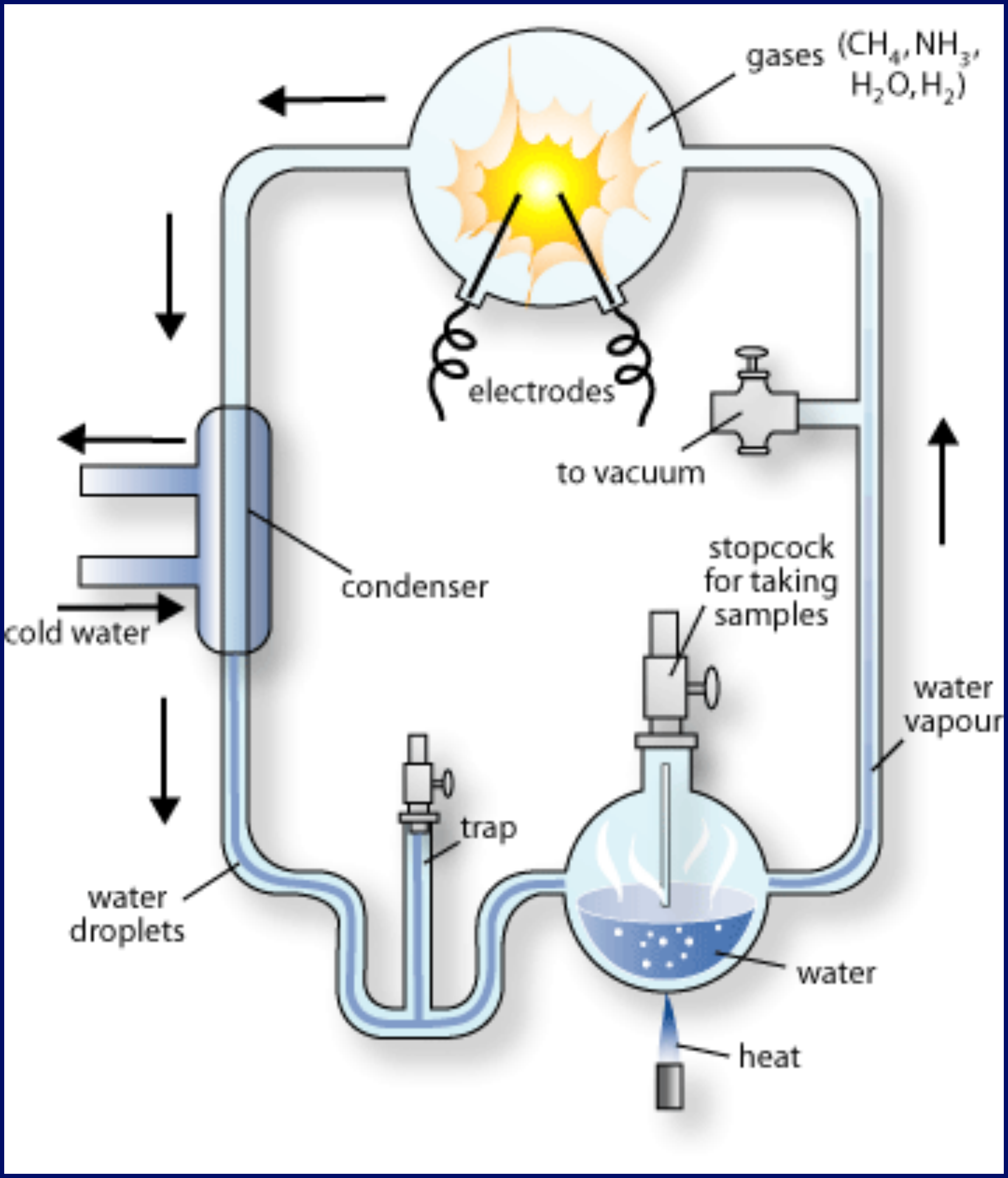
# Origin of Life: I
# Monomers to Polymers

# Synthesis of Monomers

- Life appears early on Earth (3-4 Gyr ago)
- Conditions:
  - Liquid water
    - Earth in HZ
  - Reducing or Neutral atmosphere
    - $NH_3$, $CH_4$, $H_2O$, $H_2$ or $CO_2$, $N_2$, $H_2O$ (no $O_2$)
  - Energy sources
    - Ultraviolet Light (No Ozone)
    - Lightning
    - Geothermal (Lava, Hot Springs, Vents, …)

