Our cosmic origins: from the water that we drink to the bricks of life

SUMMARY:

We know that we, mankind, are here because of the laws that govern the Universe, from the smallest to the largest scales. After all, life is just chemistry, the art of the elements, synthesised in the interiors of the stars, to bond together. But is life a “cosmic imperative” or just an “hazard”?

These lectures will attempt at answering part of this question by using the testimony imprinted in the small bodies of the Solar System and the observations of Solar-like planetary systems forming nowadays in our Galaxy.

C.Ceccarelli

Cecilia Ceccarelli

Institute de Planétologie et Astrophysique de Grenoble

Observatoire des Science de l’Universe de Grenoble

Our cosmic origins: from the water that we drink to the bricks of life

TWO THREADS,
WATER and BRICKS OF LIFE
ONE DIRECTION,
BACK TO OUR ORIGIN

ONE QUESTION IN MIND:
IS LIFE A "COSMIC IMPERATIVE" or JUST "HAZARD"?

1. Life on Earth

OSUG
Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER
SCIENCES TECHNOLOGIE SANTE

WHAT THESE LECTURES ARE ABOUT

A FAST RECALL WHERE WE ARE

what is life… but only from a chemical point of view

A BRIEF STORY ON HOW WE ARRIVED HERE

how a diffuse clump of gas and dust became our Solar System, with emphasis on its chemical evolution

A SELECTED LIST OF THE MESSAGES FROM COMETS AND METEORITES

the chemical traces -water, organics, radionuclides- of the very early phases of the Solar System and Earth formation imprinted in comets & meteorites

A GENERAL VIEW ON THE EARTH FORMATION AND THE LIFE APPEARANCE

the bricks of the Earth, the origin of the terrestrial oceans, the first chemical replicating entities and LUCA (if existed)

THE POINT ABOUT LIFE OUTSIDE THE SOLAR SYSTEM

SETI, exoplanets, interstellar voyages…

C.Ceccarelli

1. Life on Earth

1. Actually, what is life?
2. The chemistry of terrestrial life
3. The "normal" life on Earth
4. Hazard or cosmic imperative?
5. A brief overview of how we arrived here

OSUG
Observatoire des Sciences de l'Univers de Grenoble
C.Ceccarelli
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble
UNIVERSITE JOSEPH FOURIER
SCIENCES. TECHNOLOGIE. SANTE

1.1 ACTUALLY, WHAT IS LIFE ?

It might seem strange, but the notion of life has never been really clarified.
One could use what Saint Augustin said about *space* to life:

What is space?
If nobody asks me then I know it; but if someone asks and I have to explain it, then I don't know it anymore (Sain Augustin, 354-430).

OSUG

Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER
SCIENCES. TECHNOLOGIE. SANTE

1.1 ACTUALLY, WHAT IS LIFE ?

It might seem strange, but the notion of life has never been really clarified.
One could use what Saint Augustin said about space to *life*:

*What is **life**?*
If nobody asks me then I know it; but if someone asks and I have to explain it, then I don't know it anymore (Sain Augustin, 354-430).

Although we recognise life when we "see" it, its definition is far to be evident. A few examples in the next slides will illustrate why.

The answer to the question "what is space?" had to wait for the General Relativity Theory.
Analogously, a "fully scientific definition" of what is life will probably come when our understanding of biology will improve.

1.1 ACTUALLY, WHAT IS LIFE ?

*What is **life**?*
If nobody asks me then I know it; but if someone asks and I have to explain it, then I don't know it anymore (Sain Augustin, 354-430).

The question is not philosophical nor academic but very much practical for several reasons. In the context of these lectures, if we want to understand our "cosmic origins" and, in particular, the bricks of life, we'd better be clear on what we mean for "life".
Of course, on a wider, but still quite astrophysical context, this is very important to define the right experiments to search for life elsewhere than Earth, for example on Mars.

C.Ceccarelli

OSUG Observatoire des Sciences de l'Univers de Grenoble

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER SCIENCES TECHNOLOGIE SANTE

Auto-reproduction

DEFINITION
Reproduction of itself: the capacity of a living being to gather matter in the environment, to re-organise and transform it into its copy. G.-L. Leclerc, Comte de Buffon (1707-1788), was the first one to recognise the central role of reproduction in the definition of life.

