ASTRONOMY OR BIOLOGY? ⋆

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Abstract. The role of biology in astronomical phenomena and processes was first discussed extensively by us in the period from 1979-1982. The two sections reproduced below are the concluding chapters of 'Space Travellers' which we published in 1981. The ideas discussed here have turned out to be forerunners to several recent developments in astrobiology.

1. Bacteria on Planets

In this section we deal with two particular issues. Our picture has been of an immensely powerful universal biology that comes to be overlaid from outside on a planet such as our own. Wherever the broad range of the external system contains a life form that matches some local planetary habitat, the form in question succeeds in establishing itself. The external system contains a wide spectrum of choices which the local environment proceeds to select according to the particular niches that the local system provides. In our view the whole spectrum of life, ranging from the humblest single-celled life forms to the higher mammals (and beyond) must be overlaid on a planet from outside.

Bacteria exist everywhere on the Earth and in astonishing profusion. A handful of garden soil contains typically about a billion bacteria, and so do certain samples of deposits taken from the floors of the oceans. The seemingly hostile continent of Antarctica teems with bacteria – they are to be found in the soils and inside the rocks of dry valleys. and they exist and multiply towards the bottom of vast glaciers. In total, there are something of the order of 10^{27} bacteria on the Earth, of which only a minute proportion are pathogenic to man.

It is essential to all life-forms that they have access to energy. Photosynthesis, whereby sunlight provides the energy supply, is of course well-known, with chlorophyll playing a crucial role in the production of sugars from carbon dioxide and water. There is a widespread but erroneous popular view that photosynthesis is the basis of all life. Rather is it the case that the majority of bacterial forms derive their energy quite otherwise. Wherever an energy yielding chemical reaction exists, and which proceeds only very slowly under inorganic conditions, some bacterium will usually be found to be living on it, speeding the reaction catalytically. There are bacteria that live by oxidizing sulphites to sulphates, which one might perhaps

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have expected on an oxidizing planet like the Earth. More unexpected are bacteria that use free hydrogen, an entirely evanescent substance on the Earth, to reduce sulphates to free sulphur. Nor would one expect to find the bacteria that use only free hydrogen and carbon dioxide to produce methane water.

It is generally recognized that bacteria requiring free hydrogen cannot have evolved on the Earth over the last three billion years, and so they are supposed to be survivors from an earlier epoch in which free hydrogen is assumed to have been in plentiful supply. Yet the survival thread of these bacterial forms is so thin that it would surely be snapped in only a few centuries, or at most a few millennia. The clear implication is that the Earth receives a steady, continuing supply of sulphur and methane-producing bacteria, and that whenever unusual local conditions happen to set up an environment in which such bacteria can prosper they do so temporarily until the conditions change.

Modern industry, with its dumps, tips, and tailings has created exceptional niches for bacteria which are always filled, even though those conditions never existed before on the Earth, except conceivably as a short-lived fluke. There is almost nothing that, one can do in daily life which does not create a niche for some form of bacterium or protozoa. The farmer's bales of hay create a niche, and so does a bird's nest.

It is usual in biology to argue that bacteria and protozoa evolve genetically with great speed and so manage to adapt themselves to whatever possibilities the environment may offer. This view persists in spite of there being a considerable weight of evidence against it. Experiments in the laboratory over many generations have shown that bacteria do not evolve. Bacteria (and viruses) are incorrigibly stable. Experimenters can do three things to bacteria. Where varieties are already present initially, one of them can be encouraged to multiply preferentially with respect to the others. Another thing that can he done to bacteria and viruses is to ruin them. The third alternative consists in dividing up what is already there and reassembling the bits in a different order, as for instance if one were to take selected bits from two different kinds of bacteria and reassemble them in an attempt to form a new bacterium. What experiments in the laboratory cannot do, however, is to make effective new bits. This is to be expected if the bits owe their origin to a galaxy-wide evolution which gave rise to a much higher order and more subtle system than is usually supposed.

True terrestrial evolution has consisted in the fitting of bits into aggregates that were optimal to the environment, as was demonstrated for plants and higher animals by classical biology. The bits have not been evolved to fit the environment, however. They are simply the inflexible cosmic bits that could manage to survive in the environment. The distinction shows clearly in the phenomenon of adaptation. Birds, rodents, fish, and insects are clearly well-adapted to the environment in their different ways. Bacteria, on the other hand, are not closely adapted. Bacteria found in the ocean depths are not particularly adapted to those depths – they are simply bacteria that happen to function in a manner that is insensitive to high pressure.

Many forms of bacteria are found surviving under temperatures that are far from optimal. Many found in warm soils multiply better at lower temperatures than are ever found in the tropics. Others multiply best at temperatures much higher than exist on the Earth at all, above 75 °C. There is indeed a very considerable measure of *disadaptation,* which shows itself in bacteria possessing properties that are irrelevant to survival on the Earth. Resistance to enormous doses of X-rays, ultraviolet light, and resistance to great cold were examples mentioned elsewhere in our writings. The cell walls of bacteria are stronger than reinforced concrete, and this is another example. Biologists are constantly being surprised by new unearthly properties, and the erection of almost any really novel environment reveals some such property. The canning of food provided a new environment. There was a practical need to find a cheap and convenient means of sterilizing food after its sealing inside a metal can. Flooding by X-rays was tried, and it was then discovered that *Micrococcus radiophilus* was discovered. Heating was also tried and some bacteria were found to be capable of surviving temperatures above 100 °C. Water in the open expands slightly as it is heated. Water in a closed can of fixed shape cannot expand, however. Instead a high pressure is created, which can prevent the formation of bubbles of steam even above 100 °C. Likely enough it was the prevention of steam bubbles which permitted bacteria to survive in these experiments. But how could such a property ever have evolved on the Earth?

