SYMBIOSIS AND THE ORIGIN OF LIFE

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Abstract. The paper uses chemical kinetic arguments and illustrations by computer modelling to discuss the origin and evolution of life. Complex self-reproducing chemical systems cannot arise spontaneously, whereas simple auto-catalytic systems can, especially in an irradiated aqueous medium. Self-reproducing chemical particles of any complexity, in an appropriate environment, have a self-regulating property which permits long-term survival. However, loss of materials from the environment can lead to continuing decay which is circumvented by physical union between different kinds of self-reproducing particles. The increasing complexity produced by such unions (symbioses) is irreversible so that the chemical system evolves. It is suggested that evolution by successive symbioses brought about the change from simple, spontaneously arising, auto-catalytic particles to complex prokaryotic cells.

1. Introduction

The idea of symbiosis (from Greek '*sumbioein*', meaning 'to live together') has been interpreted in a wide variety of ways. In this paper, we shall apply it to the physical union between members of associating species which leads to a propagating species. A common example is a lichen, formed by the union of a fungus and an alga.

Although familiar (see Henry, 1966), symbiosis is not generally regarded as a major process in evolution, rather appearing as an extreme manifestation of association.

However, one crucial step in the evolution of higher life, the step from the prokaryotic cell to the eukaryotic, has been attributed to a series of symbioses (Sagan, 1967; Margulis, nee Sagan, 1970). Indeed, it is now commonly recognised that the chloroplast found in plant cells evolved from the symbiotic inclusion of a blue-green alga into a primitive eukaryotic cell (Ris and Plaut, 1962; Echlin, 1966; Raven, 1970; Taylor, 1970). Quite a good case can also be made for a symbiotic origin of mitochondria in eukaryotic cells (Borst and Kroon, 1969; Nass, 1969; Ashwell and Work, 1970; Borst, 1972; Linnane *et al.*, 1972). The case rests mainly on the prokaryotic character of mitochondrial DNA and ribosomal apparatus in contrast with the more elaborate nuclear DNA and the eukaryotic ribosomes in the cytoplasm.

Many chloroplastic proteins and almost all mitochondrial proteins are encoded on the nuclear DNA (Kirk, 1972; Borst, 1972; Schatz and Mason, 1974). If the symbiotic origin of these organelles is accepted, it is necessary to accept at the same time that the symbioses have been consolidated by mutation in the nuclear DNA, with some related loss of disused organelle DNA. In these instances, symbiosis and mutation would be complementary processes in evolution.

This paper presents the thesis that, in the early stages of life, symbiosis was the major evolutionary process, bringing about the change from a simple chemical environment to a biosphere of prokaryotic cells.

The thesis is supported by characterizing the growth and reproduction of living things in chemical terms so that symbiosis can be modelled as a kinetic process (Section 3). While symbiosis between associating species occurs only slightly in a medium that is adequate for the species, it can occur largely in a depleted medium. Repeated depletions can cause successive symbioses among which the more likely occur first while the less likely occur later in an evolving sequence. For kinetic reasons, the symbioses are virtually irreversible so that evolution by successive symbioses causes a rapid increase in complexity (Section 4).

To establish at what stages of life evolution by symbiosis might have been important, the spontaneous generation of propagating species is considered. In chemical terms, this means finding the conditions for the onset of auto-catalytic chemistry (Section 5). Chemically simple species can arise spontaneously whereas complex ones cannot. It is suggested, therefore, (Section 6) that life originated with simple auto-catalytic chemistry; further, that the huge range in complexity between this and the prokaryotic cell was spanned by a succession of symbioses.

Many chemical ideas are used in the development of the thesis and Section 2 (Auto-catalytic Chemistry) is included to provide the necessary background. It draws attention particularly to:

(a) the relation between chemical complexity and physical structure;

(b) the equilibrium effect in the kinetics of consecutive reactions;

(c) the kinetic consequences of the attrition caused by reactions which are not part of the catalytic sequences.

The section ends with a justification for using simple modelling techniques under conditions of depletion, even for very complex chemical sequences.

Because evolution by symbiosis can occur without mutation in DNA, the question of when mutation achieved its present importance is left quite open.

No attempt is made to reconcile the general description in this paper with ideas on the origin of life expressed in the many books and scientific papers. Rather, it is felt that the very generality may serve in developing new ideas on the origin of life, not only on Earth but on other planets, too.

2. Auto-Catalytic Chemistry

Auto-catalysts have properties in common with ordinary catalysts and it is convenient to discuss these before considering their special features.

Equation (1) is a catalytic pair:

$$R_1 + C_1 \longrightarrow C_2 + P_1 \tag{1}$$
$$R_2 + C_2 \longrightarrow C_1 + P_2$$
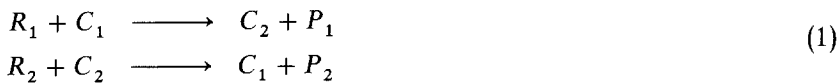
The 'catalyst' in either of its forms, C_1 or C_2, is an intermediate species which is recycled. By adding further cyclic steps it is possible to extend (1) into a catalytic sequence of any specified length:

$$R_1 + C_1 \longrightarrow C_2 + P_1$$
$$R_2 + C_2 \longrightarrow C_3 + P_2 \tag{2}$$
$$\vdots$$
$$R_n + C_n \longrightarrow C_1 + P_n$$

Cyclic sequences of reactions do not include all the energetically possible reactions among the chemical species present. Indeed, the number of energetically possible reactions increases quadratically with the number of chemical species while the number of reactions in a cyclic set increases only linearly. With increasing complexity, therefore, the cyclic set is increasingly a restricted set of reactions.