# Miller-Urey Experiment: 1953



# Products of Miller-Urey

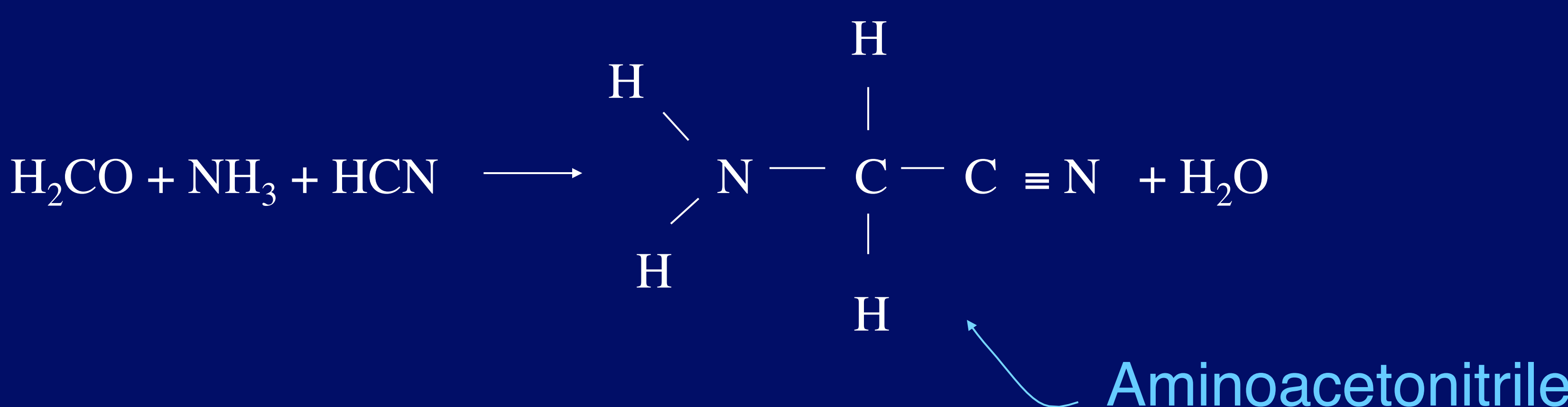
| COMPOUND | Relative Yield |
|---|---|
| **Glycine** | 270 |
| Sarcosine | 21 |
| **Alanine** | 145 |
| N-methylalanine | 4 |
| Beta-alanine | 64 |
| Alpha-amino-n-butyric acid | 21 |
| Alpha-aminoisobutyric acid | 0.4 |
| **Aspartic acid** | 2 |
| **Glutamic acid** | 2 |
| Iminodiacetic acid | 66 |
| 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 |

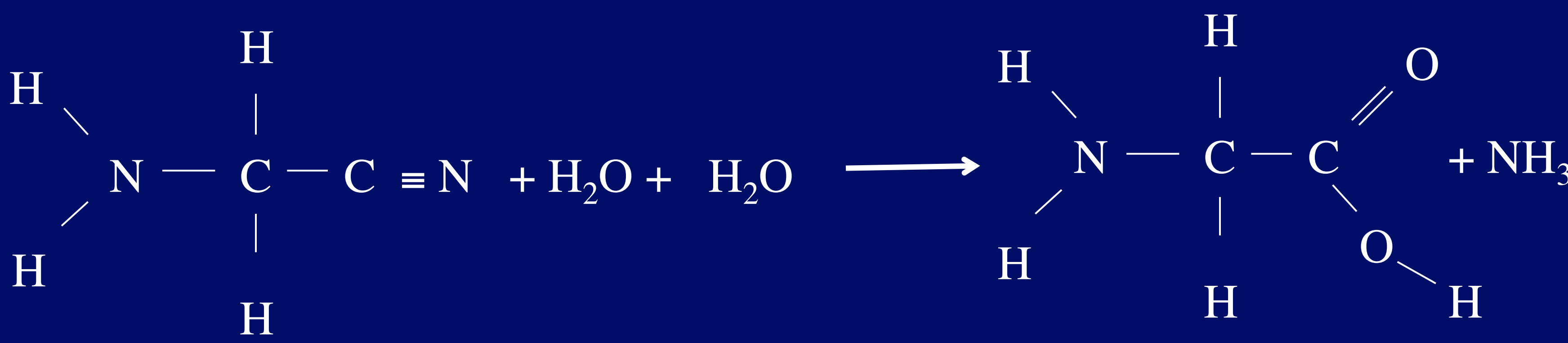
# How did Amino Acids form in Miller-Urey Experiment?