Manifestly, bacteria are a life-form that has simply been plastered over the Earth, to survive wherever it is possible to do so. The properties of bacteria have galaxy-wide quality, much wider than is needed for survival on the Earth alone. Indeed, because of the great breadth of their survival characteristics, the potentiality of bacteria to establish themselves on planets must be much greater than one would permit oneself to suppose within the narrow confines of an Earth-bound theory of the origin of life. Just because the other planets of our solar system are different from the Earth is no reason at all for thinking that life in our system must he unique to the Earth. The spread of the survival characteristics of bacteria are so great that they may well include the ability to fit environmental possibilities on some other planet or planets. In this article we shall find suggestive evidence that this is actually so for Venus, Jupiter and Saturn, and that it is possibly so for Mars, Uranus and Neptune.

We take as an indispensable requirement for the survival of bacteria that water can condense on them, and can pass to their interiors and be held there in a liquid form. This condition rules out Mercury and the Moon. The lifeless states of Mercury and the Moon show immediately in their drab lack of colour. As a valid general correlation, life and colour may be associated together, although perhaps not in what mathematicians call a one-to-one correspondence. A stricter indication of life comes when particle sizes close to 1 μm turn out to be dominant, in which connection we recall the size distribution of spore-forming bacteria given in Figure 1 taken from data given in *Bergey's Determinative Bacteriology* (Buchanan and Gibbons, 1974).

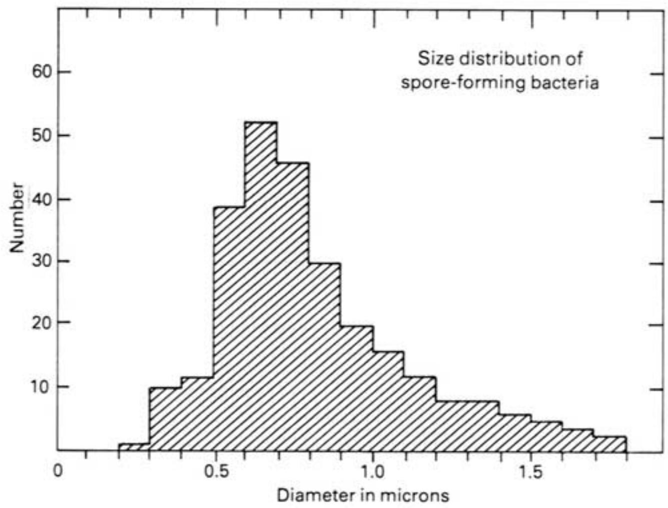

Figure 1. The size distribution of species of known spore-forming bacteria.

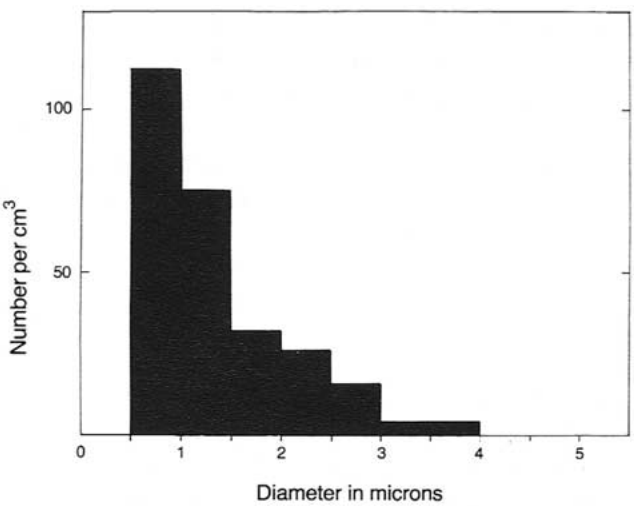

Figure 2. Distribution of particle sizes in the upper clouds of Venus (approximately 55–65 km in altitude) measured by Pioneer Venus.

The upper clouds of Venus produce a rainbow, indicating that the cloud particles are spherical and that they have sizes in the region of 1 μm (Coffeen and Hansen, 1974). The distribution of particle sizes actually measured in the upper clouds by Pioneer Venus is shown in Figure 2 (Knollenberg and Hunten, 1979). Although a considerable amount of further argument is needed before one can be satisfied about details, the correspondence of the observed particle sizes with those of bacteria tells the main story immediately.

There are two ways in which bacteria can be spherical in shape, one through forming spores and the other through restriction to the class of micrococci. Of these, spores appear the more likely possibility for the reason that the clouds of Venus are in convective motion, extending from an upper level at an altitude of 65–70 km down to an altitude of 45 km.

The temperature at 45 km is about 75 °C and at the top is about –25 °C. While survival over this range is easily possible for bacteria, the repeated variations of temperature caused by a circulating cloud system would be better resisted by bacteria capable of forming spores which are still more hardy than the bacteria giving rise to them. Thus bacteria could be rod-shaped in the lower warmer regions, but giving place to spherical spores in the cold upper regions of the clouds. In this way there is no requirement for the bacteria to be exclusively micrococci.