The reactions outside the cyclic set fall into two classes:

(a) reactions between primary reactants, R;

(b) reactions that involve the intermediate species, C.

Class (a) affects only the relative importance of the cyclic and noncyclic processes in the consumption of primary reactants. Class (b), on the other hand, withdraws intermediate species and therefore causes an intrinsic decay in the cyclic process. This decay generates significant characteristics in the kinetics of auto-catalysis (see later).

Class (a) is inhibited by the physical structures of the primary reactants, the rate of reaction being specified by 'activation energies' and 'steric factors'. Class (b) is inhibited by the physical structures associated with the catalysts themselves. If a complex catalytic sequence is to persist, there must be a correspondingly complex physical structure. The structure is built up by addition reactions.

The addition of chemical groups to make the physical structure of a complex catalyst consumes active sites on the groups. However, there are still further sites which can take part in the consecutive reactions of the cyclic set. Therefore, some of the added groups must be poly-functional.

Another important consequence of the physical structure is the proximity of active sites taking part in the consecutive reactions in the cyclic set. The effective concentration of the sites is thus raised above that expected for a homogeneous medium so that the rate for consecutive reactions is increased. This is the so-called 'equilibrium effect' (Martell, 1968) which occurs independent of changes which the physical structure may cause in activation energies or steric factors.

An auto-catalyst can be described by this pair of reactions:

$$R_1 + C_1 \longrightarrow C_2 + P_1 \qquad (3a)$$

$$R_2 + C_2 \longrightarrow C_1 + C_1 \qquad (3b)$$
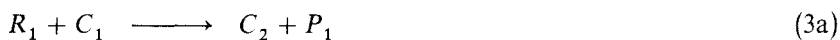
In biological parlance, (3a) represents 'growth' while (3b) represents 'reproduction'. Just as with ordinary catalysts, both (3a) and (3b) can be extended by the addition of further cyclic steps to make an auto-catalytic sequence of any specified length.

The common entities showing auto-catalytic behaviour are biological cells in which the chemical sequences are very long indeed and are, moreover, complicated by 'nested' sets of cyclic reactions. Cells also show a complex physical structure consistent with the need to restrict reactions to the cyclic sets.

Simple auto-catalytic systems in aqueous media are not common (see McNaughton, 1975, for a review). In the gaseous phase, combustion is a common manifestation. The simplest auto-catalytic system occurs in the upper atmosphere in the recombination of atomic oxygen formed from molecular oxygen by photo-dissociation:

$$O + O_2 \longrightarrow O_3 \qquad (4a)$$

$$O + O_3 \longrightarrow O_2 + O_2 \tag{4b}$$

The actual sequence is more complicated than Equation (4) because (4a) does not conserve energy and momentum together so that a temporary association with other atmospheric molecules is needed. Nonetheless, molecular oxygen here acts as an auto-catalytic particle.

Most treatments of auto-catalytic kinetics deal only with the case where Equation (3a) is much faster than (3b) so that the pair of equations can be approximated by

$$R + C \longrightarrow C + C \tag{5}$$

Even though (5) may represent the net effect of many reactions, it is common to treat C as a 'particle' which can be described by a single rate equation. Later, we will give a kinetic argument indicating the likelihood of a particle structure. If it is accepted for the immediate purposes, the growth rate is given by

$$d[C]/dt = k.[R].[C] \tag{6}$$

With ample supply of reactants ($[C] \ll [R]$), $[C]$ increases exponentially with time – the so-called 'auto-catalytic kinetics'. In biology, an example is the 'log phase' of growth in a batch culture of bacteria.

As the reactants are consumed, the rate of increase falls off. If we now include the fact that the auto-catalyst is subject to decay with a first order rate coefficient, α, a new regime appears. Equation (6) becomes

$$d[C]/dt = (k.[R] - \alpha).[C] \tag{7}$$

and, when $k.[R] < \alpha$, $[C]$ declines – the state of 'depletion'. The biological example again – bacteria exhibit the intrinsic decay expected in complex catalysts: following the log phase in a batch culture there is a 'stationary phase' and a 'phase of decline'.

Several important properties of auto-catalysts depend on these phases of expansion and decline:

(a) A single auto-catalytic species in an adequate 'pool' of reactants always goes through a phase of expansion, depletes the pool and goes into decline.

(b) If the pool is sporadically replenished with an adequate supply of reactants, the auto-catalyst expands anew with each replenishment so that its continuation is assured. This is the 'self-regulating' property.

(c) Often, the auto-catalytic process starts in a local part of the pool. In this case, it expands to deplete the whole pool. The expansion propagates as a 'front' separating the regions of adequate reactants from regions of depletion – see Frank-Kamenetskii (1969) for a mathematical treatment. A common example is an explosion front in a combustible gas mixture.

(d) If two auto-catalytic species use the same pool of reactants, they 'compete'. Because the expansion has an exponential character, even a small advantage in growth rate rapidly leads to complete dominance by the faster growing species.

(e) Under conditions of depletion, two species also compete with respect to their decay rates. However, this competition is normally manifest only when reactants are continuously or sporadically supplied.

(f) If two auto-catalytic species are in the same medium and a product of one species is a reactant for the other, the latter 'associates' with the former during a spatial expansion as described in (c) above.

Notice that the language of ecology has been used to describe the various properties because their most extensive development has taken place in ecology. However, the methods used are chemical kinetic methods and the results are independent of the complexity in the auto-catalytic particle – they apply to biological entities and to simple auto-catalytic chemistry alike.