## Strecker Synthesis e.g. Glycine Synthesis

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

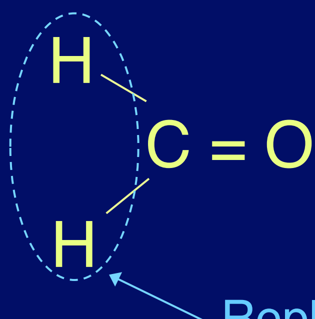
Reactive





glycine

$H_2CO$



form Aldehyde

Replace with more complex group
Get other aldehydes
They can form more complex amino acids

# Building Blocks of Nucleic Acids

Not formed in Miller-Urey, but some intermediates were

1. Ribose Sugar:

   $5\ H_2CO + Heat \longrightarrow H_{10}C_5O_5$

   [Clay Catalyst]

2. Bases

   a) Purines $5\ HCN \rightarrow H_5C_5N_5$ (Adenine)

   b) Pyrimidines

   $HC_3N$ + Urea $\longrightarrow H_5C_4N_3O$ (Cytosine)

   Cyanoacetaldehyde + Urea $\longrightarrow$ Uracil

3. Phosphate

Rock Erosion

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

Some recent progress: simulate a meteorite impact onto a mixture of clay and formamide ($HCONH_2$); all four bases produced

# Problems with Miller-Urey

$NH_3$, $CH_4$ would react to make $N_2$, $CO_2$

We now think that atmosphere was $N_2$, $CO_2$, $H_2O$

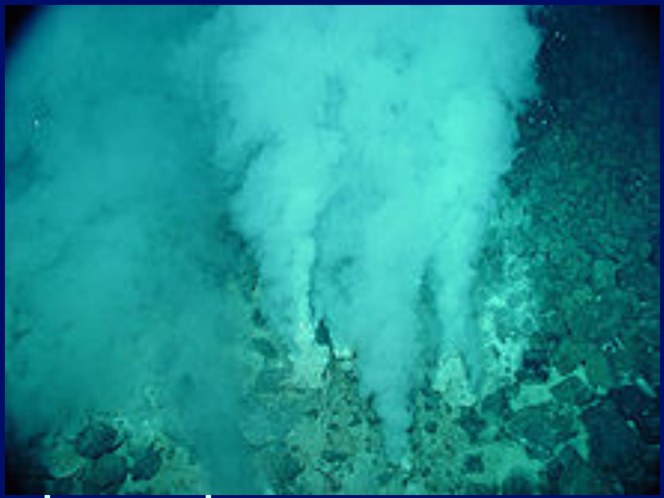
Try $N_2$, $CO_2$, $H_2O$ in Miller-Urey simulation

Get only 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

# 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

$H_2S \longrightarrow$ Bacteria $\rightarrow$ Clams, Tube Worms

Pre-biotic amino acid synthesis?

Further evolution to life? Ancient anaerobic microbes use similar chemical pathways to conditions found in alkaline vents, such as Lost City

# Alternative Delivery

2. 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 and some asteroids.

Evidence from similar molecules

(e.g. $C_2H_2$, $CH_4$, HNC, …)