A quantity called the 'refractive index' of a particle is relevant to its light scattering properties. The refractive index of water is about 1.33 and that of biological material about 1.5. Bacterial spores contain about 25% water by weight, which causes them to behave like a uniform particle with refractive index 1.44, which is exactly what is known by observations on the degree of polarization of the upper clouds of Venus.

The refractive index of sulphuric acid is 1.48, and sulphuric acid droplets with 25% water would also behave like uniform particles with refractive index 1.44. But this explanation of the upper clouds of Venus fails on a number of important points. There is no reason for such droplets to have sizes of 0.6–1.2 μm (Figure 2). Sulphuric acid droplets could, and very likely would, have a much broader size distribution than Figure 2. The 25% water concentration is an arbitrary choice, whereas for bacterial spores there is no choice, about 25% is what the water concentration must be. The chemical sampler carried by Pioneer Venus (1978) measured vapour pressures of oxygen and sulphur dioxide in the cloud regions that were thousands of times lower than one can easily have in the laboratory, and yet, even at the much higher laboratory concentrations, oxygen and sulphur dioxide do not go easily to sulphur trioxide, and thence by the addition of water to sulphuric acid. Commercial sulphuric acid is produced in two ways. The old way by a complex of reactions involving nitric acid, and the modern way by catalytic processes involving either platinum metal or vanadium oxide. Inorganic catalysts like platinum tend to become 'poisoned' under natural conditions, however – they take part in other reactions which change them. The highly effective catalysts found in nature are bacteria, which not only maintain themselves (which is all that inorganic catalysts can do) but actually increase in number through the chemical reactions which they promote. Hence to produce some sulphuric acid, which is apparently required to explain certain details of the infrared radiation emitted by the clouds of Venus, it is to bacteria that we should look. Sulphur bacteria are yellow in colour, and it is to their presence (among other non-yellow bacteria) that we attribute the pale yellow colour of the light reflected by Venus. Sulphuric acid is colourless, on the other hand, and droplets of it would not produce any such colouring.

Water is not a particularly abundant constituent of the atmosphere of Venus. The second atmospheric sample taken by Pioneer Venus at an altitude of about 46 km near the base of the lower clouds gave about 0.5% water. With this concentration, and choosing –10 °C as the lowest temperature at which the bacteria replicate, the relative humidity can be calculated to be about 85%, which is adequate for bacteria with an appreciable internal content of dissolved salts. It is important here that the problem of maintaining liquid water inside a bacterium is not simply evaporation from a free water surface but of evaporation from the outer surface of the bacterial membrane, which is markedly water-attractive. At 85% relative humidity only a quite small extra bit of holding power against the evaporation of water molecules is sufficient to stop a bacterium from drying out. However, under exceedingly dry conditions, near zero per cent humidity, bacteria must largely dry out. As bacteria circulated through the middle and lower cloud regions of Venus, they would be subject to relative humidity values that ranged from near zero in the hotter, lower regions to about 85% in the cooler, upper regions. This would provide a natural water pump with alternating phases of filling with water and of subsequent evaporation, and with each water-filling episode giving a fresh supply of nutrients to the interior of the cell.

Since Venus is exceedingly hot at ground-level (about 450 °C) it is a matter of some surprise to find evidence of life existing there. The circumstance which makes life possible is the dual circulatory pattern of the Venusian atmosphere. From the temperatures and pressures measured by Pioneer Venus one can infer the presence of a lower convective zone from ground level to a height of about 30 km. There is then still atmosphere up to about 45 km, where the second convection zone begins. It is the non-moving in-between region from 30 km to 45 km which protects life in the higher zone from being quickly swirled down to the impossibly hot conditions near the ground.

Although bacteria are small and are able to ride easily with the atmospheric motions, there must nevertheless be occasional situations where a bacterium carried down to the base of the higher convective zone fails to find an up-current on which it can ascend again. Inexorable gravity will then cause the bacterium to fall slowly down through the in-between zone until it reaches the lower convective zone, where it will quickly be snatched downward and destroyed by the heat. It is therefore to be expected that the in-between zone will contain a thin haze of slowly falling doomed bacteria, and the existence of a thin haze between altitudes of 30 km and 45 km was indeed found by Pioneer Venus.

From the data obtained by Pioneer Venus one can infer that the fall-out through the in-between zone would begin to denude a population of high-level bacteria in about 30 000 years, if the bacteria did not renew themselves. For renewal a supply of nutrients is required. Water, nitrogen. and carbon dioxide are amply available, but in addition to these main ingredients other elements – sodium, magnesium, phosphorus, sulphur, chlorine, potassium, calcium, manganese, iron, cobalt, copper, zinc, and molybdenum – are needed in smaller proportions. It can be calculated that the fall-out through the in-between zone would carry about 10 000 tonnes of these essential ingredients each year from the higher convection zone to the lower zone. How, one can ask, may such a loss from the higher zone be compensated? The answer appears to be by the infall of meteoric material from space, rather than by gas diffusion upward from the lower atmosphere. The meteoric supply to the Earth is known to be about 10 000 tonnes per year, and the supply to Venus – a very similar planet should be about the same. The problem for gas diffusion upward lies in the lack of volatility of the compounds of many of the needed elements. There is no such problem for meteors in the size range from about 0.1 mm to 1 cm, which are gasified as shooting stars on plunging at great speed into the high atmospheres of the Earth and of Venus.