In the ecological context, the self-regulating property, (b) above, specifies a condition which the environment must meet in order that an auto-catalytic species show long-term persistence. There must be periods when the supply of reactants is adequate:

$$R > \alpha/k. \tag{8}$$

It is appropriate, now, to return to the question of the physical structure associated with auto-catalytic systems. Compare two systems, both with the same cyclic sequences but with different physical structures, one being a single 'particle' and the other being in two or more particles. If they use the same pool of reactants, they compete. Regarding the various activation energies and steric factors, it is possible to say only that the single particle is likely to have an advantage in protection against decay. However, because of the equilibrium effect (see earlier) the single particle does have a considerable advantage in reaction rate. Unless this is outweighed by adverse changes in activation energies, the single particle should become dominant.

The physical structure of auto-catalytic particles is built up by addition reactions. Other addition reactions may occur as part of the cyclic sequences. In the latter case, chemical bonds which are made will later be broken and bonds which are broken will be remade. The breaking of the bonds requires energy which comes, not from thermal or radiant input, but from chemical reaction. That reaction involves the making of a stronger bond in forming the final product. Cyclic activity, then, depends on a hierarchy of bond strengths and is conspicuous in those systems where there is a range of intermediate strength bonds between the covalent and the purely physical bondings – as with metal ion coordination chemistry and hydrogen bonding. Although the final structure must contain some strong bonds, not all need be so. The only limit on binding strengths is set by the need to withstand thermal agitation in the medium in order that the particle structure is maintained.

The treatment so far has been descriptive, accepting the existence of complex auto-catalytic particles. The following sections will develop the idea that the complexity can come about by unions between simpler auto-catalytic species – by symbiosis. To justify illustrating this by computer modelling, it is necessary to consider again the representation of complex chemical sequences by approximate equations. Earlier, the pair of equations, (3), was simplified to the single equation, (5). Equation (3) gives for the growth rate of the C species, $C_1 + C_2$,

$$d[C]/dt = k_2 \cdot [R_2] \cdot [C_2], \tag{9}$$

where k_2 is the rate coefficient for Equation (3b). This is not independent of (3a) because that reaction supplies C_2. As depletion approaches, the behaviour depends on which reactant is first depleted. If R_1 is used first, C_1 accumulates; if R_2 is used first, C_2 accumulates. C_1 and C_2 can be regarded as 'states' of the C species and the final state during depletion is determined by the ratio of supplied reactants. Moreover, as depletion is approached, the overall rate is determined by the slow reaction, which is that using the depleted reactant. These considerations can be extended to a cyclic sequence of any length. If the cyclic set contains N reactions, there are N states of the C species and it can be stopped in any one by depleting the appropriate reactant. During the approach to depletion, the reaction using that reactant controls the overall rate. In biology, this property is used as an experimental tool for studying the cell cycle. For the purposes of modelling with a particular interest in the effects of depletion, then, it is enough to represent even a complex sequence by the simplest set which preserves the features used in the discussion.

3. The Kinetics of Symbiosis

Representing an auto-catalytic set by just the equations for 'growth' and 'reproduction', we can model symbiosis between auto-catalytic sets of any complexity by the following equations:

$$\left.\begin{aligned} 1 + 9 &\longrightarrow 2 + 8 \\ 2 + 10 &\longrightarrow 1 + 1 \end{aligned}\right\} \quad \text{First species} \tag{10}$$

$$\left.\begin{aligned} 3 + 7 &\longrightarrow 4 + 10 \\ 4 + 8 &\longrightarrow 3 + 3 \end{aligned}\right\} \quad \text{Second species} \tag{11}$$

$$2 + 4 \longrightarrow 5 \qquad \text{Symbiosis} \tag{12}$$

$$\left.\begin{aligned} 5 + 9 &\longrightarrow 6 \\ 6 + 7 &\longrightarrow 5 + 5 \end{aligned}\right\} \quad \text{Symbiotic species} \tag{13}$$
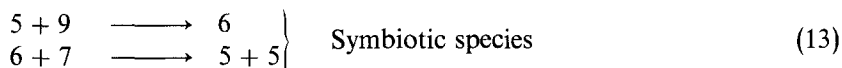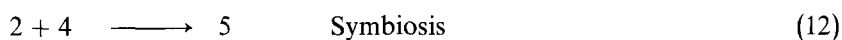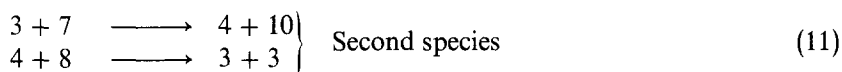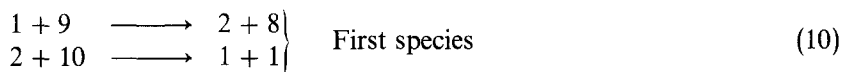
Here, the numbers stand for blocks of chemicals with a particular property. For example, 9 signifies reactants for growth of 1 and 5, while 1 and 2 are the growing and reproducing states of the first species. These equations are supplemented by a further set which represents the decay of each species. Unions between the primary species which do not lead to a propagating species contribute to decay and not to symbiosis. Notice that the first set produces material, 8, which is a reactant for the second set, while the second set produces 10 which is a reactant for the first set. This is 'association' based on the mutual exchange of materials.

A typical computer modelling is illustrated in Figure 1. Each plotting symbol represents the amount of the chemical block with the same number in Equations (10) to (13). If two symbols fall in the same place, only the larger is printed. Time, increasing downwards, is printed on the right hand side.