Cratering record on moon, …

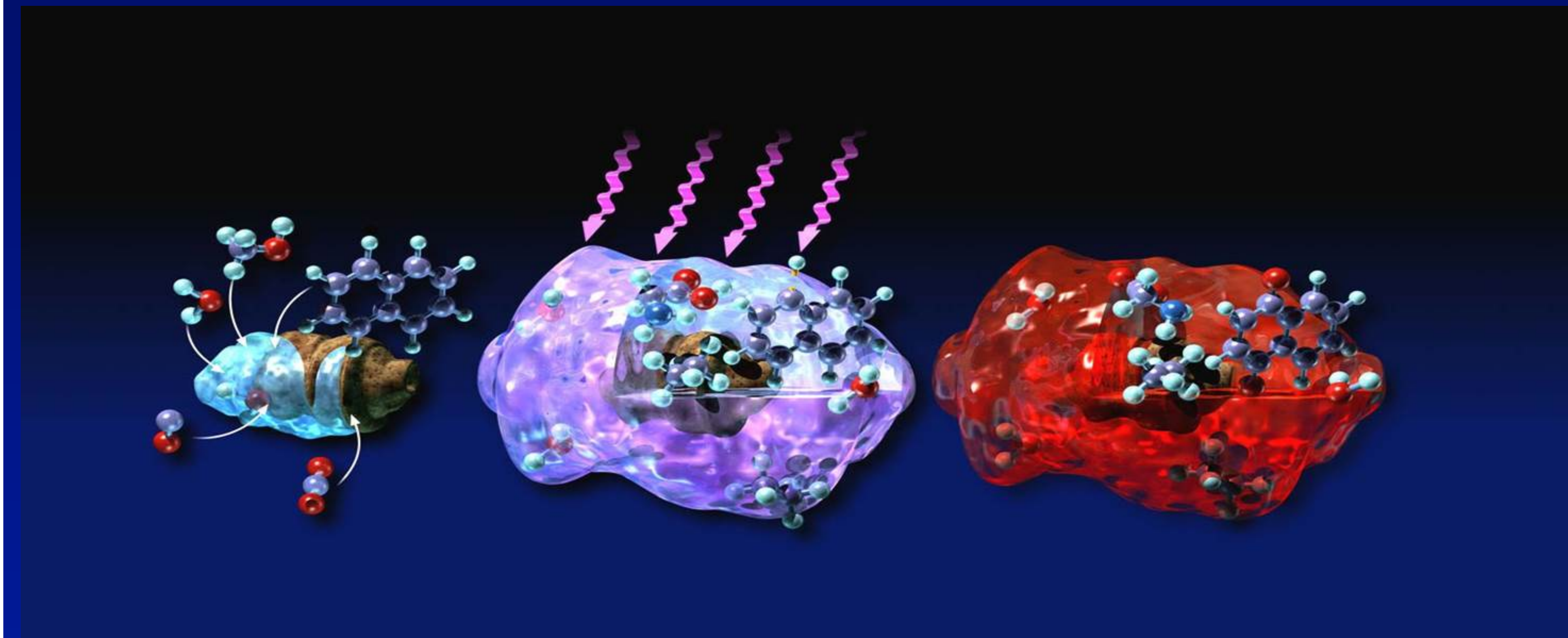
⇒ heavy bombardment early in history

Comets, asteroids, and their debris could have brought large amounts of “organic” matter to Earth

(and probably the oceans)

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

# Icy Dust as Source



Laboratory experiments show that ice mixtures exposed to ultraviolet radiation form amino acids