The size distribution of particles measured for the upper clouds of Venus is essentially maintained in the middle and lower clouds and in the haze zone of the in-between region. In the middle and lower clouds, however, there is also a considerably less numerous population of much larger particles. These we attribute to the tendency of bacteria to aggregate into colonies, a property that may well be helpful in preventing too much evaporation of water in the dry, hot conditions of the lower clouds.

The correspondence between the rate of supply of meteoric material and the rate of loss of essential nutrients down through the in-between region, about 10,000 tonnes per year in each case, suggests that the quantity of bacteria in the clouds is nutrient-limited. The clouds have built up until the drop-out at the bottom equals the supply from outside. If the supply from outside were to cease then the bacterial population would decline steadily, until after a few tens of millennia it would be possible to see down to the ground level of Venus. Such a situation may well have occurred in past times, only then there were no humans to observe the lower excessively heated surface zone of the planet.

Humans have for long looked at the red colour of Mars and seen evidence there for the existence of life. The argument was that the red colour implies a highly oxidized condition, a conclusion that a recent Mariner landing on Mars has shown to be correct. The supply of oxygen needed to produce this condition might have come from photosynthetic organisms, and this further aspect of the old argument may also be correct. But if so the organisms must have existed in the remote past when liquid water was present at the surface of the planet. The Martian surface is cut by many sinuous channels, of which that in Figure 3 is an example. It is generally agreed that these channels were made by a liquid much less viscous than molten lava, and water is a likely possibility. But there is no liquid water nowadays at the surface of Mars, and consequently (if we take the need for liquid water to be essential) there can he no active surface life. It is surprising therefore that so great an effort was made in the recent Mariner landing to look for evidence of life. It is true that bacteria in a dormant condition might survive for long periods in the Martian surface dust, but such bacteria might well need unusual conditions for growth, which could not be anticipated in a terrestrially designed experiment.

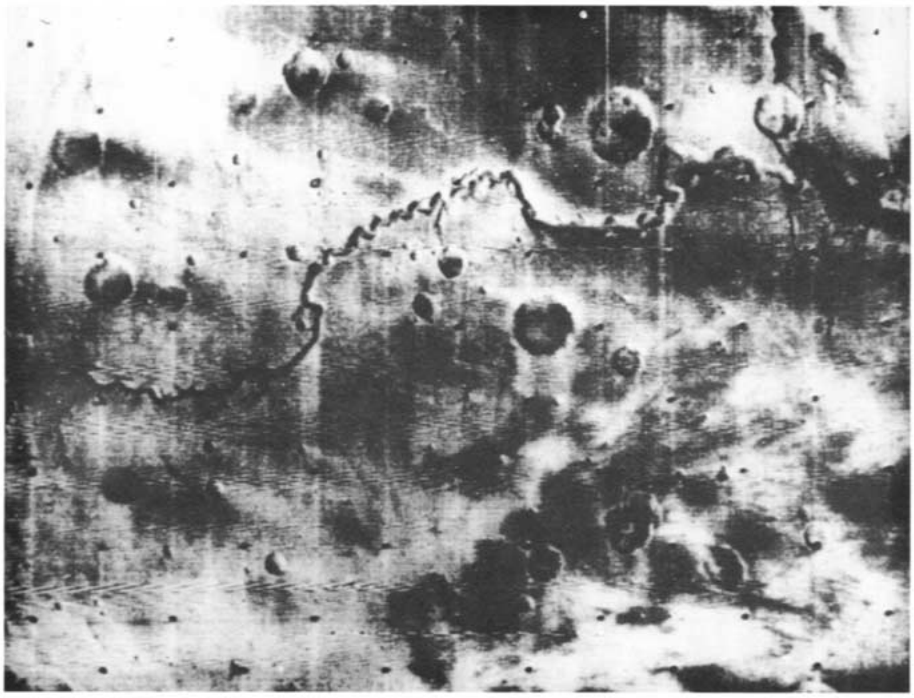

Figure 3. A sinuous channel on Mars, probably produced by the flow of liquid water (Courtesy of NASA).

If one argues analogously to the Antarctic, the best chance for life to be active on Mars would be deep inside glaciers where the temperature might rise sufficiently for water to become liquid. There would still be problems of nutrient supply, but if the glaciers themselves turn over, top to bottom from time to time, such problems would be capable of solution. The bacteria would need to live on some energy-producing chemical reaction, and, if the reaction had a gaseous product (such as carbon dioxide or methane), the possibility would exist for the building up of subsurface pockets of gas, which might explode sporadically to the surface unleashing quantities of bacteria, spores, and inorganic dust into the Martian atmosphere. In this connection we recall the vast atmospheric dust storm which greeted the arrival of a Mariner vehicle in 1971. This storm has been attributed to high winds generated by the normal Martian meteorology, but if so one might wonder why such winds are not a seasonal phenomenon. The outward explosion of microbiologically-generated gas could prove to be a better explanation.