PROBLEM
It is very easy to show the limits of this definition, as there are plenty of examples of living beings that do not reproduce themselves (for example the sterile animals, like the mules) and not-leaving entities that do (like the crystals).

This definition describes one aspect of life, but it fails to include all forms of life.

1. Life on Earth

1.1 What is life?

OSUG

C.Ceccarelli

IPAG

Metabolism

DEFINITION
From the greek μεταβολισμοχ = change, transformation. A living being consumes energy and transforms it.
In biology, metabolism is a general term that indicates all the chemical reactions that occur in the cells of an organism to produce and use the energy, to maintain their identity, and reproduce themselves.

PROBLEME
Also this definition presents evident limits. For example, the flames would be living beings according to this definition. The same applies to the a locomotive, which transforms energy into mouvement. There are plenty of similar examples…

Therefore, also this definition catches an important aspect of life but it is not a definition of it.

OSUG
Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

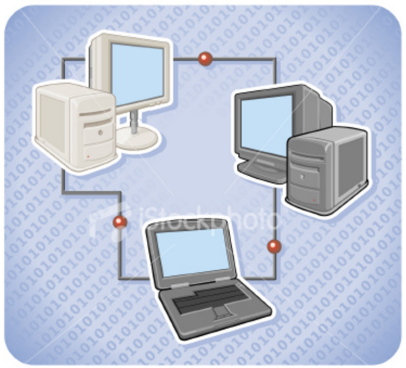
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER
SCIENCES TECHNOLOGIE SANTÉ

Reactivity/Adaptation

DEFINITION
The continuum adjustment of the internal relations to the external. In clear, living beings are systems that respond to the changes of their environment in such a way to promote their perpetuity.

PROBLEME
Once again, several examples show that even this definition has limits of applicability. For example, some computer programs can adapt to their environment, some plastics can shorter themselves with heating, mammals commit suicide…



As previously, this is an important aspect of life but it cannot constitute a definition of it.

1. Life on Earth

1.1 What is life?

OSUG

Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

IPAG

Institut de Planétologie et d'Astrophysique de Grenoble

Université Joseph Fourier

Auto-reproduction + Metabolism + Adaptation = Life

DEFINITION
Each of the previous definitions catches important aspects of life but not all of them, so one could wonder whether adding the them would end up in a working definition of life.

PROBLEME
It does not, as even considering the three definition together there are examples of not-leaving entities that possess the three characteristics, for example the flames.
Besides, some living organisms present the phenomena of *cryptobiosis* (from latin: hidden life): life stops for a limited amount of time. Simple examples are represented by the seeds of plants, or the eggs of some crustaceans. One of the most complex (and perturbing) is given by the tardigrades, marin animals alive only in contact with water.

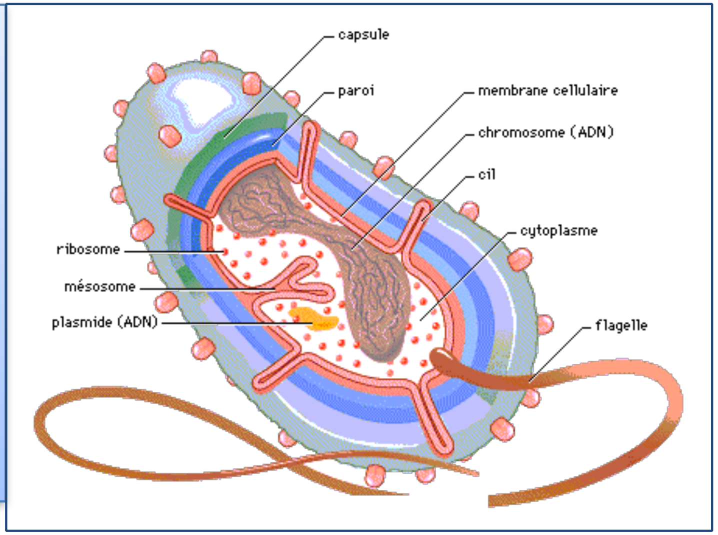
CONCLUSION: Even the addition of auto-reproduction, metabolism and adaptation does not provides us with a definition of life.
In addition, what about the time scale?