# Amino Acids in Meteorites

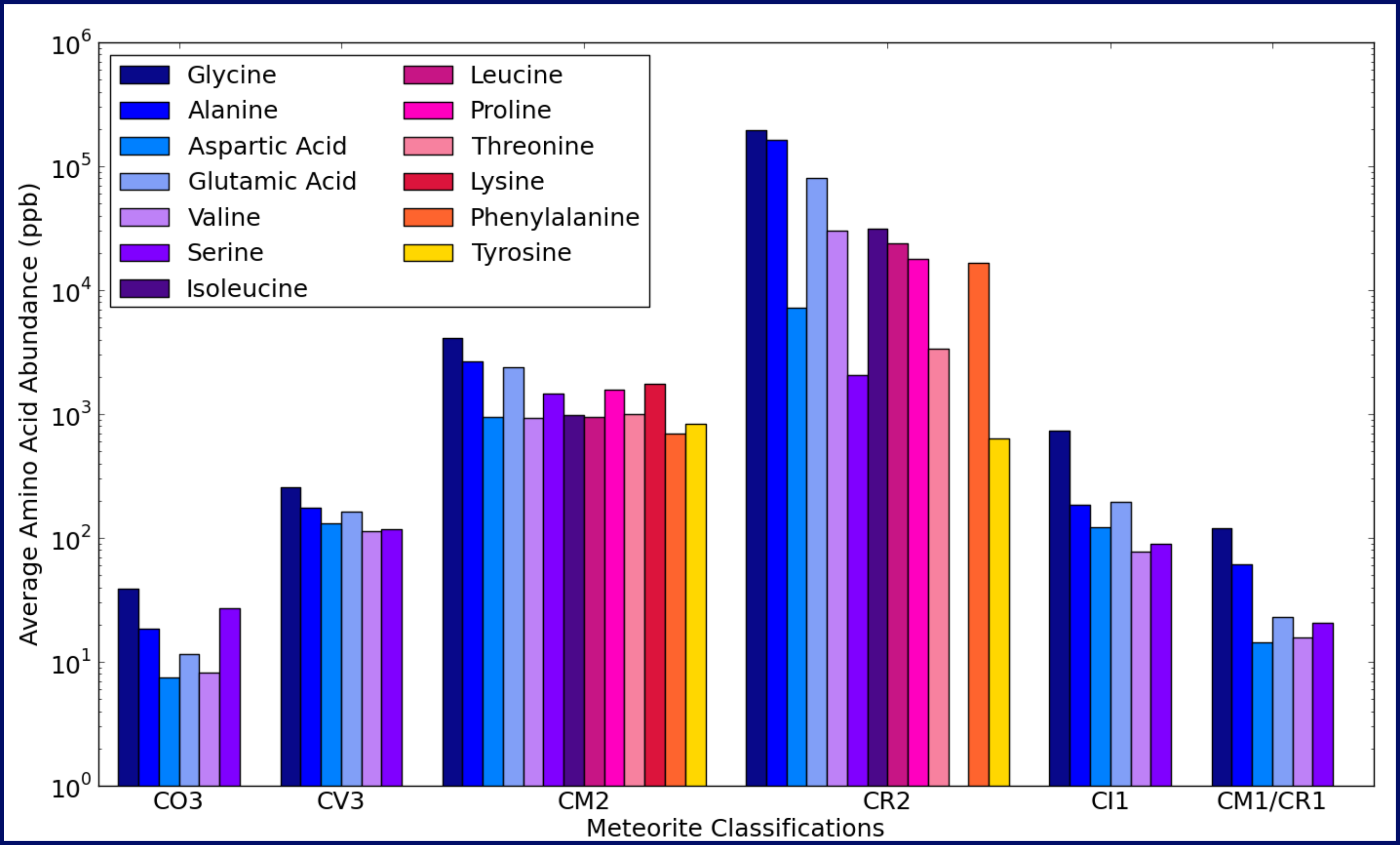
- Amino acids are found in some classes of meteorites (carbon-rich ones)
- Recent analysis of some carbon-rich meteorites found in Antarctica
  - Richest source of amino acids so far
  - Up to 250 parts per million
  - Very clearly extraterrestrial (not contamination)
    - Type of amino acids
    -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

# Amino Acids in Meteorites

Murchison meterorite

15 kinds of amino acids, some nucleic acid bases (building blocks of DNA) were found inside.

# Amino Acids in Meteorites




Cobb and Pudritz 2014

# Sources of Organic Molecules

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

Currently, Earth accretes ~ $3.2 \times 10^6$ kg $y^{-1}$ from interplanetary dust particles (IDP)

~ 10% organic carbon $\Rightarrow 3.2 \times 10^5$ kg $y^{-1}$

~ $10^3$ kg $y^{-1}$ comets

~ 10 kg $y^{-1}$ meteorites

~ $10^3 \times$ more at $4.5 \times 10^9$ yr ago (?)

(cratering record)

UV + reducing atmosphere $2 \times 10^{11}$ 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

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)