In this particular run (Figure 1), the rate coefficient for each equation in sets (10) and (11) is 0.02 and for each equation in set (13) it is 0.01, reflecting the slower growth of the more complex symbiotic species. The 'symbiosis' reaction has a rate coefficient of 0.02 – the same as for growth and reproduction of the primary species.

```
DECAY INCLUDED
  R 6  =  1.00E-02
  R 7  =  1.00E-02
  R12  =   .50E-03
  R13  =   .50E-03

                  1    2    3    4    5    6    7    8    9   10
STARTING VALUES  .01  .00  .01  .00  .00  .00 1.00 1.00 1.00 1.00

UPPER BOUND OF GRAPH = 0.6                                             TIME

I 3                                                                I       0
I 4                                                                I      50
I43                                                                I     100
I 4                                                                I     150
  4 3                                                              I     200
   4 3                                                             I     250
     4 3                                                           I     300
      4   3                                                        I     350
I5        4       3                                                I     400
I5          4       3                                              I     450
I65           4           3                                        I     500
I6 5            4             3                                    I     550
 6   5             4              3                                 I     600
  6    5              4                3                            I     650
  6    5    24           4                  3                      I     700
  6    5   24                                   3                   I     750
  6   54                                           3               I     800
  6 245                                               13           I     850
 64  5                                                  13          I     900
  6   5                                                  1 3        I     950
I46   5                                               13            I    1000
I46   5                                             1 3             I    1050
  6   5                                          13                 I    1100
  6   5                                        1 3                  I    1150
  6   5                                     13                      I    1200
  6   5                                   1 3                       I    1250
  6   5                                13                           I    1300
  6   5                              13                             I    1350
  6   5                           13                                I    1400
  6   5                         13                                  I    1450
  6   5                      13                                     I    1500
  6 5                     13                                        I    1550
  6 5                  13                                           I    1600
  6 5                13                                             I    1650
  6 5             13                                                I    1700
  6 5          13                                                   I    1750
  6 5        13                                                     I    1800
I6 5      13                                                        I    1850
  6 5   13                                                          I    1900
I6 5  13                                                            I    1950
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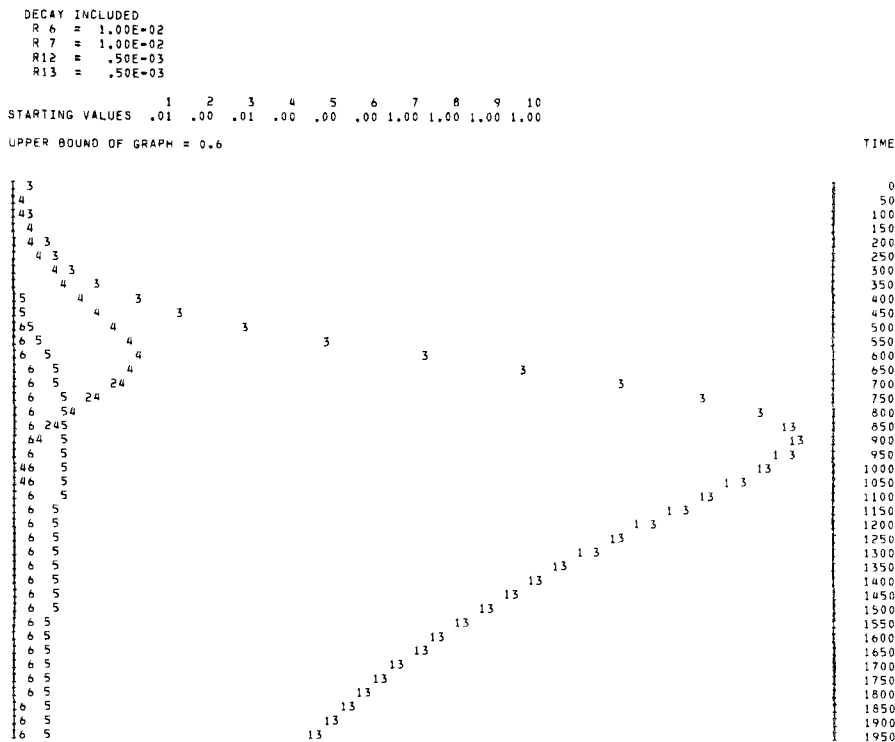
Fig. 1. Computer modelling for the time course of symbiosis. Symbols: 1 and 2, first primary species in its two forms. 3 and 4, second primary species. 5 and 6, symbiotic species.

The first order decay rate coefficients for each species in each of its two forms is a twentieth of the second order growth coefficients, defining the relative time scales for growth and decay. All reactants, 7 to 10, have the adequate value of 1.0.

Each species goes through a course of expansion and decline. When reactants are plentiful, the expansion has an exponential shape – 'auto-catalytic kinetics'. The decline sets in when the reactants become scarce – 'depletion'. The symbiotic species in each of its two forms, 5 and 6, is delayed in its expansion and decline because it starts at zero concentration and must be built up initially by the 'symbiosis' reaction (Equation (12)). Because of this delay, its entry into depletion is determined, not by its own use of reactants, but by the usage of the primary species. In spite of the large rate coefficient for symbiosis, little occurs.

It is quite otherwise under conditions of depletion. Figure 2 assembles the results of many runs like that shown in Figure 1. It plots, logarithmically, the maximum value attained by the symbiotic species (in both its forms, 5 + 6) as a function of the initial amount of the depleted reactants, 8 and 10 – tabled as 'supply' on the right hand side. Reactants 7 and 9 are supplied adequately as before. The plotted symbols represent different rate coefficients for the process of symbiosis (Equation (12)); for symbol 1 it is 2×10^{-2} (as in Figure 1), for 2 it is 2×10^{-6} and for 3 it is 2×10^{-10}.

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                          LOG(10)

           -8            -6            -4            -2        0   SUPPLY

    I      I      I      I      I      I      I      I      I

                                                        3       .00
