Origin of Life: I
Monomers to Polymers

Questions

- What two kinds of molecules are essential for all life on Earth?
- What building blocks are these two molecules made of?

Synthesis of Monomers

Life arose early on Earth

Conditions
1. Liquid Water
2. Reducing or Neutral Atmosphere
3. Energy Sources

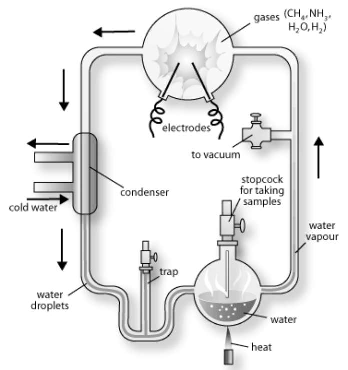
2. Reducing atmosphere
   NH_3, CH_4, H_2O, H_2

   Miller-Urey Experiment

3. Energy Sources

Ultraviolet Light (No Ozone)
Lightning
Geothermal (Lava, Hot Springs, Vents, …)

Miller-Urey Experiment



COMPOUND	Relative Yield
Glycine	270
Sarcosine	21
Alanine	145
N-methylalanine	4
Beta-alanine	64
Alpha-amino-n-butyric acid	21
Alpha-aminoisobutyric acid	0.4
Aspartic acid	2
Glutamic acid	2
Iminodiacetic acid	66
Iminoacetic-propionic acid	6
Lactic acid	133
Formic acid	1000
Acetic acid	64
Propionic acid	56
Alpha-hydroxybutyric acid	21
Succinic acid	17
Urea	8
N-methyl urea	6

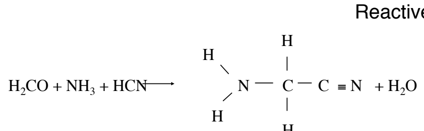
How did Amino Acids form in Miller-Urey Experiment?

Strecker Synthesis

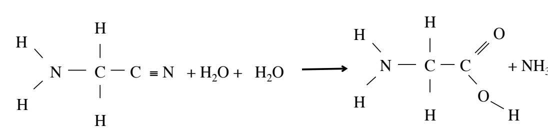
CH_4, H_2, NH_3 + Energy → H_2CO, HCN, HC_3N, Urea (H_2NCONH_2)

e.g. Glycine Synthesis

Reactive

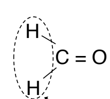


Aminoacetonitrile



glycine

H_2CO



form Aldehyde

Replace with more complex group

Get other aldehydes ↓

They can form more complex amino acids

Problems with Miller-Urey

Atmosphere was N_2, CO_2, H_2O

NH_3, CH_4 would react to make N_2, CO_2

Try N_2, CO_2, H_2O in Miller-Urey simulation

Only get trace amounts of glycine
Need CH_4 to get more complex amino acids

Need $H_2/CO_2 > 2$ to get much of any amino acid

Miller-Urey with Cosmic Rays

A group in Japan has obtained good yields of amino acids from slightly reducing gases (CO_2, CO, N_2, H_2O)

When they used high energy protons (simulate cosmic rays)

Apparently not Strecker Synthesis
(Low abundance of aminoacetonitrile)

Building Blocks of Nucleic Acids

Not formed in Miller-Urey, but some intermediates were

1. Ribose Sugar:
   $5\ H_2CO + \text{Heat} \xrightarrow{} H_{10}C_5O_5$
   [Clay Catalyst]
2. Bases
   a) Purines $5\ HCN \rightarrow H_5C_5N_5$ (Adenine)

   b) Pyrimidines
   $HC_3N + \text{Urea} \longrightarrow H_5C_4N_3O$ (Cytosine)

   (1995) Cyanoacetaldehyde + Urea $\longrightarrow$ Uracil

3. Phosphate
   Rock Erosion

Origin of building blocks of nucleic acids is less understood than amino acids

Alternative Sites

Locally reducing environments

1. Ocean vents
   Sources of CH_4 and H_2S
   Current Vents have ecosystems based on energy from chemicals - not photosynthesis
   $H_2S \rightarrow$ Bacteria $\rightarrow$ Clams, Tube Worms
   Pre-biotic amino acid synthesis?