From an analysis of reflected sunlight it has been estimated that the clouds of Jupiter consist of particles with diameters close to 0.5 μm and with refractive index 1.38. This diameter value is somewhat less than the main peak of the distribution of Figure 1 at about 0.7 μm. The calculations for Jupiter were made, however, on the assumption of spherical particles. Since Jupiter does not show a rainbow effect like Venus, it is to be doubted that this assumption of sphericity is correct, and for rod-shaped particles the calculation would be somewhat changed. The difference between the calculated 0.5 μm and the 0.7 μm of Figure 1 does not seem, therefore, to be a barrier to the particles of the Jovian clouds being interpreted as bacteria. Unlike bacterial spores, which contain about 25% water, rod-shaped bacteria, when active, contain about 70% water by weight. Estimating the equivalent refractive index of a uniform particle along the same lines as before, we obtain 1.37, which is close to the value 1.38 estimated from the reflecting properties of the clouds of Jupiter.

Water is not a problem on Jupiter. Much of Jupiter's oxygen is combined with hydrogen into water, and in the lower atmosphere below the visible upper clouds liquid water drops probably exist in profusion

We have emphasized already that bacteria are able to operate in almost any sense in which energy can be released by chemical reactions. Their many varieties simply take what is available. But if Jupiter is considered as a closed chemical system there can be very little that is available. In the absence of photosynthesis, which seems unlikely to take place low down in the clouds (except possibly under an exceptional condition to be considered later) degradable materials are not produced continuously within the system, and any degradable materials there may have been in the beginning, would long ago have been used up. So Jupiter can operate as a biological system only if degradable materials are supplied from without. Injected into the atmosphere of Jupiter, most meteoric material would, after vaporization, be degradable in this sense. Metallic iron is oxidizable in the presence of water, and there are bacteria which operate precisely on this transformation. As we have already remarked, sulphates are reducible to sulphur, and carbon dioxide is reducible to methane.

The flux of meteoric material in the neighbourhood of Jupiter has been measured to be about 100 times greater than it is near the Earth, due to a focusing effect produced by Jupiter's gravitational field. Moreover, the surface area of Jupiter is about 100 times greater than that of Earth. It follows therefore that the incidence of meteoric material onto Jupiter must be some 10,000 times greater than the incidence onto the Earth. Since the latter may be as high as ten thousand tonnes per year, the incidence onto Jupiter may well be 100 million tonnes per year. The energy produced by the chemical degradation of such a quantity of material is comparable with, but rather less than, the energy to be obtained from the burning of a similar quantity of wood. While very considerable, this amount of energy is smaller than the energy involved in photosynthetic processes on the Earth (the amount of wood grown annually is much more than 100 million tons). It must be remembered, however, that terrestrial biology operates in an oxidizing environment, which forces a high metabolic rate, otherwise the biological system would soon burn up. No such tendency to burn up exists on Jupiter. The great quantity of free hydrogen in the Jovian atmosphere removes all oxygen, and bacteria could survive there in a dormant condition for a very long time. Destruction rates would be low and populations could gradually be built up over extended periods. The ochre, red, and brown belts and spots of Jupiter can be identified with sulphur and iron bacteria.

It is one of the remarkable features of meteoric material that all size ranges contribute appreciable quantities of mass. This is true even for large bodies several kilometres in radius. It has been estimated that two or three such bodies hit the Earth in a million years, and for Jupiter there would correspondingly be two or three large bodies in a century, each contributing about 100 million tons of nutrient material in one sudden burst. A kilometre-size object hitting Jupiter's atmosphere at high speed would be disintegrated into heated gas that would be sprayed out over a considerable area, but still over an area that was small compared to the vast total area of Jupiter. It would form a spot, a spot in which the supply of nutrients for biological activity was exceptionally high, so that a large bacterial population would be built up in the resulting area. It is possible in this way to understand the origin of the spots of Jupiter, of which the Great Red Spot is the best-known example.

The possibility exists for a feedback interaction to be set up between the properties of a localized bacterial population (for example, the infrared absorption and emission properties of the bacteria) and the general meteorology of Jupiter's atmosphere. If bacterial populations on Jupiter have become adapted to the meteorology there, it is possible that evolution has produced a situation in which populations are able to prevent supplies of nutrient materials from being swept away from them by atmospheric motions. In a measure they may have become able to control the meteorology, and thus to hold together spot concentrations of nutrient materials. This may well be the explanation of the persistence of spots, and in particular the remarkable persistence of the Great Red Spot.

Let us now turn to meteoric materials in the form of tiny submicron particles. These too must make an appreciable contribution to the supply of nutrient material. Such particles are always electrically charged by sunlight, and being of small mass they are subject to deflection by the strong magnetic field of Jupiter, which causes them to rain down on the polar regions of the planet rather than on the equatorial zone. Bacterial activity resulting from this specifically polar accretion of fine meteoric particles may well be responsible for the remarkable dappled appearance of Jupiter at its poles.

At first sight one might think that photosynthesis would he impossible on Jupiter. At the upper cloud levels where sunlight is available the temperature is probably too low to permit bacterial activity, and at lower levels where the temperature rises to appropriate higher values there can be little penetration of sunlight. In the neighbourhood of spots the clouds are by no means smoothly layered, however. If sunlight can ever penetrate far enough to reach places where water is liquid, photo effects become possible. We remarked above that without sunlight, and in the presence of free hydrogen, bacteria can reduce sulphates in the presence of water. With sunlight, however, both reduction and oxidation become possible. A

