



THE MOLECULAR HISTORY OF LIFE

FALL 2023



EARTHRISE

DECEMBER 24, 1968
APOLLO 8 MISSION
ASTRONAUT WILLIAM ANDERS



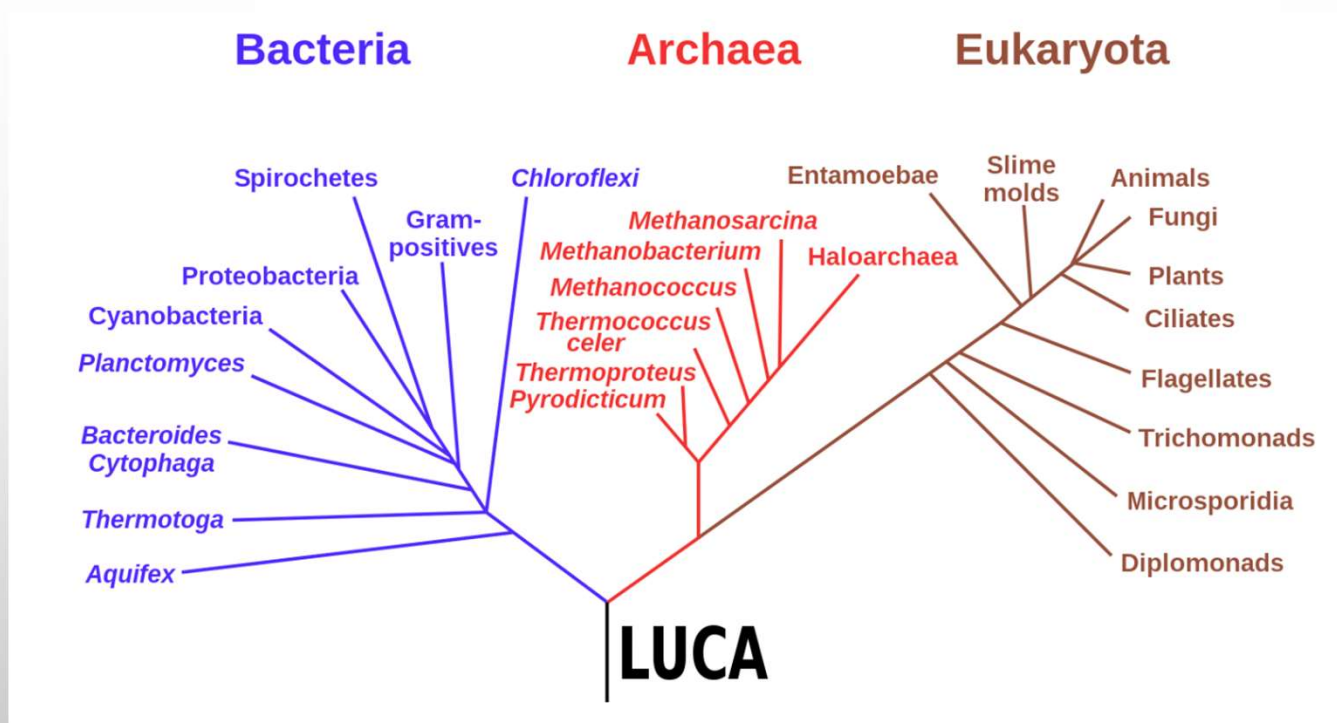


BLUE MARBLE

- APOLLO 17 MISSION
- DECEMBER 7, 1972
- DISTANCE OF 28,000 MILES







LUCA's Beginnings



HOW TO APPROACH THE STUDY OF LIFE BEGINNINGS

- **TOP-DOWN:**

- WHAT WE KNOW FOR SURE IS WHAT FORMS LIFE TAKES IN THE PRESENT
- “THE PAST IS NEVER DEAD. IT’S NOT EVEN PAST” (WILLIAM FAULKNER; REQUIEM FOR A NUN)
- THE HISTORY IMBEDDED IN PRESENT DAY LIFE (MOLECULAR EVOLUTION AND PHYLOGENY)
- FOSSIL EVIDENCE

- **BOTTOM-UP:**


- WHAT WE KNOW ABOUT GALACTIC EVOLUTION AND EARTH FORMATION
 - EARLY EARTH
- 






LIVING SYSTEMS ARE

- **HIGHLY ORGANIZED**
 - BUT... ENTER THERMODYNAMICS
 - SYSTEMS TEND TO **DIS**-ORGANIZE → INCREASE ENTROPY
 - TO REMAIN ORGANIZED, ENERGY MUST BE EXPENDED
 - THIS IS THE CONCEPT OF **METABOLISM**: A BIOLOGICAL SERIES OF MECHANISMS THAT ENSURE THAT LIVING SYSTEMS REMAIN ORGANIZED

 - **IMBEDDED IN (BUT SEPARATE FROM) AN ENVIRONMENT**
 - NEED TO SENSE THEIR ENVIRONMENT
 - ADAPT
- 




LIVING SYSTEMS (CONT.)

- **INFORMATION SYSTEM** → A SET OF “RULES AND REGULATIONS” FOR BOTH CONSTRUCTING AND MAINTAINING THE ORGANIZED STRUCTURE
 - **MEANS OF REPRODUCTION** → A MECHANISM FOR STORING THE INFORMATION SYSTEM ABOVE TO PASS ON THE SET OF INSTRUCTIONS TO THE PROGENY
 - **VARIATION** BUILT IN THE FUNCTIONS ABOVE → REPRODUCTION WITH VARIATION
 - **LIVING SYSTEMS EVOLVE**
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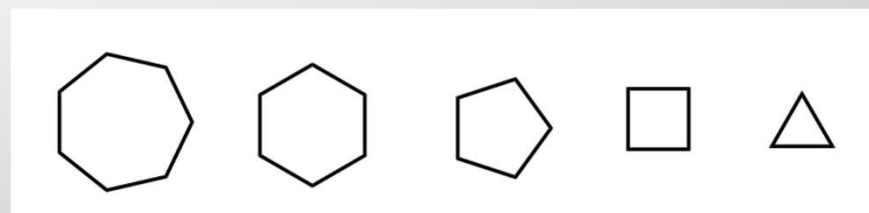
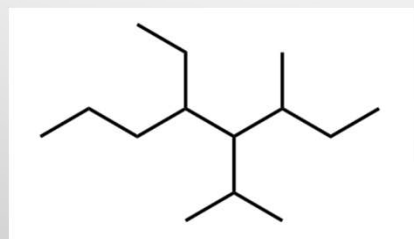
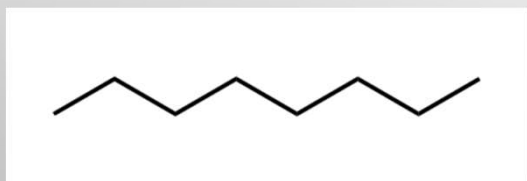