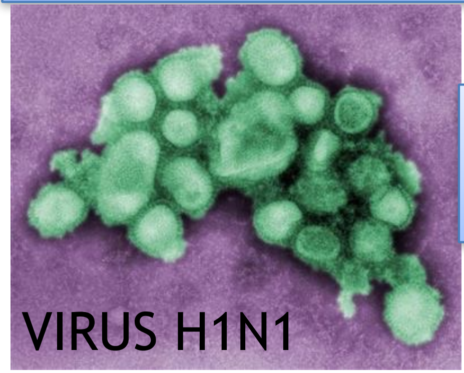

tardigrade

C.Ceccarelli

AND IF WE MOVE TO SMALLER SCALES?

One could use the same previous definitions to the smaller scale of the cells. In practice, however, the situation does not really improve.
How do we define a cell in a general term, for example? And does cell means life?



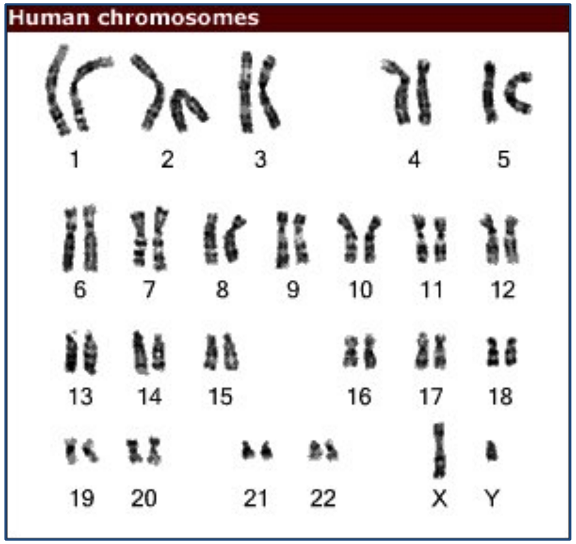


By the way, is a virus life?
…not even biologists agree on that…

Moving to the molecular scale would not help either.
After all, even though life is based on molecules, they are not living beings, it is their organisation that makes a living being.

DARWINIAN EVOLUTION

The terrestrial life is based on the darwinian evolution, namely the transmission of the information at each replication, which also implies the metabolism (to create the replica). It is the best replicated entity that better copes with the environment and resources that survives and can replicate, add a modification and improve….



OSUG

C.Ceccarelli

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER

THE TERRESTRIAL LIFE

Let's be pragmatic and just focus on the terrestrial life, and the three aspects that we know are **necessary** to it:

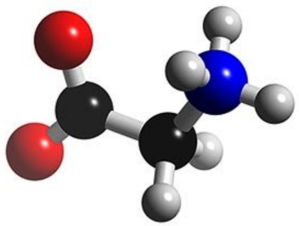
MATTER
ENERGY
INFORMATION

And now let's see why life is what we know, and why the threads of these lectures are water and organic molecules.

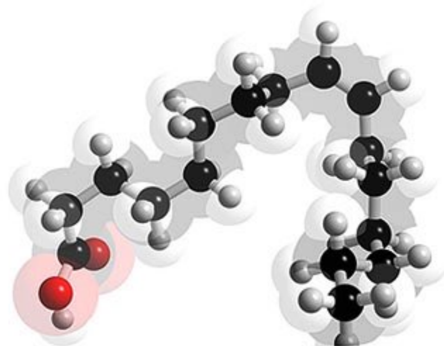
C.Ceccarelli

1.2 THE CHEMISTRY OF TERRESTRIAL LIFE

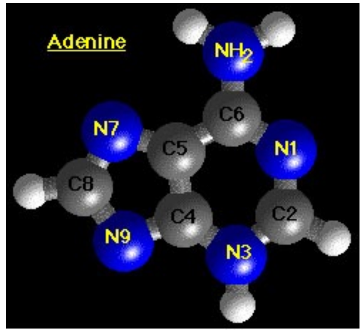
All living organisms, from microbes to men, are made up of the same basic components: amino acids, fatty acids, alcohols, and nitrogenous bases, etc.
We are talking of about 50 small molecules of less than 100 atoms of carbon, with hydrogen, oxygen, nitrogen and other elements in smaller quantities.