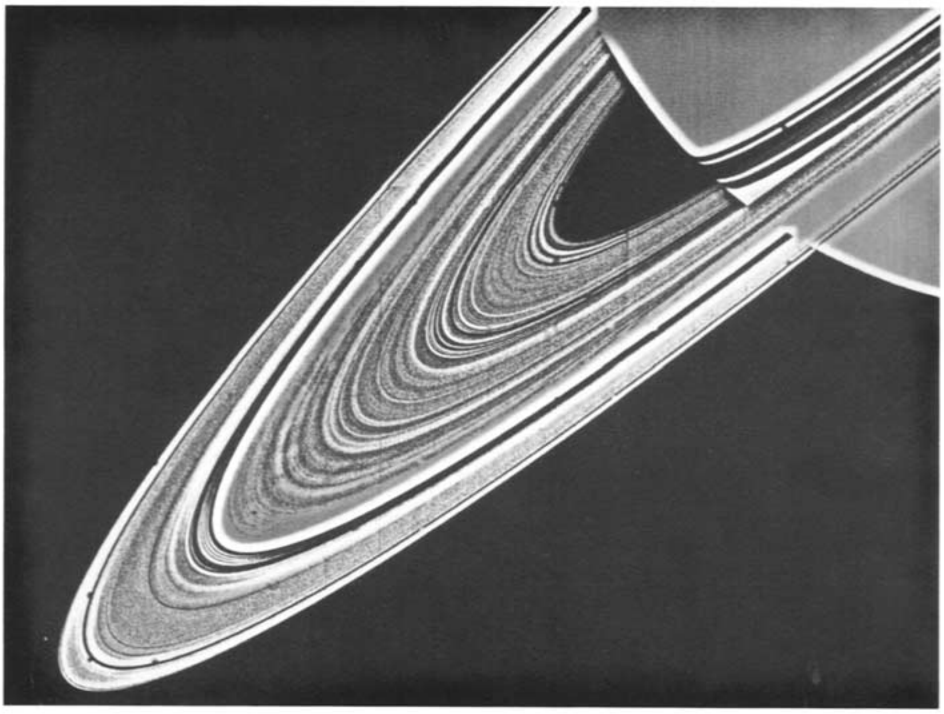

Figure 4. The Saturnian ring system photographed by Voyager 1 (Courtesy of NASA).

wider range of bacterial colours then arises, with the addition of purple, blue, and green to the yellows, reds, and ochres of the reducing bacteria. Such a situation may not be inconsistent, with recent observations from Voyager I. Occasional blue colours are seen on Jupiter, suggesting that the special conjunction of sunlight and liquid water may sometimes arise there.

Astronomical observations, particularly the most recent Voyager 1 data, show a generally similar situation with respect to colour on the main body of Saturn, including the presence of spots although with more yellow and green than Jupiter. The well-developed polar coloration and the absence of exceptionally large spots suggests that meteoric additions to Saturn may well be much more in the form of a rain of tiny particles than as large spot-forming bodies.

The rings of Saturn seem also to contain large quantities of bacteria-sized particles. Spectacular pictures of the ring system relayed from cameras on Voyager 1 in November 1980 revealed many surprising features. The so-called Cassini division between the two outer bright rings, the A- and B-rings, was seen to be populated by many rings of fine particulate material. The Saturnian ring system, which has been likened to the grooves on a gramophone record, is shown in Figure 4.

Two aspects of these recent observations are particularly noteworthy. Several spoke-like structures have been found to appear in the B-ring – Saturn's brightest

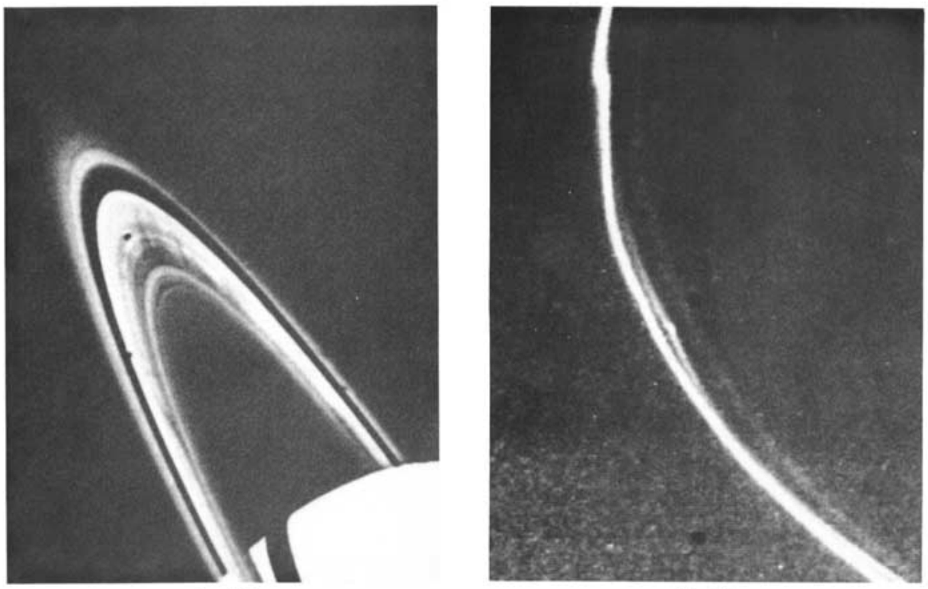

Figure 5. (Left) Rings of Saturn showing radial togues in the B-ring. The touges are comprised of bacteria sized particles (Courtesy of NASA). (Right) The outer F-ring comprised of bacteria-sized particles has a braided structure (Courtesy of NASA).