Alternative Delivery

Molecular clouds - strongly reducing, contain many molecules used in Miller-Urey (H_2, NH_3, H_2O, CH_4) and intermediates (HCN, H_2CO, HC_3N) and aminoacetonitrile (glycine precursor)

Problem: These would not have survived in part of disk where Earth formed

But interstellar ices can get incorporated into comets
Evidence from similar molecules
(e.g. C_2H_2, CH_4, HNC, …)
Clearly indicates interstellar chemistry

Cratering record on moon, …
⇒ heavy bombardment early in history

Comets and their debris could have brought large amounts of "organic" matter to Earth
(and probably some of the oceans)

Some evidence for non-biological amino acids in layer deposited after asteroid impact 65 million years ago

Amino Acids in Meteorites

- Amino acids are found in some classes of meteorites (carbon-rich ones)
- Recent analysis of some carbon-rich meteorites found in Antarctica
  - Richest source of amino acids so far
  - Up to 250 parts per million
  - Very clearly extraterrestrial (not contamination)
    - Type of amino acids
    - ^{13}C is enhanced (opposite of what life does)

Sources of Organic Molecules

Quantitative comparison by Chyba & Sagan, Nature 1992, Vol. 355, p. 125

Currently, Earth accretes ~ 3.2×10^6 kg y^{-1} from interplanetary dust particles (IDP)
~ 10% organic carbon $\Rightarrow$ 3.2×10^5 kg y^{-1}
~ 10^3 kg y^{-1} comets
~ 10 kg y^{-1} meteorites

~ $10^3 \times$ more at 4.5×10^9 yr ago (?)
(cratering record)
UV + reducing atmosphere 2×10^{11} kg y^{-1}
But if $H_2/CO \lesssim 0.1$ IDP's dominant source

So if atmosphere very neutral, IDP's may have been important

Most of mass in IDP's in range of size ~ 100 μm
mass ~ 10^{-5} g
Complex structure - composites of smaller grains some carbon rich
Enhanced deuterium implies low T

Deuterium enhancement also found in interstellar molecules
May imply connection back to interstellar chemistry

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2 kinds (mass ranges) can supply organic matter

1. Interplanetary dust particles ($m \lesssim 10^{-5}$ g)
2. Smaller meteorites ($m \lesssim 10^8$ g)

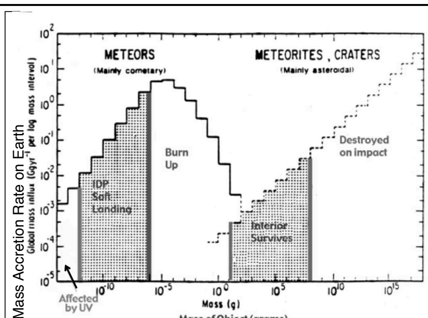


FIG. 1 Infall rate of meteoritic matter on Earth (adapted from ref. 5). Intervals where organic matter can survive passage through atmosphere are shaded. The curve on the right is based on the relation[5] $N = 0.54\, r^{-2.1}$ (N = number of impacts per Myr, r = radius in km), for an assumed density of 3 g cm^{-3}. The corresponding mass accretion rate (Gg yr^{-1}) between r_1 and r_2 is $15.83\,(r_2^{0.9} - r_1^{0.9})$.

E. Anders (1989) Nature, 342, 255

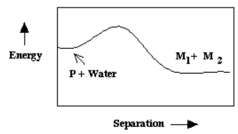
For example…

The Austin Marathon Fireball

Synthesis of Polymers

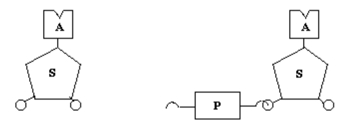
$M_1 + M_2 \longrightarrow P + H_2O$

$\longleftarrow$ more likely in liquid H_2O



Solutions: Remove H_2O (Drying, Heat)
Sydney Fox $\longrightarrow$ Proteinoids
Energy Releasing Reactions (H_2NCN or HC_3N)
Catalysts: Clays

Problem is worse for Nucleic acids because more complex



nucleoside

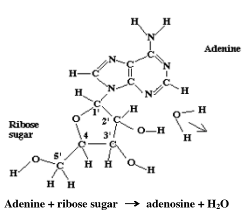
nucleotide

↑

Monomers of nucleic acids

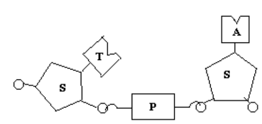
Synthesis of Adenosine

Base on 1' Carbon (Why?)



Also phosphates 3' & 5' carbons

Otherwise, you are likely to get Misalignment



Leslie Orgel has had some success in getting high percentage of correct linkages, in presence of Zinc ions.