GLYCINE



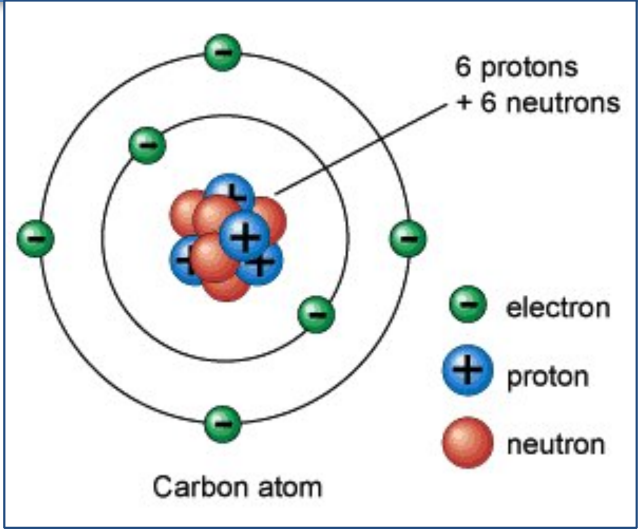
PALMITOLEIC ACID

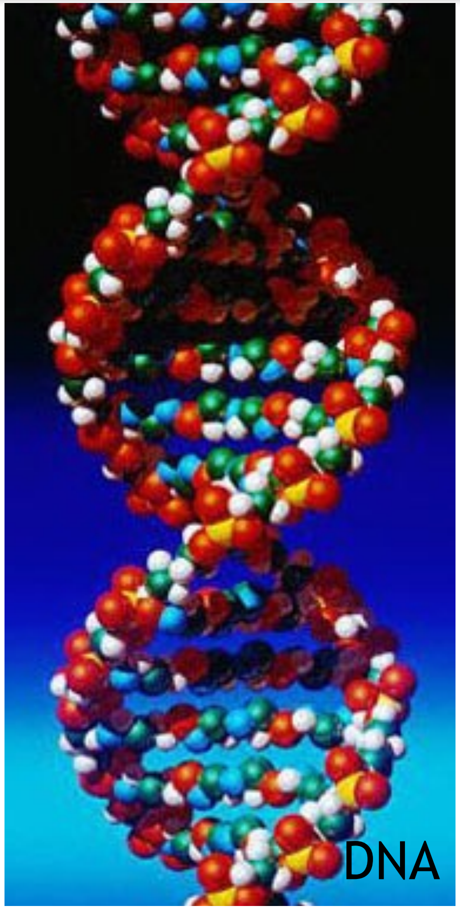


The composition in larger structures (proteins, glucides, nucleic acids, lipids etc) is at the base of the differences between the organisms, from a chemical point of view.

WHY CARBON

The basic element, present in all the previous mentioned molecules, is carbon => *terrestrial life is based on the carbon chemistry*.
This is not just an hazard, there are two simple reasons for that.