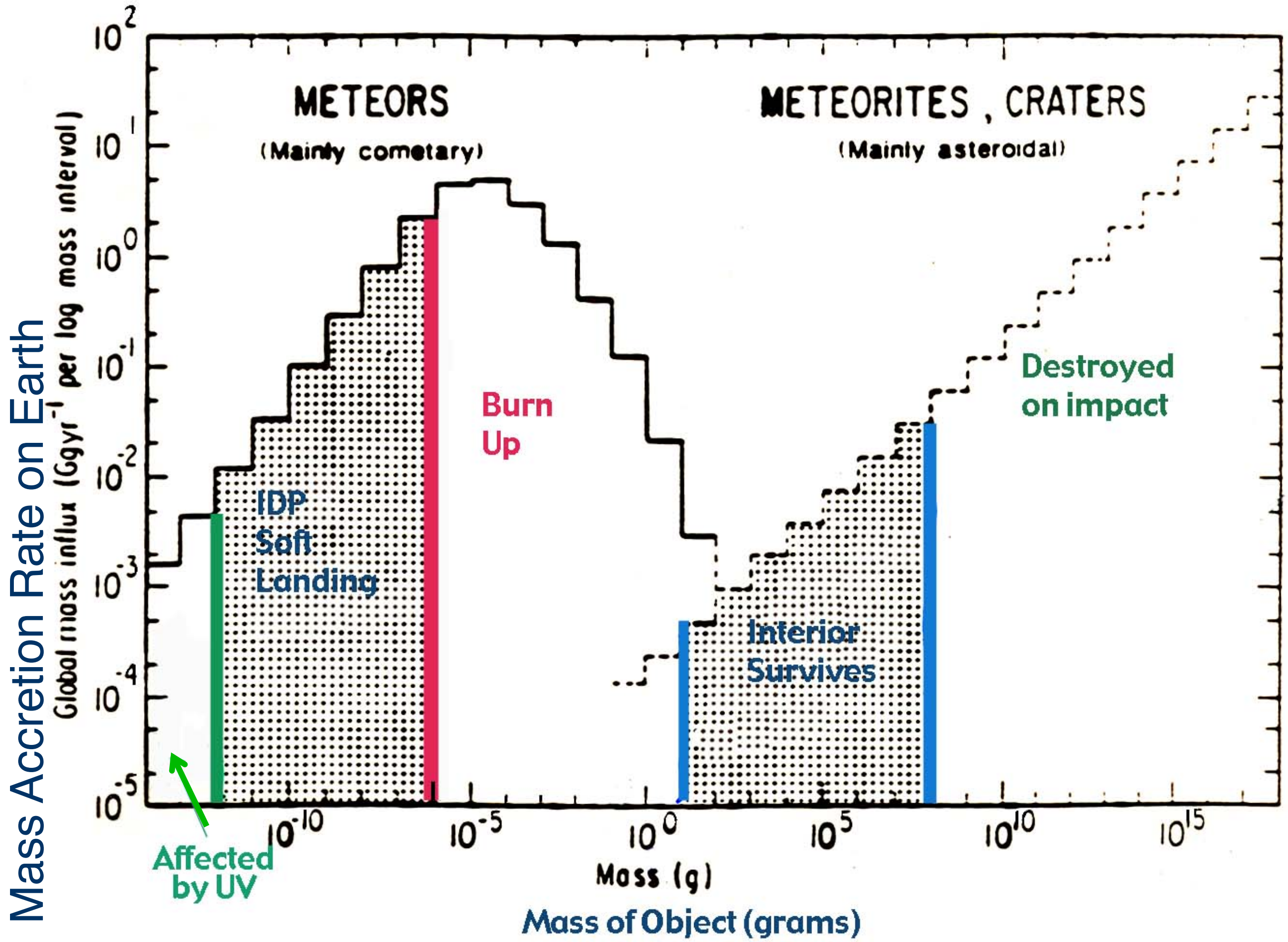


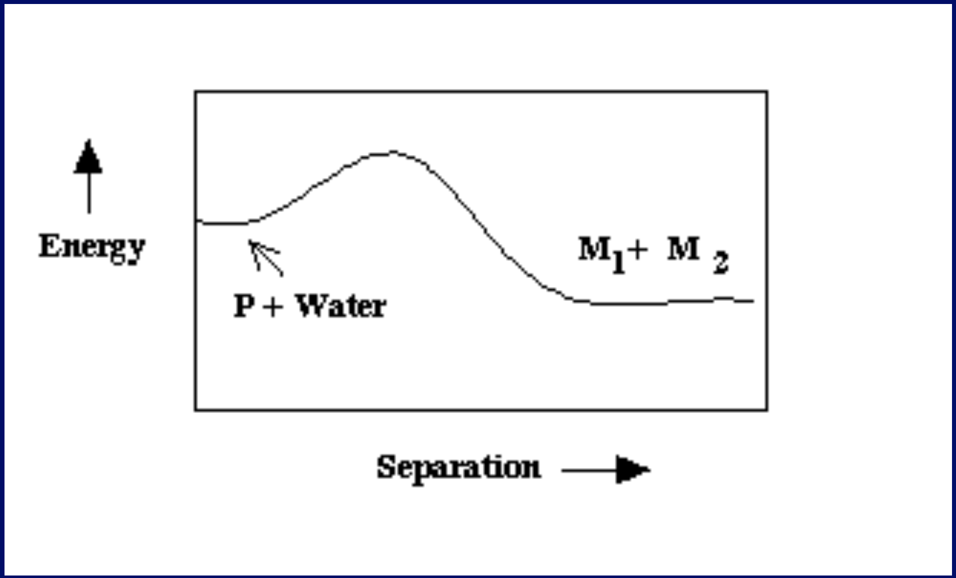

FIG. 1 Infall rate of meteoritic matter on Earth (adapted from ref. 5). Intervals where organic matter can survive passage through atmosphere are shaded. The curve on the right is based on the relation[5] $N = 0.54\ r^{-2.1}$ ($N$ = number of impacts per Myr, $r$ = radius in km), for an assumed density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