THE ESSENTIALS OF LIFE

- HIGH LEVELS OF ORGANIZATION
 - A SOURCE OF ENERGY TO COUNTERACT ENTROPY
 - CLEAR BOUNDARIES BETWEEN THE LIVING ENTITY AND THE ENVIRONMENT
 - INFORMATION SYSTEMS
 - REPRODUCTION AND BUILT-IN VARIATION
 - EVOLUTION
- 

ESSENTIAL #1: HIGH-ORDER ORGANIZATION

- CARBON-BASED CHEMISTRIES
- APPROXIMATELY 45-50% OF ALL BIOMASS IS CARBON
- CARBON IS THE 15TH MOST ABUNDANT ELEMENT IN EARTH'S CRUST AND THE 4TH MOST ABUNDANT ELEMENT IN THE UNIVERSE BY MASS
- IT CAN FORM STABLE BONDS WITH ITSELF AND OTHER ELEMENTS, ADOPTING CHAIN CONFIGURATIONS, BRANCHED CHAINS AND RING STRUCTURES → EXTRAORDINARY VERSATILITY




- THERE ARE OVER 10,000,000 COMPOUNDS DESCRIBED SO FAR, AND MANY MORE THAT ARE THEORETICALLY POSSIBLE

HIGHER ORDER STRUCTURES → MACROMOLECULES

- THESE CARBON-CONTAINING MOLECULES CAN IN TURN LINK TOGETHER TO FORM MACROMOLECULES → ENORMOUS INCREASE IN POSSIBLE COMPLEXITY
- IN BIOLOGICAL SYSTEMS: CARBOHYDRATES, PROTEINS AND NUCLEIC ACIDS
- CARBOHYDRATES: SIMPLE SUGARS CAN LINK TOGETHER TO FORM HIGHER-ORDER CARBOHYDRATES (E.G. STARCH, CELLULOSE)
- PROTEINS: CHAINS OF AMINO ACIDS (20 DIFFERENT AMINO ACIDS)
- NUCLEIC ACIDS (RNA AND DNA): CHAINS OF NUCLEOTIDES (4 DIFFERENT NUCLEOTIDES)



AND FOR THE SCIENCE FICTION FANS AMONG US

- CAN LIFE BE SILICON-BASED?
 - WHY IS SILICON ATTRACTIVE?
 - MORE ABUNDANT THAN CARBON: THE SECOND MOST ABUNDANT ELEMENT IN THE EARTH'S CRUST, AFTER OXYGEN
 - 2 (FAIRLY) SCIENTIFIC CRITERIA:
 - CAN SILICON PROVIDE CHEMICAL DIVERSITY AND COMPLEXITY?
 - CAN SILICON PROVIDE STABILITY WHILE ALLOWING FOR CHEMICAL REACTIVITY?
- 

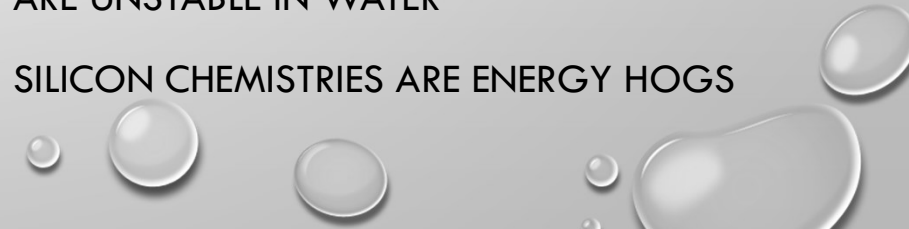


- **CARBON**

- CAN CONCATENATE
- CAN BIND HYDROGEN, OXYGEN, NITROGEN, SULFUR, AND INDIRECTLY: PHOSPHORUS, AND METALS SUCH AS IRON, MAGNESIUM, AND ZINC → THIS PROVIDES EXPANDED POSSIBILITIES FOR BIOCHEMICAL REACTIONS
- CARBON CHEMISTRIES ARE WATER FRIENDLY
- CARBON CHEMISTRIES ARE LESS EXPENSIVE ENERGY-WISE