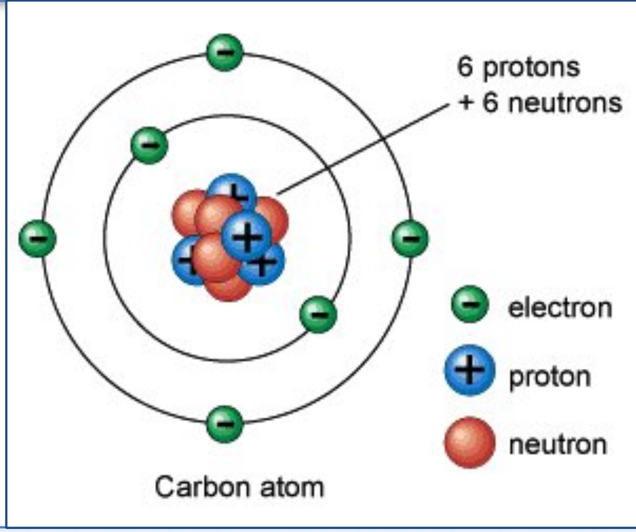


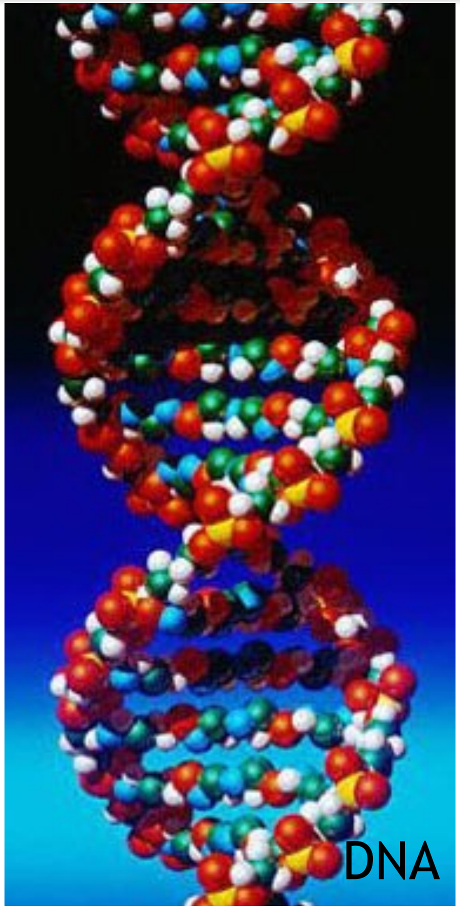


C.Ceccarelli

WHY CARBON

The basic element, present in all the previous mentioned molecules, is carbon => *terrestrial life is based on the carbon chemistry*.
This is not just an hazard, there are two simple reasons for that.





1) The particularity of the carbon chemistry, because of its electronic structure:
The electronic structure of carbon allows to build up long chains of atoms, where the backbone are carbons to which oxygen, hydrogen and other atoms are added. The larger the chain the richer the information that can be passed and modified, a requisite for life.

OSUG
C.Ceccarelli
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble
Université Joseph Fourier

WHY CARBON

1. Life on Earth

1.2 Chemistry of terrestrial life

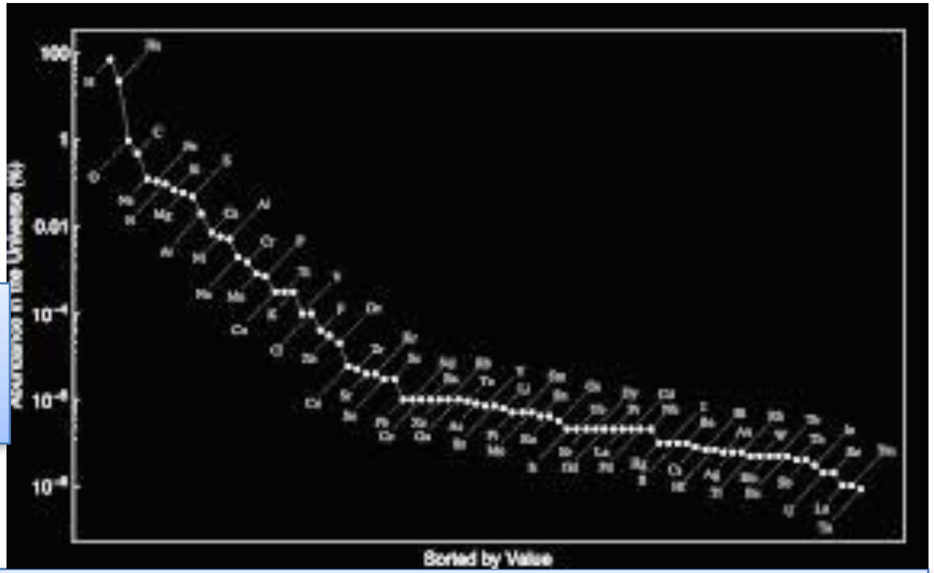
C.Ceccarelli

2) The abundance of carbon atoms

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

Carbon is not the only element with an electronic structure able to form chains. Silicon, Germanium and Tin can do it too.

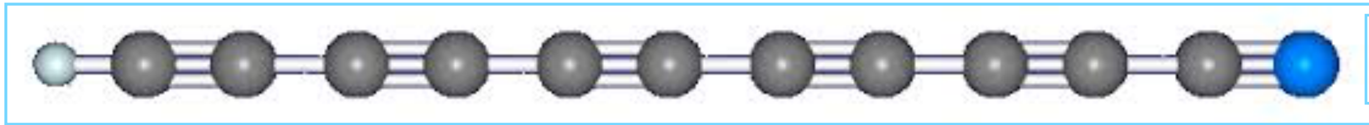
However, Si, Ge and Sn have smaller abundances,



and are trapped in the refractory components of the Inter-Stellar Medium, the dust grains: they are not available to make molecules, they make Earths.

WHY CARBON

IS THIS A SURPRISE? NO: WE SEE IT IN THE ISM!



$HC_{11}N$

It is not by chance that the longest molecules detected in the ISM are all carbon chains!