                                                        3       .01
                                                        3       .02
                                                       32       .03
                                          3            21       .04
                              3                     2   1       .05
                       3                          2     1       .06
                    3                           2       1       .07
                 3                            2         1       .08
               3                            2           1       .09
              3                           2             1       .10
             3                            2             1       .11
            3                           2               1       .12
           3                            2               1       .13
           3                           2               1       .14
          3                           2                 1       .15
          3                           2                 1       .16
          3                           2                 1       .17
         3                            2                 1       .18
         3                            2                 1       .19
         3                            2                 1       .20

    I      I      I      I      I      I      I      I      I
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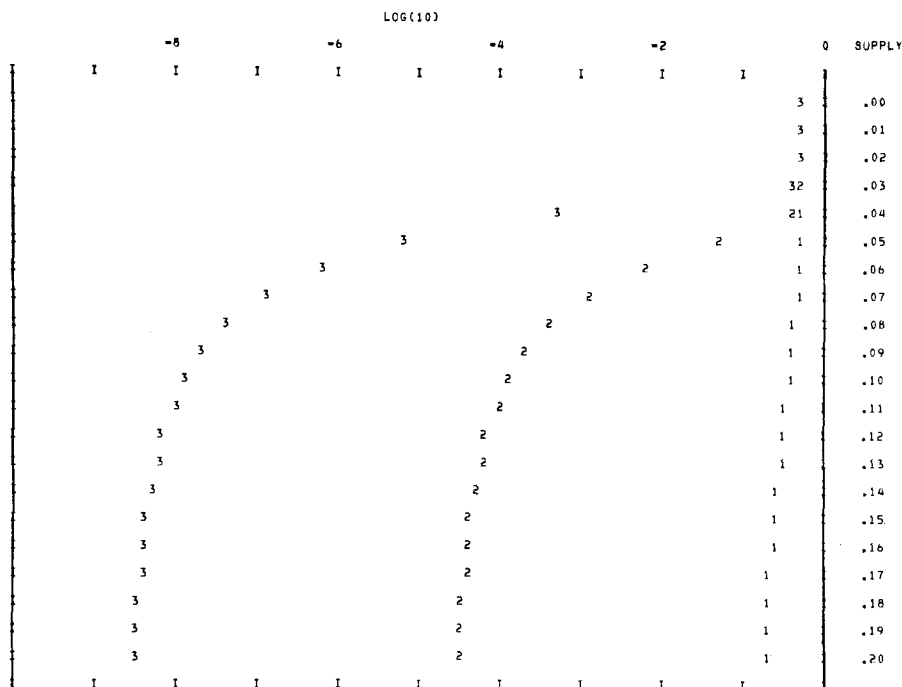
Fig. 2. Maximum concentration of symbiotic species (logarithmic scale to base 10) as a function of the initial supply of depleted reactants. Symbols: 1, rate coefficient for symbiosis = 2×10^{-2}. 2, coefficient = 2×10^{-6}. 3, coefficient = 2×10^{-10}.

Figure 2 shows that, with severe initial depletion in the reactants exchanged for association, the rate coefficient for symbiosis is almost immaterial – symbiosis will occur. If depletion is not so severe, the rate coefficient determines whether or not an appreciable amount of symbiotic species will be formed. Indeed, the change from little formation to major formation is abrupt. The abruptness depends on the amount of auto-catalytic amplification in the system – i.e., on the adequacy to which the non-depleted reactants are supplied.

Given an assemblage of associating species receiving a variable supply of reactants, Figure 2 indicates further that repeated symbioses will occur in a progressive succession so that the system evolves. In the early stages of this evolution, associating species with large rate coefficients for symbiosis unite leaving species with smaller coefficients. With the passage of time, more severe depletions bring about symbioses with small rate coefficients leaving only species with very small coefficients.

The preceding section on auto-catalytic chemistry supplies background which leads to the following points:

(a) Auto-catalytic species bring about the depletions which can lead to unions.

(b) Mutually associating species are already adapted to form a propagating species as the result of a union, i.e., the union can be a symbiosis.

(c) Symbiosis increases the complexity of the auto-catalytic particles.

(d) On account of its greater complexity, a symbiotic species is likely to have a 'generation time' longer than the generation times of its component species in a

medium that is adequate for them all. It is therefore at a competitive disadvantage unless the reactant shortages which initiated it continue.

(e) Because the reactants exchanged between the components of a union are not dispersed into the medium, they have an effective concentration very high compared with those which would normally appear in the medium (the equilibrium effect). The union therefore persists even if the depleted reactants are supplied in adequate amount. Practically speaking, symbiosis is irreversible.

(f) The binding forces which hold the union together can be of any strength so long as the product can withstand the thermal agitation in the medium. It is important, though, that the network of forces within the physical structure is sufficiently defined to restrict chemical activity to the cyclic reactions.

(g) Symbiosis brings together entities that 'work', in the sense of being propagating species, and it yields a product that also works. There is no need for further adaptation through mutation, although such later changes may take place.

4. Evolution by Symbiosis

A succession of symbioses taking place during the early evolution of life would have increased the complexity of living things greatly. To assess the importance of this increase, first consider unions between specimens of similar complexity. A union doubles the complexity. Ten unions increase it a thousand-fold while twenty unions would make a million-fold increase. The 'similar complexity' restriction can be removed by noting that, if only one component of a union were simple, the union would replace it with a relatively complex species. It follows that a million-fold increase in complexity would take less than forty unions, the number depending on the distributions of sizes and of rate coefficients for union.

With this capacity for increasing complexity, evolution by symbiosis could have spanned the gap in complexity between simple chemical systems and the prokaryotic cell.

It must be realised, though, that the possibility of spanning this gap depends on having an assemblage of associating auto-catalytic species at all levels of complexity right down to simple chemicals. Auto-catalytic systems are not common in everyday chemistry, seeming hard to make. However, a consideration of their nature suggests conditions under which they can arise spontaneously. The two key properties again are, (1) The cyclic set of reactions is a restricted set from among all energetically possible reactions in the medium. (2) The restriction is brought about by a particle structure formed by a succession of addition reactions.