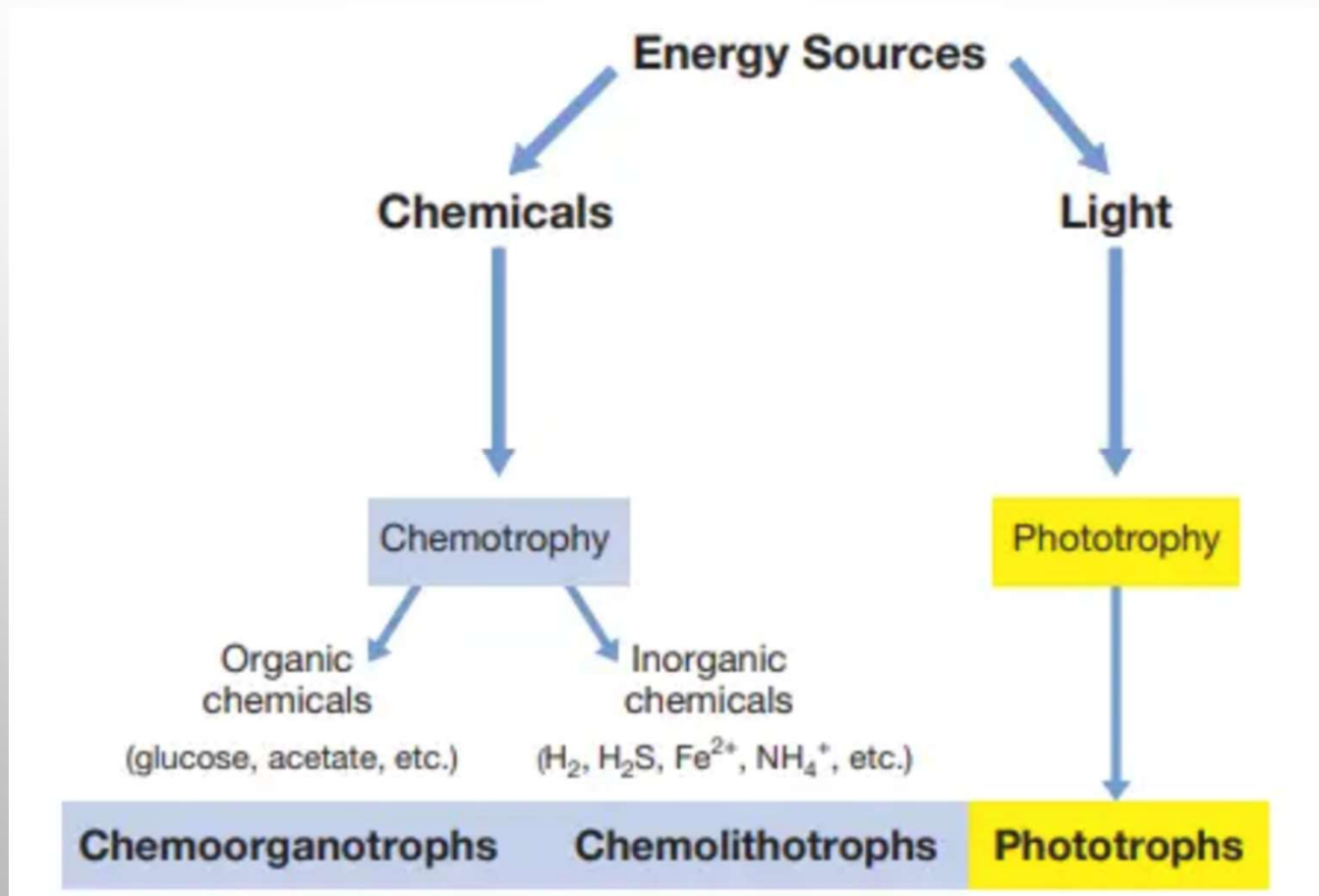
- **SILICON**

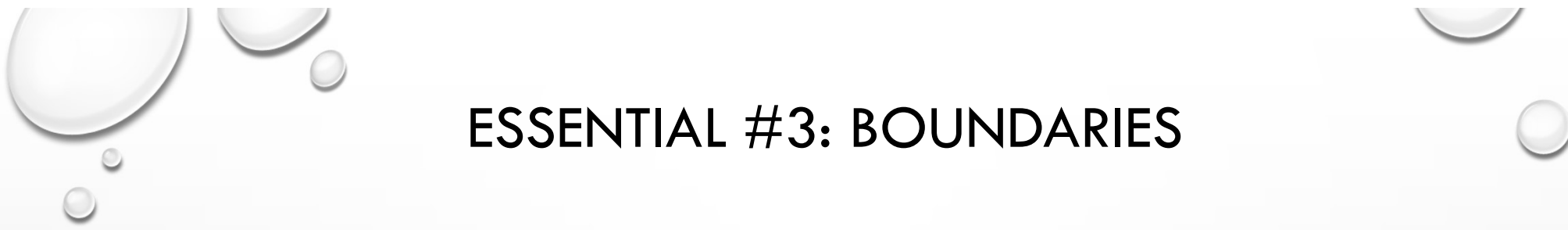
- CAN CONCATENATE
 - VERY HIGH AFFINITY FOR OXYGEN. CAN BIND VERY FEW OTHER ELEMENTS. SILICON ATOMS ARE MUCH BIGGER THAN CARBON ATOMS AND THAT MAKES IT MORE DIFFICULT TO BIND → MUCH LESS POTENTIAL BIOCHEMICAL ACTIVITIES
 - MOST POTENTIAL REACTIONS INVOLVING SILICON ARE UNSTABLE IN WATER
 - SILICON CHEMISTRIES ARE ENERGY HOGS
- 

THE TAKE-HOME


- DUE TO THE VERY HIGH AFFINITY OF SILICON FOR OXYGEN THE MOST COMMON STABLE POLYMERS OF SILICON ARE BUILT FROM A MESHWORK OF SI-O CHAINS INSTEAD OF LINEAR SI-SI POLYMERS
- THE EXCESS COSMIC ABUNDANCE OF ELEMENTAL OXYGEN ENSURES THAT THE GREAT MAJORITY OF THE AVAILABLE SILICON IS ALMOST EXCLUSIVELY, AND STABLY, BONDED TO OXYGEN (IN THE FORM OF UNREACTIVE SILICA; THINK QUARTZ, GLASS)
- THEREFORE, WHILE “CARBON CHEMISTRY IS THE CHEMISTRY OF LIFE, SILICON CHEMISTRY IS THE CHEMISTRY OF ROCKS”
- IN THE WORDS OF MIT SCIENTISTS PETKOVSKI ET AL., PUBLISHED IN 2020: **THE SUBSTANTIAL ENERGY NEEDED TO TURN ROCKS INTO LIFE, COMPARED TO THAT NEEDED TO TURN CO₂ INTO LIFE, ARGUES AGAINST SILICON**

ESSENTIAL #2: A SOURCE OF ENERGY



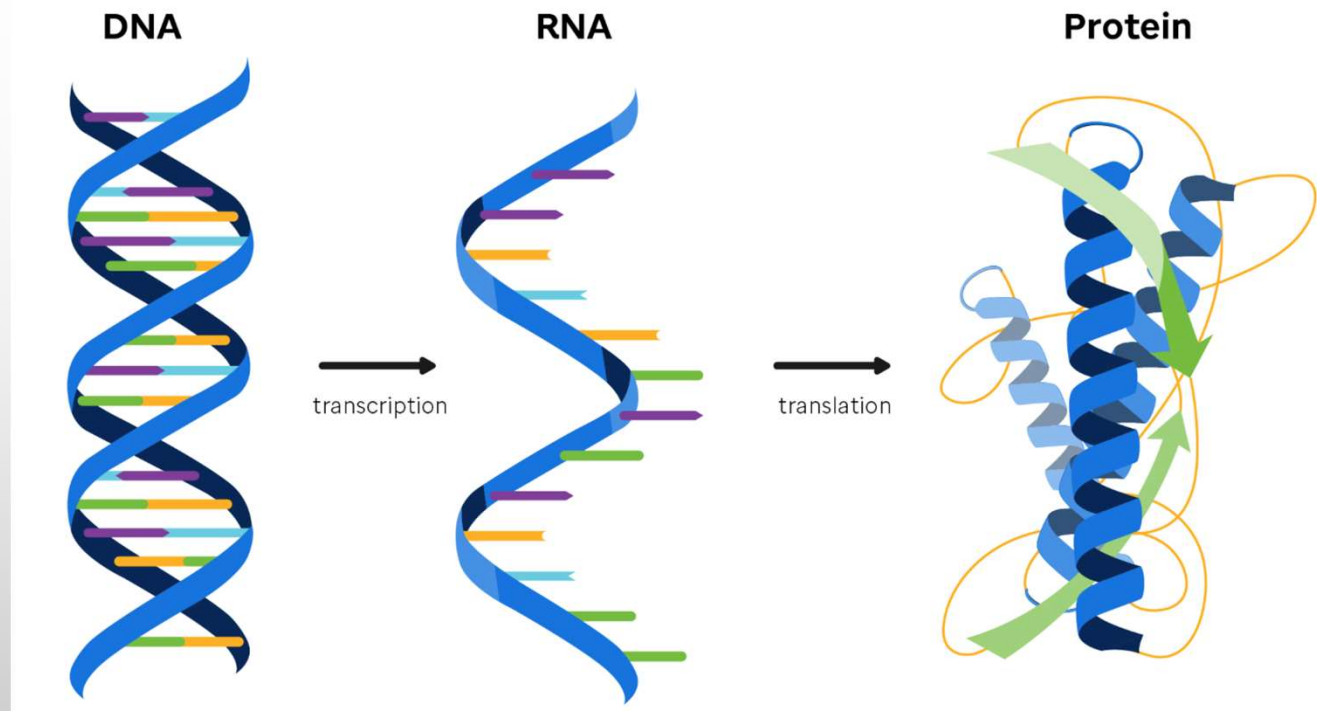


ESSENTIAL #3: BOUNDARIES

- ALL MODERN CELLS ARE BOUNDED BY MEMBRANES COMPOSED OF PHOSPHOLIPIDS (COMPOUNDS OF LIPIDS AND PHOSPHATE GROUPS)
 - ORIGIN OF LIFE SCENARIOS MUST THEN ACCOUNT FOR SELF-ORGANIZING MEMBRANE COMPONENTS
- 