Experimental Results

Sugar + base + heat yield some nucleosides

Activated nucleosides + phosphoric acid + Zn^{+2}

Get polymers up to 50 nucleotides in length

linkages (mostly) correct

The Odds

- We need to get an “interesting” polymer
  – Enzyme
  – Self replicator
- Properties of polymer depend on
  – Order in which monomers combine
- If we combine monomers at random,
  – How likely to get something interesting?

Statistics of an unlikely event

Random reactions in primordial soup?
Unlikely event versus many trials
Probability Primer: Consider tossing 10 coins

Probability of all heads = product of prob.

$$P = \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) \cdots \left(\frac{1}{2}\right)^{10} = \frac{1}{1024}$$

Probability of getting 10 amino acids ⟶ protein

Chosen from 20 in a particular <u>order</u>

$$\left(\frac{1}{20}\right)^{10} = \frac{1}{1 \times 10^{13}}$$

Based on discussion by R. Shapiro

But if you try many times, the chance of success is higher

$$P(r) = \frac{n!}{r!\,(n-r)!}\; p^r\,(1-p)^{n-r}$$

r = # of successes   p = prob. of success on each trial

n = # of trials

n! = n (n-1) (n-2) … 1

e.g. make $n = \frac{1}{p}$ (flip all 10 coins 1024 times)

$$P(1) = \frac{n!}{1!\,(n-1)!}\left(\frac{1}{n}\right)\left(1-\frac{1}{n}\right)^{n-1} = 0.37$$

Chance of one or more successes = 0.63

For reasonable chance need $n \sim \frac{1}{p}$

How many do we have to get right?

1. How many atoms?

Lipids	$10^2 - 10^3$
Enzymes, RNA	$10^3 - 10^5$
Bacterial DNA	$10^8 - 10^9$
Bacterium	$10^{11} - 10^{12}$
Human Being	$10^{27} - 10^{28}$

If we choose from H,C, N, O (ignore S,P)
probability of right choice 1/4
So for enzyme: $(\frac{1}{4})^{10^3} \sim 10^{-600}$

# of trials: R. Shapiro computes
$N = 2.5 \times 10^{51}$ (surely an overestimate)
$n \ll \frac{1}{p}$ for <u>simple</u> enzyme

2. What if we start with amino acids?
   Need ~ 10^{13} trials to get 10 amino acid protein

To get 200 amino acids in right order

$\left(\frac{1}{20}\right)^{200} = 10^{-260}$ Hopeless!

Need something besides random combinations
Selection (Natural?)

Improving the Odds

Many proteins composed of interchangeable segments (Domains)

10 to 250 amino acids

One domain found in ~ 70 different proteins

Intermediate building blocks?

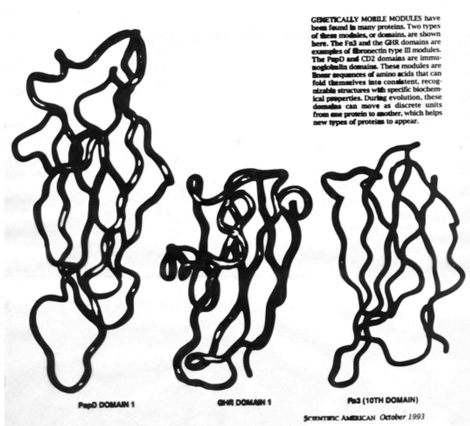
If so, may only need to get enough amino acids in right order for a domain

e.g. 18 amino acid domain

$P = \left(\frac{1}{20}\right)^{18} = 10^{-23}$

Also, many variations in amino acids don't destroy function

and many different sequences may be interesting



Scientific American Doolittle & Bork
Oct. 1993, pg. 50

Proteins made of domains, assembled in various ways
10-250 amino acids for ones containing disulfide bonds

18 - 100 for those without

Of all amino acids available

$\left(\frac{1}{20}\right)^{40}$ or $\left(\frac{1}{20}\right)^{18}$

$\log_{10} = 40 \log 20$	$-18 \log 20$
$= -52$	$= -23.4$
so 10^{-52}	$10^{-23.4}$

Interesting fact on how the improbable happens

1st winner of Texas Lotto lottery
Picked all 6 numbers correctly in the <u>same</u> order as they were drawn.

Each number runs from 1 to 50, and once chosen, cannot be repeated (balls are taken from a box).

So the odds against getting them in order is

$$\left(\frac{1}{50}\right)\left(\frac{1}{49}\right)\left(\frac{1}{48}\right)\left(\frac{1}{47}\right)\left(\frac{1}{46}\right)\left(\frac{1}{45}\right) = \frac{1}{11{,}441{,}304{,}000}$$

You don't need to get them in the same order to win - odds against winning include any combination, so 1 in 16 million