# Synthesis of Polymers

$M_1 + M_2 \longrightarrow P + H_2O$

$\longleftarrow$ more likely in liquid $H_2O$



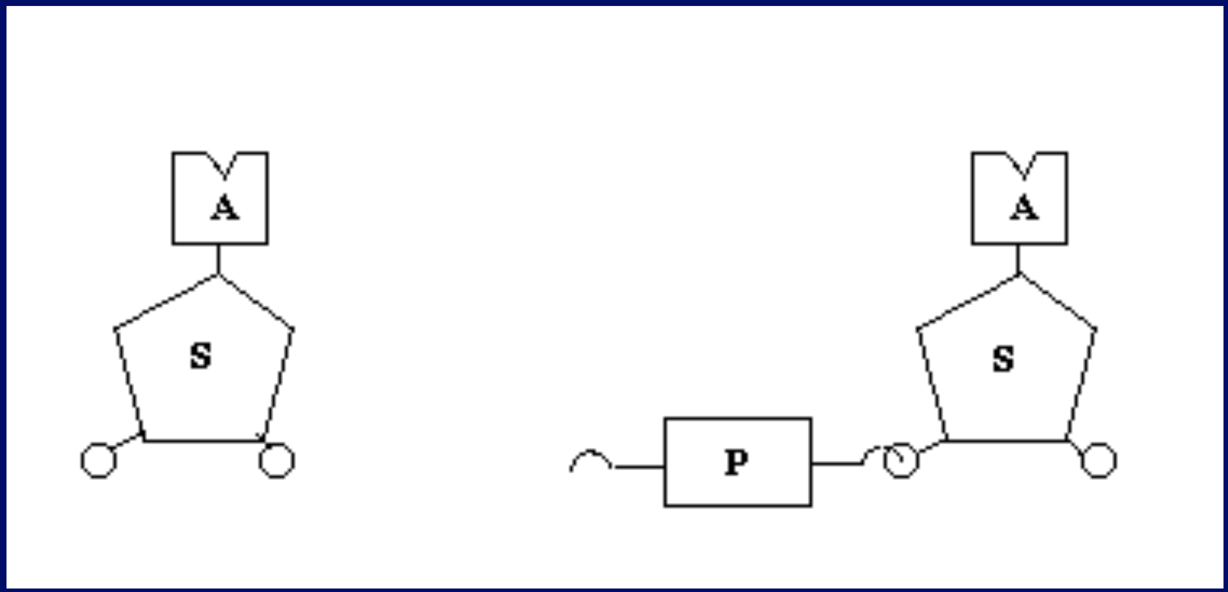

Solutions: Remove $H_2O$ (Drying, Heat)

Sydney Fox $\longrightarrow$ Proteinoids

Energy Releasing Reactions ($H_2NCN$ or $HC_3N$)