ESSENTIAL #4: INFORMATION SYSTEM

- PROTEINS ARE THE BUILDING BLOCKS OF PRESENT BIOLOGICAL SYSTEMS
- MODERN CELLS ENCODE INSTRUCTIONS IN DNA (AND RNA)
- INSTRUCTIONS COME AS A “READING” EQUIVALENCE BETWEEN THE NUCLEIC ACIDS SEQUENCE AND THE AMINO ACIDS IN THE PROTEINS THEY ENCODE
- THIS IS BIOLOGY’S CENTRAL DOGMA



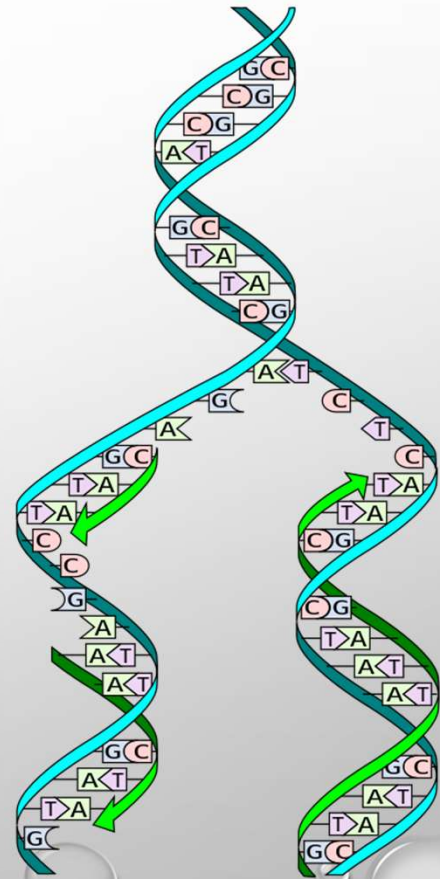


HOWEVER...

- THIS COMPLEX SYSTEM CAN BE SIMPLIFIED
 - ORIGIN OF LIFE SCENARIOS NEED ONLY CONSIDER:
 - 1) A SYSTEM THAT CAN ENCODE INFORMATION, AND
 - 2) A SYSTEM THAT CAN CARRY OUT METABOLISM
- 

ESSENTIAL #5 AND #6: REPRODUCTION AND EVOLUTION

- REPLICATION OF THE INFORMATION SYSTEM
- ORIGIN OF LIFE SCENARIOS HAVE TO ACCOUNT FOR AN INFORMATION SYSTEM THAT IS ALSO CAPABLE OF MAKING FAITHFUL COPIES OF ITSELF
- THE SYSTEM CANNOT BE COMPLETELY ERROR-FREE



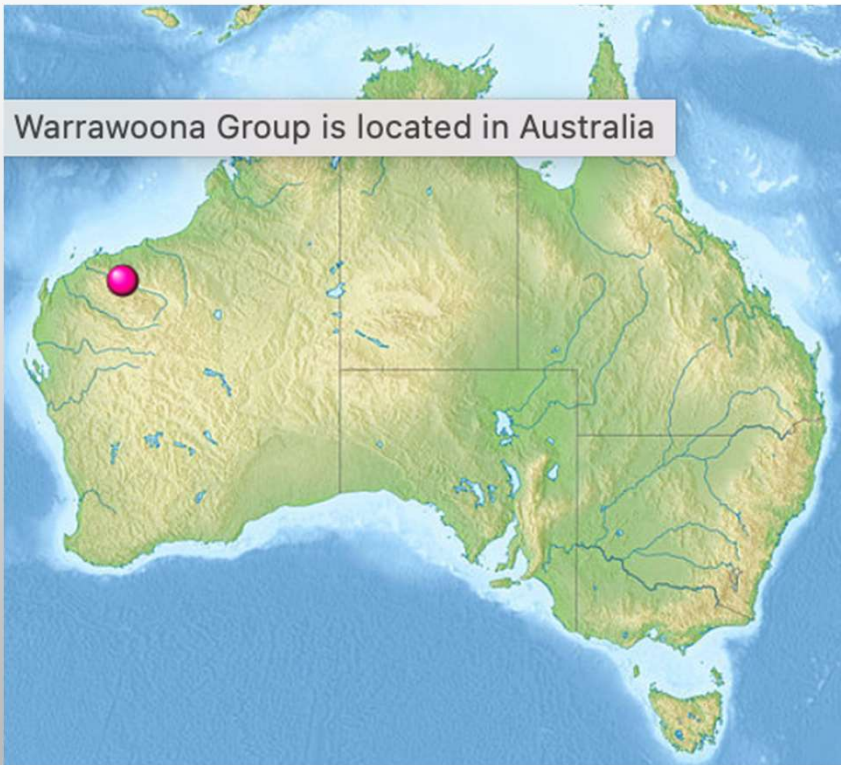


- WHEN DID LIFE START?