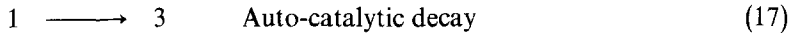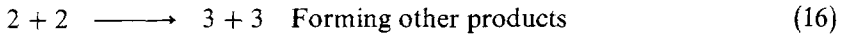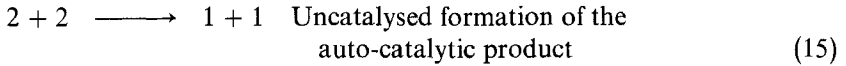
5. Spontaneous Generation

Auto-catalytic particles can only show auto-catalytic behaviour in an appropriate reaction mixture – i.e., one which contains all the primary reactants for the auto-catalytic set. The auto-catalytic set can be described as a catalytic extension of an uncatalysed set. Therefore, the reaction mixture must be able to yield the auto-catalytic product by an uncatalysed pathway. For example, the auto-catalytic

molecular oxygen illustrated in Equation (4) can be formed directly from atomic oxygen by

$$O + O \longrightarrow O_2 \tag{14}$$

(with the same caveats as before about addition in the gaseous phase). While the auto-catalytic pathway predominates in the upper atmosphere, the direct pathway may predominate at very high densities of atomic oxygen. The relative importance of the two pathways depends on kinetic conditions.

Figure 3 illustrates the general principle with a computed example. It is based on the following set of equations:

$$2 + 2 \longrightarrow 1 + 1 \quad \text{Uncatalysed formation of the} \atop \text{auto-catalytic product} \tag{15}$$

$$2 + 2 \longrightarrow 3 + 3 \quad \text{Forming other products} \tag{16}$$

$$1 \longrightarrow 3 \quad \text{Auto-catalytic decay} \tag{17}$$

$$1 + 2 \longrightarrow 1 + 1 \quad \text{Auto-catalytic formation} \tag{18}$$

Here, 1 is the auto-catalytic product treated as particles, 2 is the reaction mixture without regard to its details and 3 signifies 'other products'. Notice that this is a one-equation treatment of auto-catalysis compared with the two-equation treatment used for symbiosis.

Initially, reactants are supplied in unit quantity while 1 and 3 are zero. The rate coefficients for Equations (15), (16) and (17) are 10^{-4}, 10^{-2} and 10^{-2} respectively.
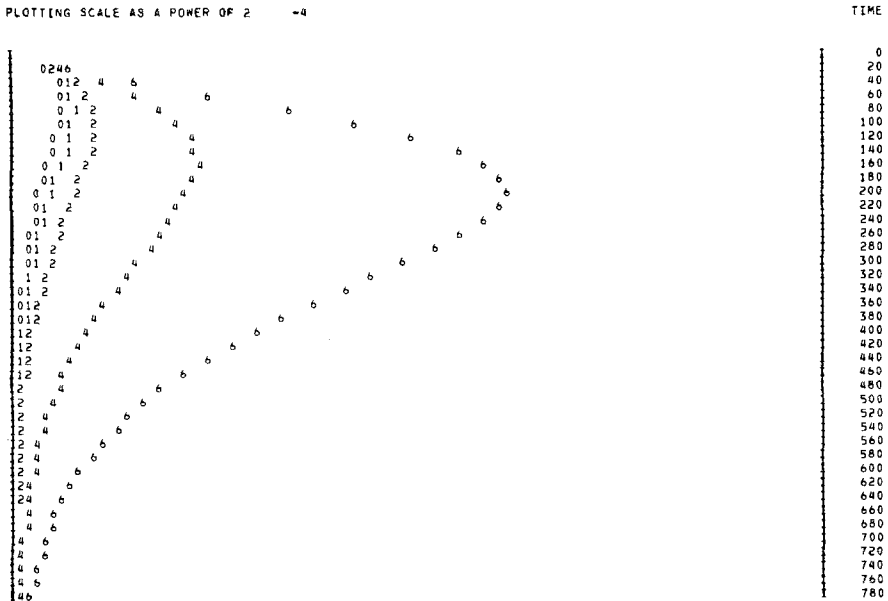

Fig. 3.   The spontaneous generation of an auto-catalytic species. Symbols: Rate coefficient for auto-catalytic formation $= N \times 10^{-2}$, where N is the plotted symbol. The full scale of the figure is $2^{-4} = 0.0625$.

The rate coefficient for Equation (18) is displayed in units of 10^{-2} as the plotting symbol for the auto-catalytic concentration – thus, the symbol 4 signifies a rate coefficient of 0.04.

From Figure 3, even if there is no auto-catalytic formation (symbol 0) the concentration of auto-catalytic product rises to a peak and then declines. Auto-catalytic formation increases the peak value to a small extent for small rate coefficients but very considerably once a threshold has been passed. Beyond the threshold, the time course shows the usual phases of auto-catalytic kinetics and depletion.

In the computer run just given, the uncatalysed formation of the auto-catalytic product had a rate coefficient a hundredth that for forming other products (Equations (15) and (16)). If the uncatalysed formation is very much slower, the threshold for the onset of auto-catalytic kinetics will not be reached. The equation for un-catalysed formation is a conventional representation of a set of binary chemical reactions, and its rate coefficient, therefore, expresses the combined probabilities of all the separate reactions in the set, not allowing for any effects of the product's particle structure once it is formed. As complexity increases, the combined prob-ability falls rapidly. If the auto-catalytic set (which is simply related to the un-catalysed formation) contains more than half a dozen binary reactions, the prospect of exceeding the threshold for auto-catalytic kinetics is essentially zero.

So far, the reaction mixture has been supposed given. Now consider how it may come about. The physical structure of auto-catalytic particles is built up by the addition of poly-functional groups. The reaction mixture supplies these either directly or in the form of compounds protected by added groups. As products are formed, either an auto-catalytic particle or any other, active sites are closed off by addition reactions. A way of making the reaction mixture, then, is to reverse the chemistry by photo-dissociation, both supplying chemical potential and creating active sites. For example, the reaction mixture for the auto-catalytic oxygen molecule is atomic oxygen from the photo-dissociation of O_2.

If the radiant energy is supplied continually, chemical activity in a complex medium eventually depends on the cyclic formation and dissociation of a set of molecules – the remainder after non-cycling molecules have ceased chemical activity. This reaction mixture may form an auto-catalytic product, even though the rate be small compared with the rate for forming other products. The recycling by photo-dissociation allows all products to attain finite equilibrium concentrations even though, like the auto-catalytic product, they may be subject to decay.

The auto-catalytic product differs from other products in having the threshold for auto-catalytic kinetics discussed above. In Figure 4, the recycling by photo-dissociation has been added to the equation set for Figure 3 (Equations (15) to (18)) using a rate coefficient of 0.01:

$$3 \longrightarrow 2 \quad \text{Photo-dissociation of other products} \tag{19}$$
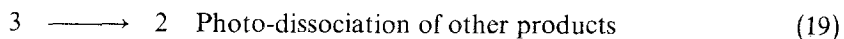
Notice that the equilibrium values are high if the threshold (≈ 0.02) has been exceeded. Although a large proportion of reaction in the mixture goes by the auto-catalytic pathway, it is only during the transient establishment of equilibrium that auto-catalytic kinetics can be observed.