ring seen from the Earth (Figure 5 Left). These spokes appeared as dark tongues in images that Voyager 1 relayed whilst being above the rings on their sunward side but as the spacecraft went below the rings the same structures appeared as bright tongues. From this single observation we can infer that the particles in the tongues have the dimensions of bacteria. Such particles scatter sunlight mainly in the forward direction, so that they appear bright when the Sun is behind them, but dark when the Sun is in front. Another baffling feature of the new data concerns the braided and twisted appearance of the outer F-ring, which is also made up of bacterial-size particles (Figure5 Right). Since two small icy satellites have been discovered in orbits that straddle the F-ring, a possible resolution of this peculiar ring structure is that its particles are currently being spewed out from the two icy satellites designated S13 and S14. These satellites, which have sizes appropriate to large comets, may have become trapped in the gravitational field of Saturn and been melted in their interiors due to tidal effects, or due to the effect of collisions with smaller objects. Such satellites would act like biological pressure cookers, releasing jets of microorganisms, which had been produced in their melted interiors. We envisage a situation where the F-ring is woven *in situ* from jets of material thus released from S13 and S14. Magnetic effects, which involve the coupling of electrically charged bacteria with the planetary magnetic field, could play a role in maintaining both the twisted structure of the F-ring and the structure of the radial tongues seen in the B-ring.

No observations are yet available to determine the sizes of the particles which constitute the clouds of Uranus and Neptune. The atmospheres of these two planets are known, however, to contain vast quantities of methane, as do Saturn to a lesser extent, and Jupiter to a still smaller extent. The existence of methane may also be indicative of bacterial activity. Astronomers have been content to accept the methane observed in the atmospheres of the four large outer planets of the solar system as the outcome of a thermodynamic trend of carbon compounds to go to methane at low temperature and in the presence of an ample supply of free hydrogen. But if one takes a vessel containing a mixture of free hydrogen and carbon monoxide or carbon dioxide the separate gases persist unchanged for an eternity. The 'trend' is so slow as to be essentially zero. It is in such circumstances that catalysts are used in the laboratory and in industry. Of all catalysts, bacteria are the most efficient. Indeed the methame reproducing bacteria have evolved precisely to speed the conversion of carbon dioxide and hydrogen into methane and water. If the conversion happened at all readily under inorganic conditions there would be no niche for these bacteria. The natural explanation for the quantities of methane present in the atmospheres of Jupiter, Saturn, Uranus, and Neptune is that methanogenic bacteria have been active there in the reduction of carbon monoxide and carbon dioxide. The scope for such bacteria on the outer planets is clearly enormously greater than it is on the Earth, where this class of bacteria has been able to establish only a small toe-hold. Such bacteria could be responsible for the white zones of Jupiter, and for the generally uncoloured appearances of Uranus and Neptune.

2. Biology or Astronomy in Control?

For an externally impressed biological system to gain a toe-hold in a new environment, as for instance bacteria which are incident from space upon some new planet, it is essential that the external system be already equipped for survival in the new environment. Once a toe-hold becomes established, however, a two-way adaptation can develop. The basic components (genes) of the biological system could become selected to match the environment, or the cosmically-imposed components could be built (without being much changed individually) into structures better suited to the environment. In both of these cases it is the biological system that makes changes in response to the restrictions imposed by the physical aspects of its surroundings. This is one direction in which adaptation can take place. The other direction is through the biological system altering the environment itself. It is this second way with which we shall be concerned in this final section.

Terrestrial biology has changed the composition of our atmosphere, it affects the break-up of rocks into soil, it affects the rates of run-off of surface waters and of evaporation from the land, and it even influences in some degree the Earth's climatic zones. We similarly expect biology elsewhere to influence local conditions. The meteorology of the atmosphere of Jupiter was mentioned in the preceding section as a possible example, and perhaps the meteorology of Venus may also be affected. These are minor effects, however, compared to what biology may be capable of achieving on an astronomical scale.

It is interesting that issues that would influence the well-being of life on a cosmic scale turn out to involve problems which have been under active consideration in astronomy for more than a generation, and for which no satisfactory inorganic solutions have been found. These issues involve the star formation process and its relation to the interstellar grains. The unresolved issues are as follows:

What decides the rate at which stars form from the interstellar gas?

When they are formed what decides the mass distribution of stars?

What decides the rotations of the stars. and whether they are formed with planetary systems?

What decides how star formation is correlated throughout a whole galaxy, leading to the production of both grains and stars on a far-flung basis, often with the appearance of a new set of spiral arms for a galaxy?

The answers to these questions are almost certainly connected with the existence of a magnetic field everywhere throughout our galaxy. But the nature and origin of the galactic magnetic field is a further unresolved problem, and so the additional question must be added:

How did the magnetic field of our galaxy come into being?

This further question has proved so baffling that many astronomers have given up hope of answering it, by claiming the magnetic field to be truly primordial, it being imposed on the Universe at the moment of its origin. The magnetic field is what it is, because it was what it was, right back to the first page of Genesis. If this view, is correct the situation is crude, uncontrolled, and unsatisfactory.