Catalysts: Clays

Problem is worse for Nucleic acids because more complex



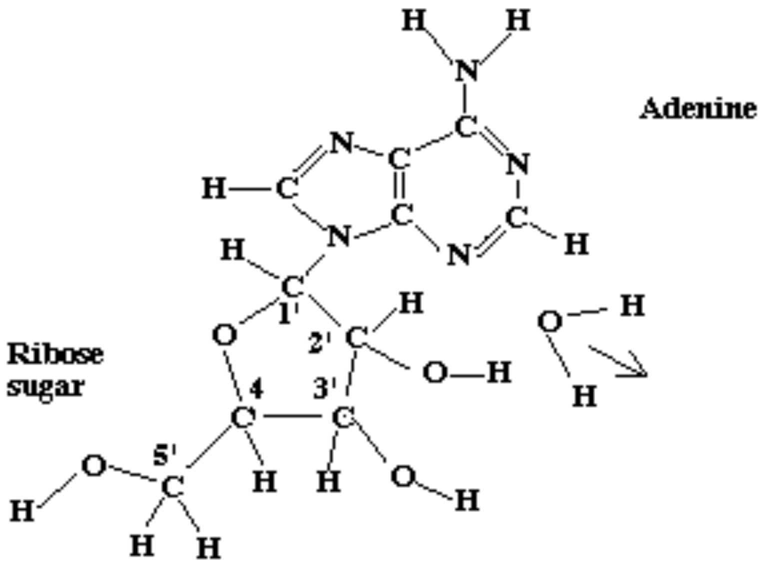

nucleoside

nucleotide

Monomers of nucleic acids

# Synthesis of Adenosine

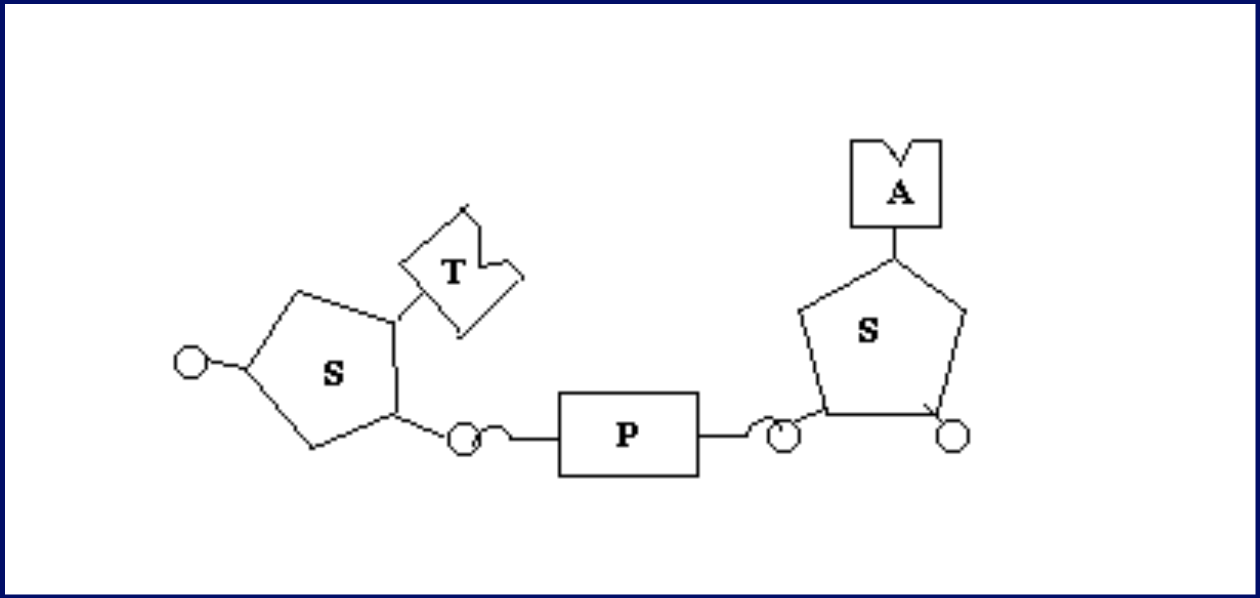
Base on 1' Carbon (Why?)




Adenine + ribose sugar → adenosine + $H_2O$

Also phosphates 3' & 5' carbons

Otherwise, you are likely to get Misalignment



# New Approach

- Progress from a group in England
  - Mix HCN, $H_2CO$, … and phosphate
  - Energy led to nucleotides without making sugars, bases. Different route.
  - Linkages not all correct
  - But exposure to ultraviolet destroyed incorrect ones.
  - Clay soils can catalyze polymerization into nucleic acids.

# 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 $\longrightarrow$ protein

Chosen from 20 in a particular order

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

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: $\left(\frac{1}{4}\right)^{10^3} \sim 10^{-600}$

# of trials: R. Shapiro computes

$N = 2.5 \times 10^{51}$ (surely an overestimate)

$n \ll \frac{1}{p}$ for simple 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

# Summary

- Reactions in atmosphere (Miller-Urey) or sea vents or delivery from space can provide some monomers
- Formation of monomers of proteins easier than for nucleic acids
- Making polymers easier for proteins
- New route for synthesis of nucleotides is promising
- Have to get selection started before polymers get too complex