```
PLOTTING SCALE AS A POWER OF 2      -1                                              TIME

|                                                                              |    0
|6                                                                             |   20
|46                                                                            |   40
|24  6                                                                         |   60
|124  6                                                                        |   80
|12  4    6                                                                    |  100
|12   4      6                                                                 |  120
|12    4        6                                                              |  140
|12      4         6                                                           |  160
|012       4            6                                                      |  180
|012         4             6                                                   |  200
|012          4               6                                                |  220
|012           4                 6                                             |  240
|012            4                  6                                           |  260
|01  2            4                   6                                        |  280
|01  2              4                   6                                      |  300
|01  2                4                  6                                     |  320
|01  2                 4                  6                                    |  340
|01  2                   4                 6                                   |  360
|01  2                     4                6                                  |  380
|01   2                     4                6                                 |  400
|01   2                       4              6                                 |  420
|01   2                        4              e                                |  440
|01   2                          4             6                               |  460
|01   2                           4             6                              |  480
|01   2                            4             6                             |  500
|01   2                             4             6                            |  520
|01    2                             4            6                            |  540
|01    2                               4           6                           |  560
|01    2                                4          6                           |  580
|01    2                                 4          6                          |  600
|01    2                                  4         6                          |  620
|01    2                                   4        6                          |  640
|01    2                                    4       6                          |  660
|01     2                                    4      6                          |  680
|01     2                                      4     6                         |  700
|01     2                                       4    6                         |  720
|01     2                                        4   6                         |  740
|01     2                                         4  6                         |  760
|01     2                                          4  6                        |  780
```
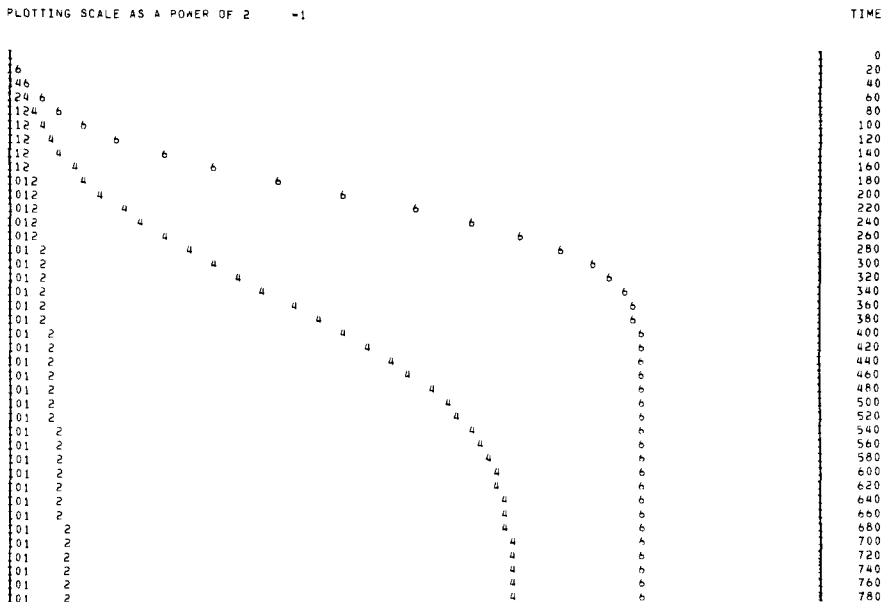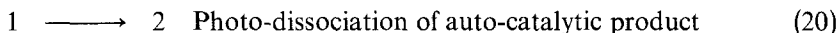
Fig. 4. Effect of irradiation on spontaneous generation. Symbols are the same as in Figure 3. Other products photo-dissociated but not the auto-catalytic species. Full scale is $2^{-1} = 0.5$.

If the auto-catalytic product itself is subject to photo-dissociation (acting as a decay term additional to Equation (17)),

$$1 \longrightarrow 2 \quad \text{Photo-dissociation of auto-catalytic product} \tag{20}$$

the threshold for auto-catalytic kinetics is raised. If Equation (20) also has coefficient of 0.01, an auto-catalytic rate coefficient of 0.04 is then just above threshold.

6. The Origin and Evolution of Life

The foregoing chemical kinetic ideas suggest a straightforward description for the origin and evolution of life.

Consider the point that a complex auto-catalytic product has essentially zero prospect of exceeding the threshold for auto-catalytic kinetics through spontaneous generation. The first auto-catalytic entities, then, were chemically simple, being formed by sequences of only a few binary reactions.

The spontaneous generation is greatly enhanced if the reactants are continuously recycled within the mixture by photo-dissociation. In these circumstances, cyclic sequences are 'selected' by the rejection of non-cyclic sequences. It is likely, then that the first auto-catalytic entities arose in an irradiated aqueous medium – aqueous rather than gaseous to promote addition reactions.