- FOSSIL EVIDENCE

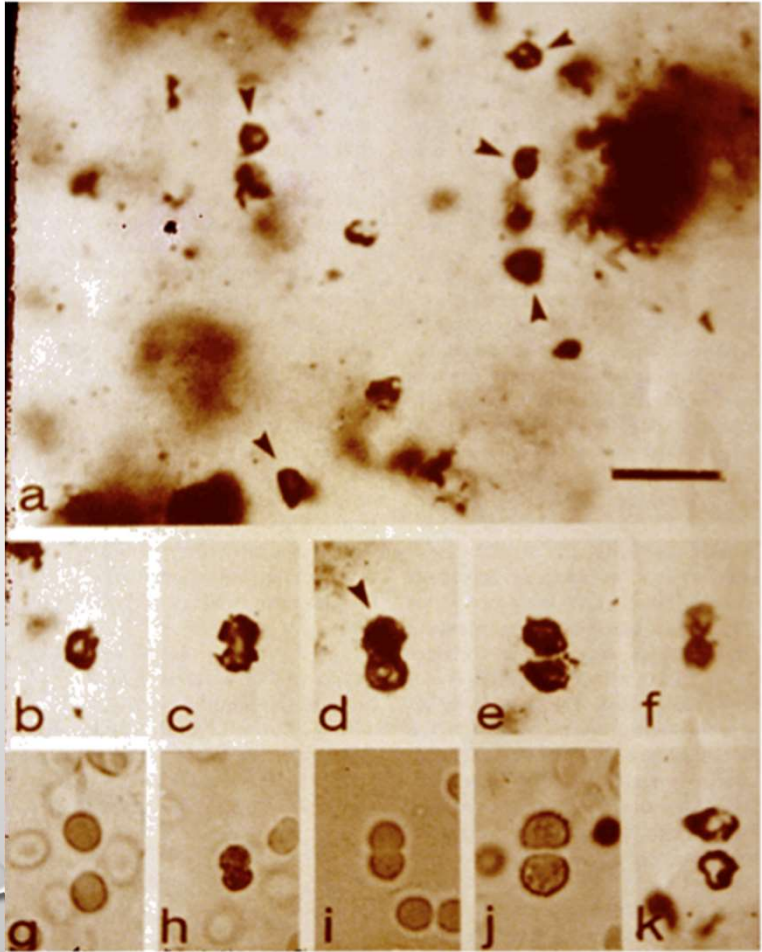
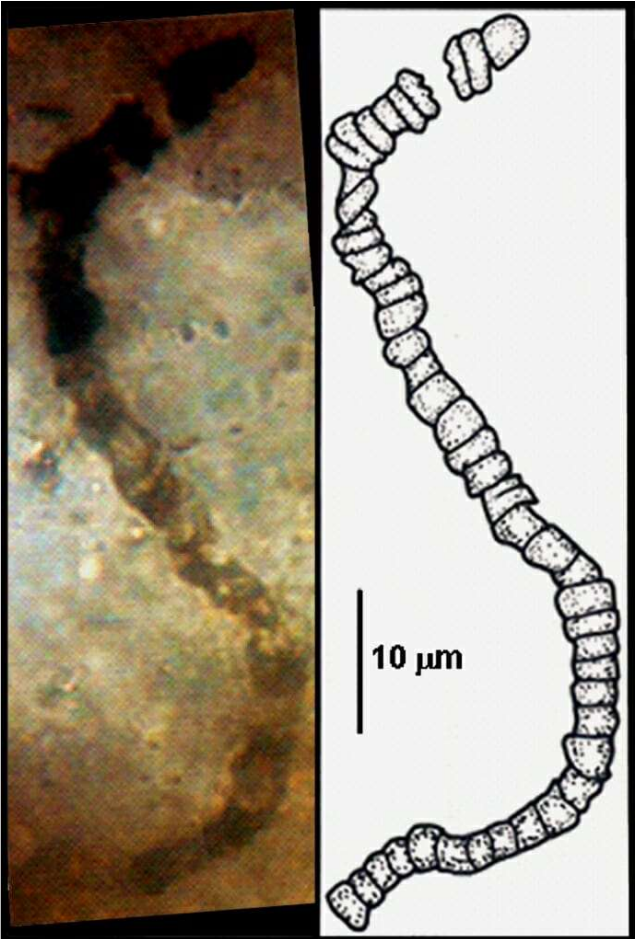


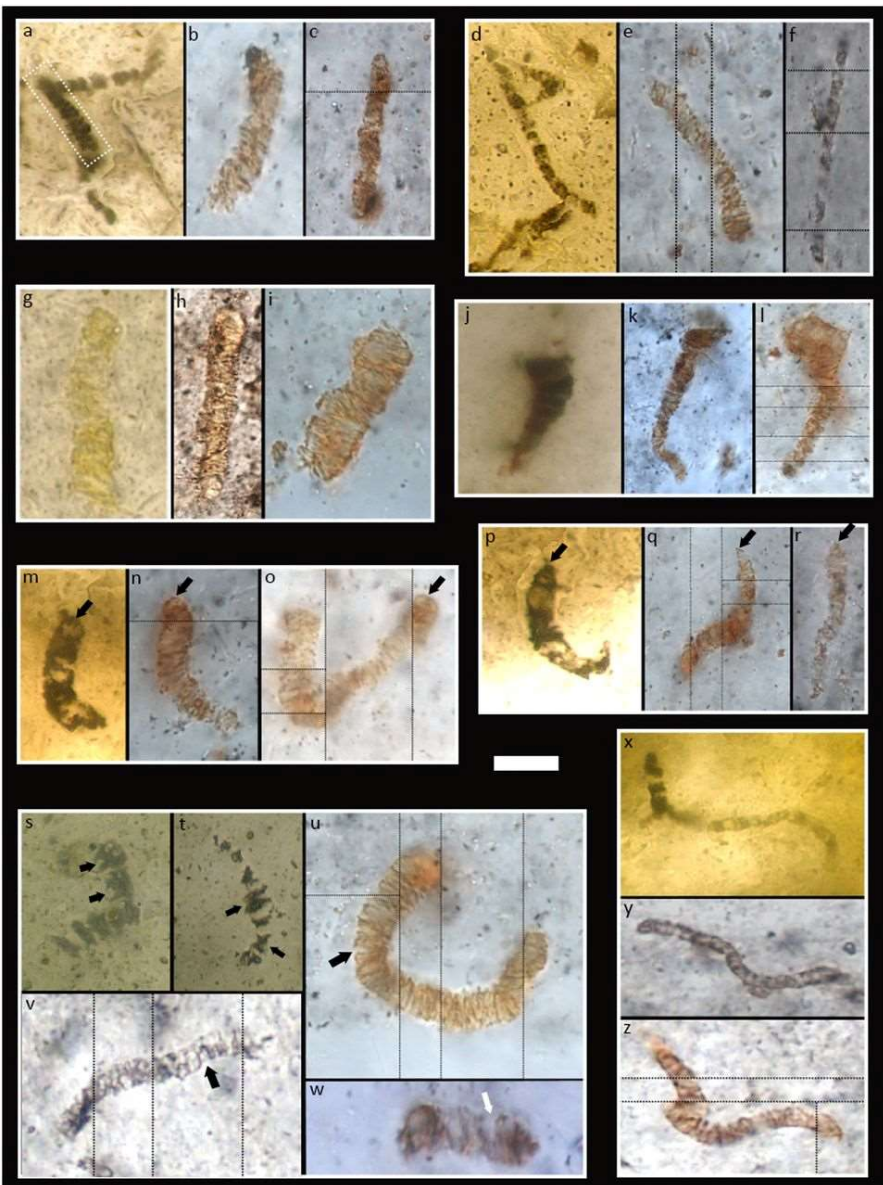
EARLIEST FOSSILS (MICROFOSSILS)