6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	$HC_{11}N$
l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{60} *
C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN 2014	C_{70} *
CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$		
CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
NH_2CHO		H_2NCH_2CN	CH_3CH_2SH (?)				
C_5N		CH_3CHNH					
l-HC_4H *							
l-HC_4N							
c-H_2C_3O							
H_2CCNH (?)							
C_5N^-							
HNCHCN							

Actually, all molecules with more than 5 atoms all contains C.

C.Ceccarelli

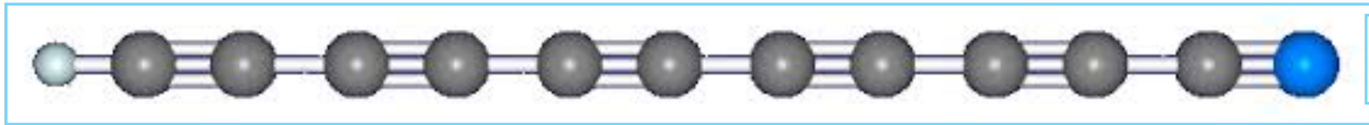
WHY CARBON

1. Life on Earth

1.2 Chemistry of terrestrial life

C.Ceccarelli

IS THIS A SURPRISE? NO: WE SEE IT IN THE ISM!



$HC_{11}N$

WE'D BETTER UNDERSTAND ORGANIC CHEMISTRY IN SPACE!
IT *MIGHT* HELP US TO UNDERSTAND THE ORIGIN OF LIFE ON EARTH…

6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	$HC_{11}N$
l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{60} *
C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN 2014	C_{70} *
CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$		
CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
NH_2CHO		H_2NCH_2CN	CH_3CH_2SH (?)				
C_5N		CH_3CHNH					
l-HC_4H *							
l-HC_4N							
c-H_2C_3O							
H_2CCNH (?)							
C_5N^-							
HNCHCN							

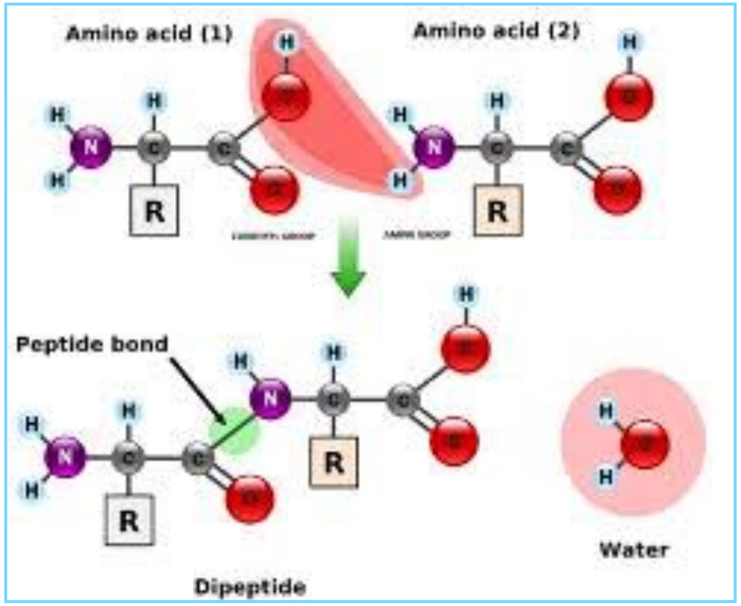
THE OTHER ELEMENTS

Life on Earth uses whatever is at its disposition

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

Carbon is not the only element necessary for life. Oxygen, nitrogen, sulphur and phosphorous are also indispensable to life, but they are needed in much smaller quantity.

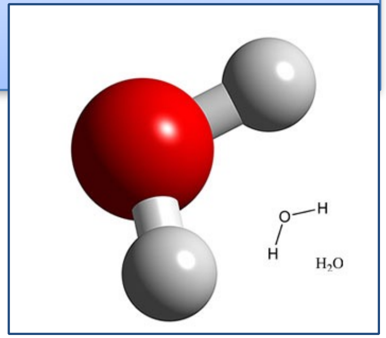
For example, the peptide bonds, which combine CHON elements, are at the basis of the structure of the proteins, which ensure the majority of cellular functions.



C.Ceccarelli

THE ROLE OF WATER

All living beings on Earth are constituted by a large fraction of water.



The bacterium Escherichia coli contains 70% water.

