitable planets. To achieve population stability, it must utilise all habitable planets in a volume of our Galaxy that grows by 2% per year.

The task becomes hopeless when the colonised volume ceases to grow at 2% per year, and so offset population growth. This limit is reached, even with 'perfect' velocity-of-light spaceships, when the civilisation has expanded to just 150 light-years from Earth.

In a sphere of radius 150 light-years there may be about 400 planets habitable by Man. But at a growth rate of 2% per year, the hypothetical population will increase by a factor of 400 in just 300 years. This puts our problem into a chilling perspective. Even interstellar colonisation with perfect efficiency, using velocity-of-light spacecraft, could only buy 300 years of time against a steady 2% population growth.

Only a reduction of this growth, not hopeful thoughts about the vastness of the Galaxy, can alleviate this frightening numerology. 'Galactic Man' would be no more protected against exponential growth by his mobility than is 'planetary Man' today.

This illustration (first brought to my attention by Sebastian von Hoerner of the U.S. National Radio Astronomy Observatory, a well-known thinker in the field of interstellar contact) provides an extreme example of something we shall encounter often in subsequent lectures: that is, a problem with no *purely technological* solution. The only long-term solution to the problems presented by human population growth is to change human behaviour, the collective goals of human society, in such a way as to limit or remove the growth. The solutions to these problems cannot lie fully within the area of expertise of the natural scientist or engineer.

FINALE

Only if we succeed in prolonging the lifetime of human society to astronomical time-scales will we reach a situation where we face a true necessity for interstellar migration. The Sun has about 4 billion years of stable hydrogen-to-helium fusion ahead of it. Then it must begin the series of adjustments forced on every star when the hydrogen runs low. In the case of the Sun there is little doubt that it will evolve into a red giant - a bloated condition in which the main body of the star becomes inflated by energy released in gravitational collapse of its all-helium core. When this occurs, the hot surface of the Sun will move outwards, consuming Mercury, Venus and the Earth in turn. Jupiter may rapidly lose its hydrogen, and dwindle to a heavier-element shadow of its present self, evaporated down to Earthlike proportions by the increased heat supply from the inflated solar surface.

There is little hope however that Jupiter would become habitable by Man at this stage - there would not be the hundreds of millions of years of stable thermal equilibrium in this latter-day Solar System that it experienced when it was newly born. The Sun will become a variable star, collapse again to a nova ejecting heavy elements into interstellar space in violent outbursts possibly only tens or hundreds of years apart, and will eventually end up as a cooling, compressed white dwarf. Even if the outer planets survived the violent phase without being stripped of their atmospheres, they would end up even more frozen than they are today, for the white dwarf Sun will be less luminous than now by a factor of at least 100.

Our Solar System environment is thus fundamentally doomed. Our terrestrial environment may be threatened on a more immediate time-scale by the consequences of geomagnetic field reversals, which temporarily reduce or remove our protection from energetic solar particles, or of nearby supernovae which could deluge the Earth with lethal radiation.

On the immediate time-scale, we should recognise ourselves as the greatest environmental hazard, as subsequent lectures will discuss. On this immediate scale, astronomy offers no hope of extraterrestrial solutions to terrestrial problems. Indeed, I personally feel that our astronomical knowledge simply throws these problems into sharper focus by demonstrating the inaccessibility of all plausible alternatives to Earth.

Astronomy shows that our environment is the end product of a long chain of events in the evolution of the stellar population of the Milky Way begun some twenty billion years ago when the rotating protogalaxy began to condense out of a primeval fluctuation in the expanding fireball. The Earth is a tiny and incidental detail in the cosmic scheme. It is also the detail to which we are adapted, and the only one of its kind within reach.

SUGGESTIONS FOR FURTHER READING:

Red Giants and White Dwarfs, by R. Jastrow (also recommended for reading to supplement the first lecture) provides a well-written survey of some of the material presented here.

More searching, and more comprehensive, is *Intelligent Life in the Universe* by I.S. Shklovskii and C. Sagan, a Delta paperback ($3.45). This book is a product of a unique collaboration between a leading Soviet astronomer and a leading American space scientist. It provides a very readable account of the evolution of planets, of life on Earth, and of our knowledge of conditions elsewhere in the Solar System. It also deals at length with possibilities for interstellar communication.

The "boundary conditions" for human life, and the likelihood of satisfying them elsewhere in the Universe, are discussed by Stephen Dole in his book *Habitable Planets for Man* published by American Elsevier in 1970 (2nd edition).

Interstellar Communication, edited by A.G.W. Cameron (Benjamin 1963) contains careful discussions by several authors of the possibility that other civilisations exist in the Milky Way, and assesses the likelihood of achieving some form of contact with them.

Earth, Moon and Planets by F.L. Whipple also gives a good, modern discussion of physical conditions in the Solar System. This book was published by the Harvard University Press in 1968.

An authoritative discussion of recent space probe studies is given by V.R. Eshleman, 'The Atmospheres of Mars and Venus', an article in the March 1969 *Scientific American.*

A classic article on life beyond the Solar System is 'Life Outside the Solar System', by Su-Shu Huang, in April 1960 *Scientific American.*

'The Extraterrestrial Imperative' by K.A. Ehricke *(Bulletin of the Atomic Scientists,* November 1971 issue) reviews what might eventually be achieved in space if, in my view, the social evolution of 'planetary Man' can be stabilised first. Ehricke expresses greater hope that 'space' will help solve terrestrial problems.

APPENDIX #1. The Habitable Zone of a Star

Suppose that a given life-form requires an environment with a maximum stellar energy supply e_1 per unit time per unit area, and a minimum energy supply e_2 per unit time per unit area; that is, the actual energy supply e must satisfy $e_1 > e > e_2$. If $e > e_1$, the life-form is "fried", if $e < e_2$ it is "frozen". Suppose that the central star of the planetary system under consideration has a luminosity L. Then the condition $e_1 > e > e_2$ defines a range of distances from the star habitable by this life form. The nearest distance d_1 is given by

$$e_1 = \frac{L}{4\pi d_1^2}$$

and the furthest, d_2, by

$$e_2 = \frac{L}{4\pi d_2^2}$$

The life-form must be provided with a planet at a distance d such that $d_1 < d < d_2$. If the planetary system is confined to a fundamental plane, as our Solar System,is, the area of the habitable zone of this plane is

$$A = \pi(d_2^2 - d_1^2$$

$$= \frac{L}{4}\left(\frac{1}{e_2} - \frac{1}{e_1}\right)$$

Thus A is proportional to L, the luminosity of the star. This is true for stars at any stage of their evolution. For stars in the hydrogen-to-helium conversion phase, the most luminous stars are also the hottest, and the least luminous are the coolest.