To understand the difficulty of the problem, suppose we were to try to generate the magnetic field of our galaxy with the aid of an enormous electric battery, with one terminal connected to the centre and the other terminal to the outside of the galaxy. With the battery switched on, an electric current would begin to flow through the interstellar gas. Owing to a phenomenon known as 'inductance', the electric current would at first be exceedingly small, but as time went on the current would become stronger, and as it did so the magnetic field associated with the current would increase in its intensity. Suppose we allow the current to grow for the whole age of our galaxy, about 10,000 million years. What voltage do we need for the battery so that after 10,000 million years the resulting magnetic field will be as strong as the galactic magnetic field is actually observed to be? The answer is about 10,000,000 million (10^{13}) Volts. What process, we may ask, could have produced a battery of such enormous voltage that could operate for a time as long as 10,000 million years? A conceivable answer is a stream of electrically charged interstellar grains projected at high speed, 100 km s^{-1} or more, into an electrically neutral gas, a process in some respects similar to that which drives a terrestrial thunderstorm. The required projection speeds of $\sim$100 km s^{-1} are attainable by radiation pressure. The remaining problems are first to attain systematic directivity for a stream of grains, and second to maintain electrical neutrality in the gas through which the stream passes (when neutrality fails in a terrestrial thunderstorm there is a lightning flash, and the electric battery is instantly dissipated). With inorganic grains it is difficult, if not indeed impossible, to resolve these issues. Bacteria, on the other hand, have far more complex properties than inorganic grains, and may be able to exert a control both on stream directions and on the neutrality of the interstellar gas. The issue is not proved, but it is conceivable, and if it were to happen, bacteria would be well-placed to control the whole process of star formation.

The nutrient supply for a population of interstellar bacteria comes from mass flows out of the large galactic population of old stars (100,000 million of them), which may well have had an inorganic origin. 'Giants' arising in the evolution of such stars experience a phenomenon in which material containing nitrogen, carbon monoxide, water, hydrogen, helium, some refractory solid particles and supplies of trace elements flows continuously outward into space. In total from all giant stars, a mass about equal to the Sun is expelled each year to join the interstellar gas. This is the nutrient supply.

The problem for interstellar bacteria is that the nutrient supply cannot be converted immediately into an increase of the bacterial population, because of the need for liquid water, which cannot exist at the low pressures of interstellar space. Water in interstellar space exists either as vapour or as solid ice, depending on its temperature. Only through star formation. leading to associated planets and smaller bodies, can there be access to liquid water. Conditions suited to the presence of liquid water can exist over long periods of time on planets like the Earth. Liquid water need not exist, however, for long periods of time, since bacteria can multiply so extremely rapidly given suitable conditions. Shorter periods could exist on bodies much smaller than planets and in the early high-luminosity phase of newly formed stars the bodies could lie far out from the stars, at much greater distances than the Earth is from the Sun. In the case of our own solar system, liquid water could quite well have existed in the early days far out towards the periphery, and it could have existed at the surface of bodies of lunar size or inside still smaller bodies. The nutrients present in the outer regions of the solar system must have exceeded by many millions the amount at the Earth's surface. Hence the short-lived conditions associated with star formation must be of far greater importance to the population of interstellar bacteria than the long-lived, more or less permanent environment provided by planets like the Earth.

It has long been clear that the detailed properties of our own solar system are not at all what would be expected for a blob of interstellar gas condensing in a more or less random way. Only by a very strict control of the rotation of various parts of the system could such an arrangement as ours have come into being. The key to maintaining control over rotation would seem to lie once again in a magnetic field, as indeed does the whole phenomenon of star formation. The surest way for interstellar bacteria to prosper in their numbers would be through maintaining a firm grip on all aspects of the interstellar magnetic field. By so doing they would control not only the rate of star formation but also the kinds of star systems that were produced.

The multiplying capacity of bacteria is enormous, as we pointed out in earlier chapters. To go from an individual bacterium to the number of all the interstellar grains requires about 170 doublings. When conditions are optimal a bacterial population can double in a few hours, so 170 doublings take less than a month. Of course such a prodigious explosion in number would never literally be achieved because of practical limitations occurring in the availability of nutrients. Nevertheless, there is evidence that whole galaxies are overwhelmed from time to time by comparatively rapid and very large scale episodes of grain formation. as for instance the galaxy M82. This example is far from unique. There are many cases of galaxies embedded in a vast cloud of particles. On a lesser scale, there is a similar distinction between two appendages to our own galaxy, the Large and Small Magellanic Clouds.

For a generation or more astronomers have been accustomed to thinking of star-forming episodes accompanied by the production of vast clouds of interstellar grains. The episodes are sometimes local but they are often galaxy-wide. They are thought to be triggered by some large-scale event, the after effects of which linger on for some considerable time, several hundred million years. The condensation of the exceptionally bright stars which delineate the spiral structures of galaxies has often been associated with these episodes. From our argument it seems then that even the origin of the spiral structures of galaxies may well be biological in its nature.

The potential of bacteria to increase vastly in their number is enormous. It should occasion no surprise, therefore, that bacteria are widespread throughout astronomy. Rather would it be astonishing if biological evolution had been achieved on the Earth alone, without the explosive consequences of such a miracle ever being permitted to emerge into the Universe at large. How could the Universe ever be protected from such a devastating development? This indeed would be a double miracle, first of origin. and second of terrestrial containment.

Some biologists have probably found themselves in opposition to our arguments for the proprietary reason that it seemed as if an attempt were being made to swallow up biology into astronomy. Their ranks may now be joined by those astronomers who see from these last developments that a more realistic threat is to swallow up astronomy into biology.

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