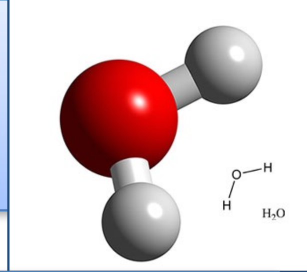
The body of a jellyfish contains 94-98% water.

Plants contain up to 90% water.

The human body contains 60-70% water.

C.Ceccarelli

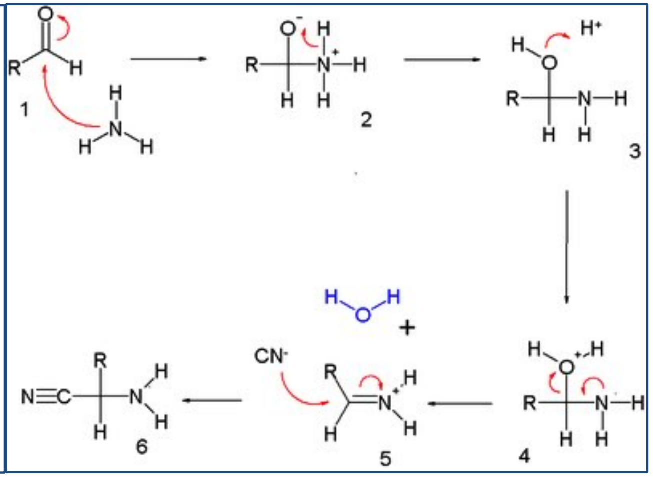
THE ROLE OF WATER

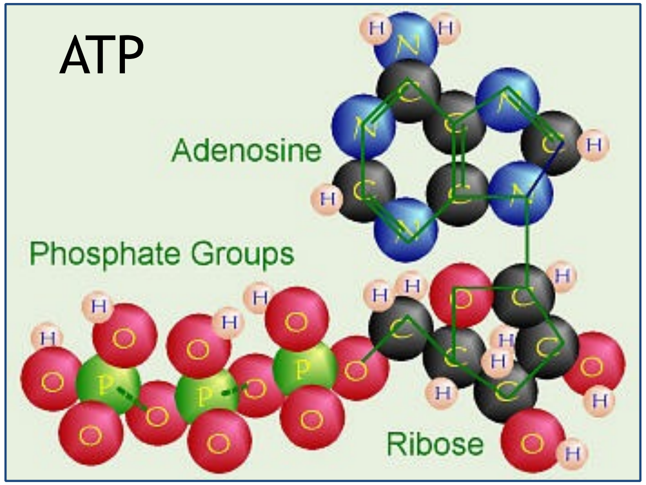


Some important functions of water

1) Water is an extremely efficient solvant, which facilitates the formation of large and complex molecules (for example the formation of amino acids via the Strecker synthesis).
2) Water permits the hydrolysis of the ATP (Adenosine TriPhosphate) and, consequently, to transmit energy to the living beings.

Strecker amino acids synthesis





3) In addition, water has a large capacity and remains liquid in a relatively large temperature interval.

1. Life on Earth

1.2 Chemistry of terrestrial life

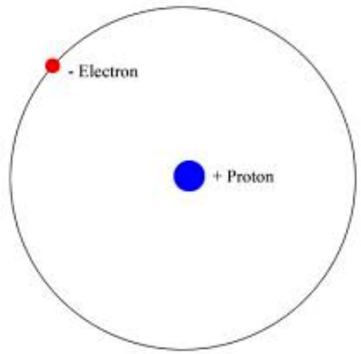
OSUG

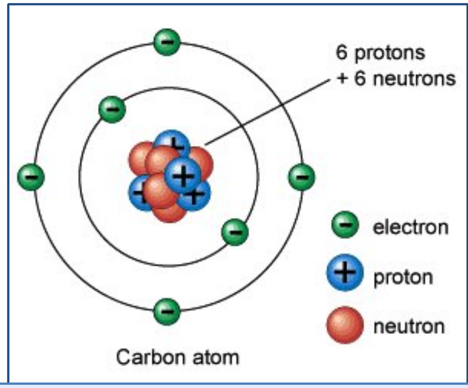
C.Ceccarelli

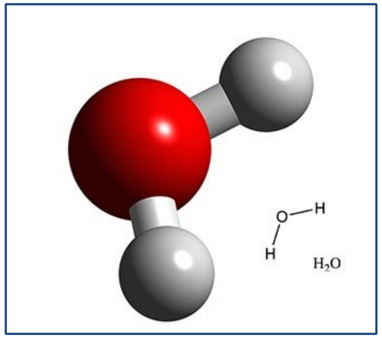
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