- COLLECTED IN 1999
- EARLIEST SHORELINE DEPOSITS IN WESTERN AUSTRALIA
- ~3.5 GA
- KEPT AT THE NATURAL HISTORY MUSEUM, LONDON
- RE-ANALYZED IN 2017
- RESEARCHERS FROM UCLA AND UW MADISON

EARLIEST FOSSILS





Startling conclusions

The microfossils analyzed belong to at least seven well defined microbiological taxa, including Bacteria and Archaea

Both methanogens (methane-producing organisms) and methanotrophs (methane-consuming organisms)

In an early Earth, with methane being a large component of its atmosphere, by 3.5 Ga there were well-established microbial communities involved in methane cycling

AND EVEN EARLIER: STROMATOLITES

EARLY MICROBIAL MATS MACROFOSSILS (WESTERN AUSTRALIA)~3.8 GA



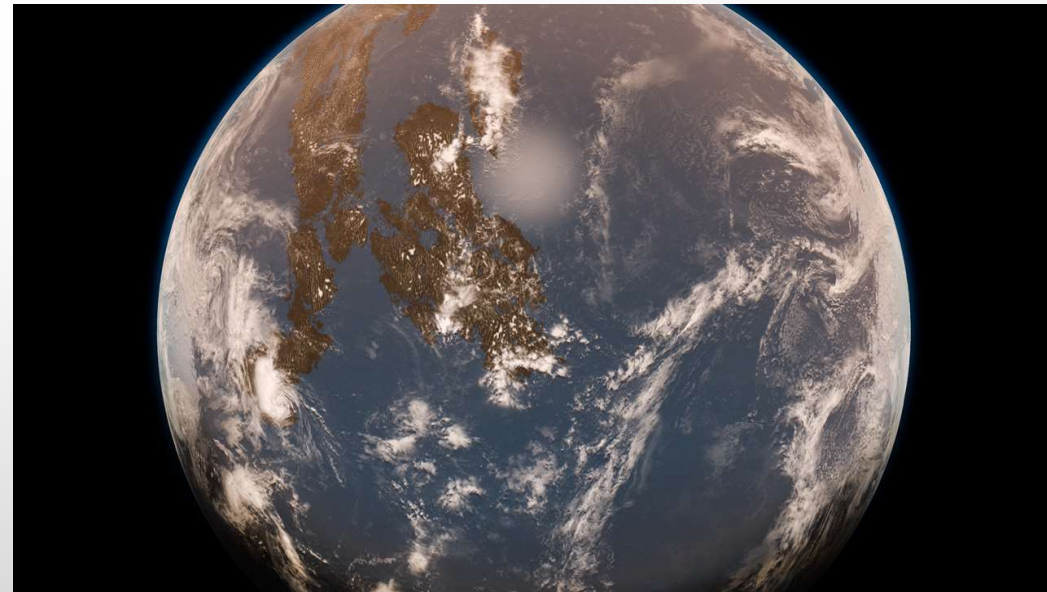
Present Day Stromatolites
Shark Bay, Australia



Fossilized stromatolite

A (VERY) BRIEF HISTORY OF PLANET EARTH

- EARTH FORMED CA. 4.5 BILLION YEARS AGO (GA)
- ACCRETION FROM THE SOLAR NEBULA (ROTATING CLOUD OF INTERSTELLAR DUST AND GASES)
- OLDEST ROCKS ARE 4.4 GA
- EARTH GOT ITS WATER FROM THE BOMBARDMENT OF WATER-RICH ASTEROIDS SHORTLY AFTER IT FORMED



OUR PLANETARY COMPANIONS

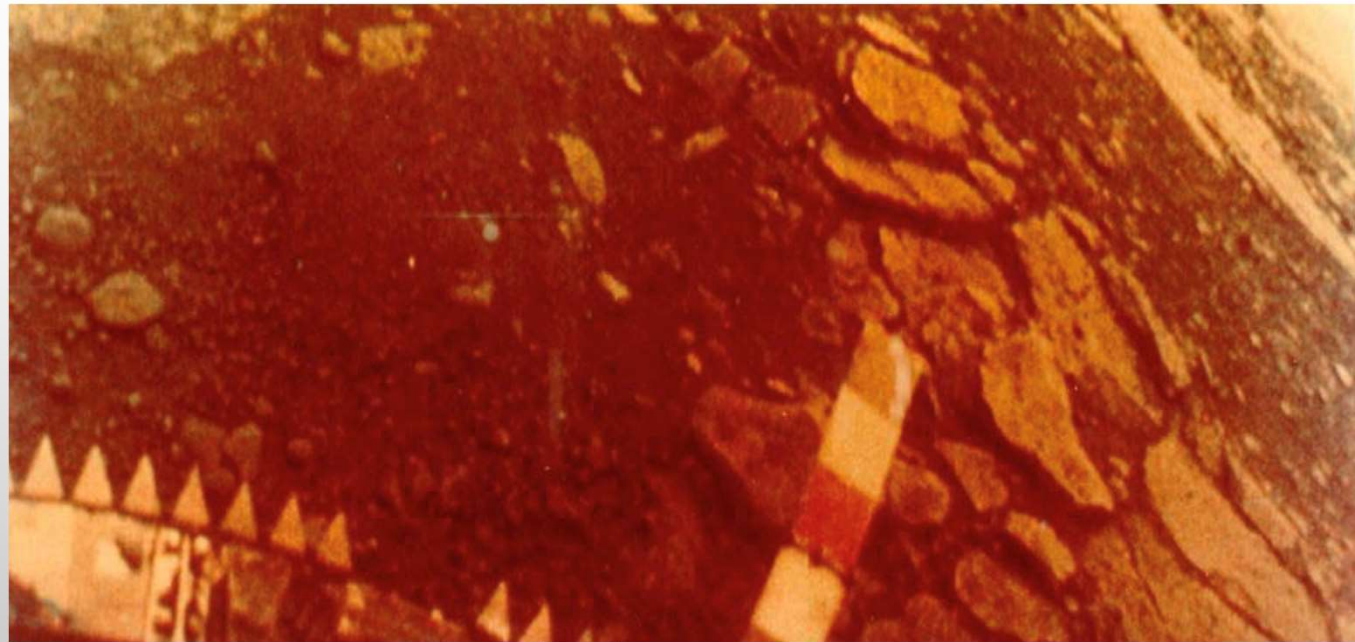


- ALL THREE PLANETS HAD (AT SOME POINT) LARGE AMOUNTS OF WATER FROM DE-GASSING OF HYDROUS MINERALS FROM MANTLE AND FROM COMET IMPACTS

WHAT HAPPENED TO VENUS?