If the spontaneous generation yielded a variety of auto-catalytic species among which there were relations between the various products and reactants, spatial associations would arise with patches of adequate supply and depletion. In the depleted regions, the potential for symbiosis would be there.

If particular reacting materials were withdrawn from the medium, say by pre-cipitation, their continued depletion would lead to symbioses. A succession of with-drawals would cause evolution by symbiosis with consequent increase in the com-plexity of the auto-catalytic species.

Of course, it is not possible to say how far evolution by symbiosis would continue. However, because it increases complexity much more effectively than evolution by mutation, it is tempting to conclude that evolution by symbiosis produced the complexity of the prokaryotic cell, by which time only symbioses with very small rate coefficients would be occurring. If so, the symbioses postulated for evolution to the eukaryotic cell (Sagan, 1967; Margulis, 1970) could be regarded as identifiable steps at the end of a series of symbioses going right back to a simple chemical environment.

It is interesting to speculate on what the simplest auto-catalytic things might have been, remembering that a variety of them must have been possible in order that evolution by symbiosis could occur. Speculation can be controlled by listing their various properties:

(a) They possessed physical structure built by addition reactions.

(b) Their chemistry involved intermediate strength bonding to allow cyclic action.

(c) Their chemistry also involved branching reactions.

(d) Poly-functional groups formed easily.

(e) Steric considerations were important, even at the simplest level.

(f) Cyclic reaction times were very short. This follows from the direct relation between cycle time and complexity.

(g) At least some components of the system absorbed solar radiation.

One class of compounds has all these properties – the coordination compounds of metal ions in aqueous solution.

7. Discussion

Various authors have discussed auto-catalysis in relation to the origin of life or the nature of living things (e.g., Hinshelwood, 1946; Ycas, 1955; Calvin, 1956, 1969; Allen, 1957, 1970; Anker, 1961; Morowitz, 1967; Rössler, 1971; Eigen, 1971). The present paper adds to that earlier work the idea that a complex auto-catalytic system must have physical structure restricting activity to the catalytic sequence. The role of symbiosis in evolution can then be treated as a chemical kinetic problem. Likewise, the spontaneous generation of auto-catalytic activity is a kinetic question which is susceptible to more complete analyses than it has been possible to give here.

McNaughton (1975) summarized current ideas on the origin of life and, in the course of doing this, listed the various reasons which have been advanced for invoking auto-catalysis:

(a) To maximize material turnover rates (Ycas, 1955);

(b) To explain the origin of stereo-isomeric one-sidedness in biology (Frank, 1953).

(c) To speed up the rate of formation of catalysts and provide a basis for selection (Calvin, 1956).

(d) As reflexive catalysis, to provide a self-reproducing system simpler than nucleo-protein on which natural selection could operate (Allen, 1957).

Rather, Section 2 of this paper seems to indicate that the significant property of an auto-catalytic system is the ability to recover number densities when reactants are replenished – the self-regulating property for which the limit is specified by equation (8). When conditions are such that Equation (8) is no longer being met for particular depleted reactants, symbiosis with an associating species avoids continuing decay and a new, more complex, auto-catalytic activity persists.

Because symbioses are for practical purposes irreversible, assemblages of auto-catalytic species evolve with definite trends of increasing complexity and longer generation times. Here is a factor in 'time's arrow' additional to those which Blum (1968) discussed. In rough figures: – The simplest auto-catalytic entities had equivalent molecular weights of a few hundred daltons while prokaryotic cells are around 10^{12} daltons; 'generation times' for the simplest were likely to have been in the micro-second range to use the very short lifetimes of photo-excited states, while prokaryotic cells have generation times measured in thousands of seconds. Although this range of complexity can be spanned in some 60-odd symbioses, a very much greater number would have taken place during the evolution of the prokaryotic cell (less than a thousand-million years) to maintain species diversity at each level of complexity.

Apart from the interest associated with the origin of life, this work may have a practical bearing on the structure of the present-day cell. Because auto-catalysis is an exceedingly conservative process, the cell repeats the history of its successive symbioses in its internal cycles. Mutations create 'noise' obscuring this history, but it should be possible to make out at least some of the steps. The theory of evolution by successive symbioses would thus become a principle for resolving structure in the cell.

Acknowledgement

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