- THE ATMOSPHERE IS ENORMOUSLY DENSE WITH CO₂ → GREENHOUSE EFFECT INCREASED THE SURFACE TEMPERATURE ON VENUS TO >450 °F
- LIQUID WATER EVAPORATED
- THEREFORE, THERE WAS NO LIQUID WATER PRECIPITATION TO REMOVE CO₂ FROM THE ATMOSPHERE
- VENUS REMAINED A VERY HOT PLACE WITH A VERY DENSE ATMOSPHERE OF MOSTLY CO₂

Venus surface from Soviet Venera lander



WHAT HAPPENED TO MARS?

Surface Mars

- IN THE FIRST 500 MA, IT HAD ABUNDANT WATER (RIVERS AND OCEANS)
- THEN THE LIQUID IRON CORE SOLIDIFIED DUE TO COOLING
- THE MAGNETIC FIELD DISAPPEARED → COULD NOT HOLD ON TO ITS ATMOSPHERE
- THE IMPACT OF SOLAR WIND WOULD HAVE BLASTED THE WATER OUT OF THE SURFACE
- MARS HAS A VERY THIN ATMOSPHERE (1/100TH EARTH'S), MOSTLY CO₂
- NO OZONE



WHAT HAPPENED TO EARTH?

- EARTH WAS STRUCK IN A GLANCING IMPACT BY A MARS-SIZE METEOR
- THE RUBBLE THROWN INTO SPACE FORMED THE MOON
- THIS IMPACT EXPLAINS WHY EARTH SPINS SO FAST (EARTH SPINS ONCE A DAY, VENUS ONLY SPINS ONCE EVERY 244 DAYS)
- THIS HELPS STABILIZE CLIMATE EXTREMES
- HOW DID WE ESCAPE THE “VENUS TRAP”?
- THE MOON-FORMING IMPACT BLEW AWAY THE CO₂-RICH ORIGINAL ATMOSPHERE
- NOT AS MUCH CO₂ AS VENUS → NO HUGE GREENHOUSE EFFECT
- LIQUID WATER RAIN COULD WASH ATMOSPHERIC CO₂ INTO THE OCEANS IN THE FORM OF CARBONATE ROCKS

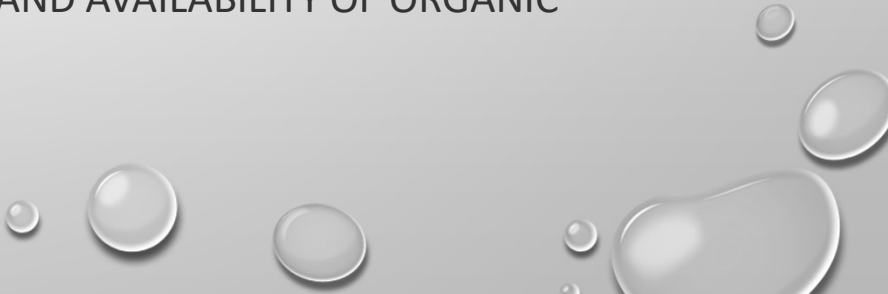
ANCIENT EARTH WAS A WATER WORLD

DONG ET AL. (HARVARD), 2021

- PRESENTLY, WATER COVERS CA. 70% OF EARTH'S SURFACE
- TODAY'S MANTLE SEQUESTERS A SIMILAR AMOUNT IN ITS MINERAL STRUCTURES
- EARLY IN EARTH'S HISTORY THE MANTLE WAS FOUR TIMES WARMER AND WOULD NOT HAVE BEEN ABLE TO HOLD THAT MUCH WATER
- THEREFORE, THE WATER MUST HAVE BEEN ON THE SURFACE
- NEW DATA SUGGESTS THAT CA. 4 GA EARTH'S OCEANS HELD ABOUT TWICE AS MUCH WATER (THIS WOULD HAVE SUBMERGED THE CONTINENTS TO MT. EVEREST!)
- WATER WOULD HAVE PENETRATED AND WEAKENED THE CRUST, CREATING SUBDUCTION ZONES WHERE ONE SLAB OF CRUST SLIPPED BELOW ANOTHER → WELCOME TO **PLATE TECTONICS!**
- SCIENTISTS BELIEVE THAT PLATE TECTONICS IS ESSENTIAL FOR LIFE TO DEVELOP. THE REPEATED PRODUCTION AND DESTRUCTION OF CRUST BY PLATE TECTONICS BOTH RELEASES CARBON DIOXIDE TO THE ATMOSPHERE AND REMOVES IT, HELPING KEEP TEMPERATURES ON EARTH SIMILAR OVER BILLIONS OF YEARS.
- THIS NEW SCENARIO FOR EARLY EARTH HAS IMPLICATIONS FOR HOW WE THINK OF LIFE'S BEGINNING



EARLY EARTH'S ATMOSPHERE

- FOR DECADES, SCIENTISTS BELIEVED THAT THE ATMOSPHERE OF EARLY EARTH WAS HIGHLY REDUCED, MEANING THAT OXYGEN WAS GREATLY LIMITED
 - OXYGEN-POOR CONDITIONS WOULD HAVE RESULTED IN AN ATMOSPHERE FILLED WITH METHANE, CARBON MONOXIDE, HYDROGEN SULFIDE, AND AMMONIA
 - RECENT RESEARCH FROM SCIENTISTS AT RPI SUGGESTS THAT EARLY ATMOSPHERE WAS DOMINATED BY THE MORE OXYGEN-RICH COMPOUNDS FOUND WITHIN OUR CURRENT ATMOSPHERE — INCLUDING WATER, CARBON DIOXIDE, AND SULFUR DIOXIDE
 - THIS NEW SCENARIO GREATLY INCREASES THE KIND OF ORGANIC MOLECULES THAT CAN RESULT FROM ABIOTIC SYNTHESIS, INCREASING THE RICHNESS AND AVAILABILITY OF ORGANIC MOLECULES TO JUMPSTART LIFE ON EARTH
- 

ORGANIC COMPOUNDS EVERYWHERE...

- IN LABORATORY SIMULATIONS OF THE SOLAR NEBULA (THE CLOUD OF GAS AND DUST FROM WHICH THE SUN AND THE PLANETS FORMED) IRRADIATED WITH HIGH ENERGY ULTRAVIOLET RADIATION, “A SURPRISINGLY RICH MIXTURE OF ORGANICS IS MADE” (RESEARCHERS FROM U CHICAGO, FROM 2012 ON)
- THESE INCLUDE MOLECULES OF BIOLOGICAL INTEREST, SUCH AS AMINO ACIDS, NUCLEOBASES AND AMPHIPHILES, WHICH MAKE UP THE BUILDING BLOCKS OF PROTEINS, RNA AND DNA, AND CELLULAR MEMBRANES, RESPECTIVELY
- AND ORGANIC COMPOUNDS ARE COMMONLY FOUND IN METEORITES AND COMETS

GIFTS FROM OUTER SPACE: THE ASTEROID RYUGU



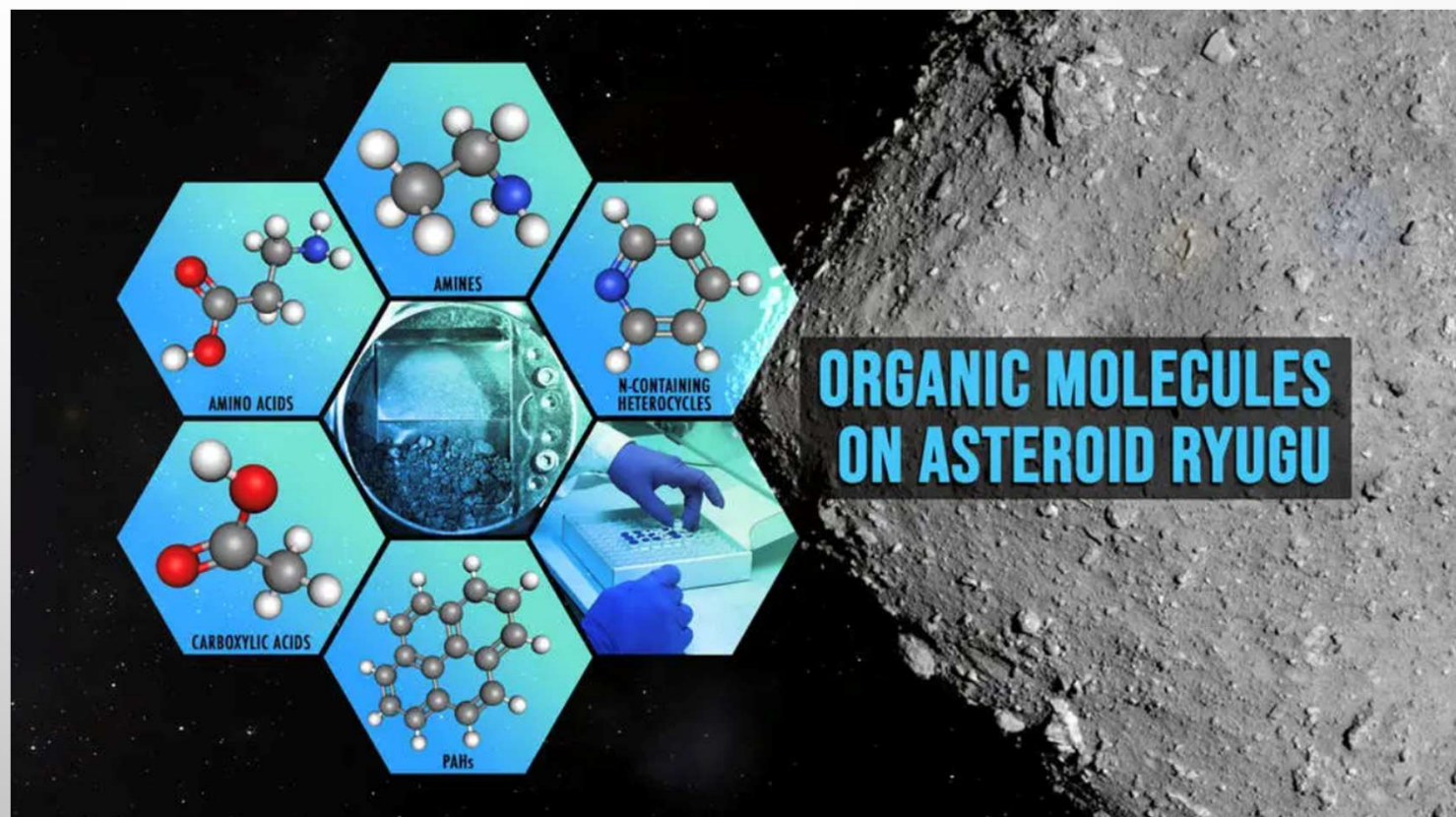
- DISCOVERED IN 1999; MIT AND NASA COLLABORATION
- CA. 900 METERS IN DIAMETER; 300 MILLION KM FROM EARTH
- THE JAPAN AEROSPACE EXPLORATION AGENCY SPACECRAFT *HAYABUSA2* WAS LAUNCHED IN DECEMBER 2014
- ARRIVED AT THE ASTEROID ON 27 JUNE 2018
- COLLECTED 5.4 GRAMS OF MATERIAL, BOTH SURFACE AND SUBSURFACE
- MATERIALS NOT WEATHERED BY SUNLIGHT OR COSMIC RAYS
- DELIVERED TO EARTH IN SEALED CAPSULES → UNEXPOSED TO OUTSIDE AIR → NO CONTAMINATION
- IT RETURNED MATERIAL FROM THE ASTEROID TO EARTH IN DECEMBER 2020

ANALYSIS

- IN SEPTEMBER 2022 THE *HAYABUSA 2* INITIAL ANALYSIS STONE TEAM ANNOUNCED THE RESULTS OF THEIR STUDY AT THE **LUNAR AND PLANETARY SCIENCE CONFERENCE 2022**
- RYUGU SAMPLES CONTAIN GRAINS THAT WERE FORMED AT HIGH TEMPERATURES ABOVE 1000 °C, WHICH FORMED CLOSE TO THE SUN AND WERE LATER TRANSPORTED TOWARDS THE OUTER SOLAR SYSTEM
- THE PARENT BODY OF RYUGU ACCUMULATED 2 MILLION YEARS AFTER THE FORMATION OF THE SOLAR SYSTEM
- THE 100 KM LARGE PARENT BODY WAS THEN DESTROYED BY A <10 KM LARGE IMPACTOR, WITH AN IMPACT SPEED OF ABOUT 5 KM/S. RYUGU THEN FORMED FROM MATERIAL FAR FROM THE IMPACT

ANALYSIS (CONT.)

- FOUND CARBONATED LIQUID WATER CONTAINING SALTS AND ORGANIC MOLECULES
- CARBON-RICH STRAIGHT CHAIN HYDROCARBONS
- REPORTED IDENTIFYING 20 DIFFERENT AMINO ACIDS
- AND IN MARCH 2023 THEY IDENTIFIED URACIL AND VITAMIN B3 (CLOSELY RELATED TO ADENINE)



AND ON SUNDAY SEPTEMBER 24TH THE OSIRIS-REX CAPSULE RETURNED HOME

- NASA MISSION - OSIRIS-REX (ORIGINS, SPECTRAL INTERPRETATION, RESOURCES IDENTIFICATION AND SECURITY-REGOLITH EXPLORER)
- LAUNCHED IN 2016
- RETRIEVED MATERIAL FROM THE ASTEROID BENNU
- AWAITING DATA...