Université Joseph Fourier

THE ABUNDANCE OF THE ELEMENTS AND THE EFFICIENCY OF LIFE







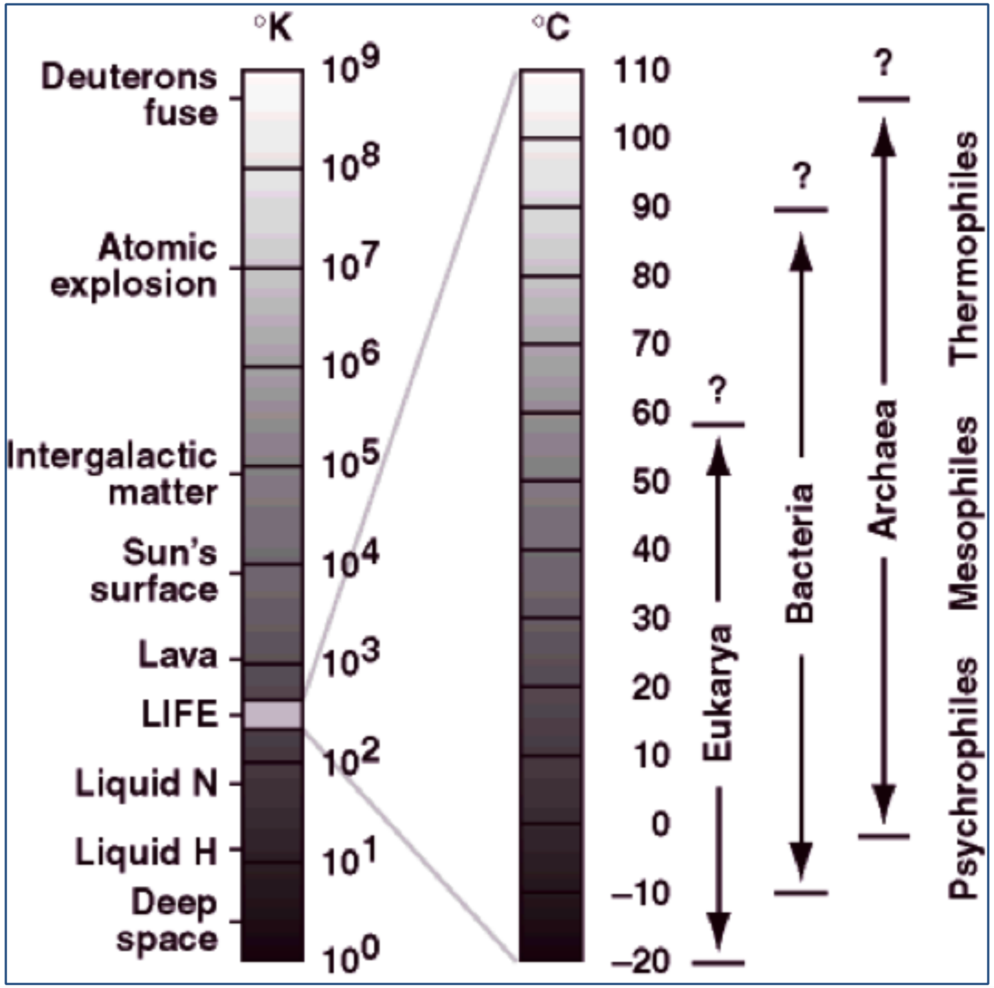
Hydrogen, oxygen and carbon are the three elements most “used” by life. They are also the three most abundant elements (which participate to the chemistry game) in the present Universe.

Terrestrial life uses what is at its disposition.

ELEMENT	SYMBOLE	ABONDANCE EN NOMBRE
HYDROGENE	*H*	*1*
HELIUM	*He*	*0.07*
OXYGENE	*O*	6.7×10^{-4}
CARBONE	*C*	3.7×10^{-4}

C.Ceccarelli

1.3 "NORMAL" LIFE ON EARTH



Life on Earth has developed over a temperature range relatively small, where water is in the liquide state.
We, humans and the large majority of animals and plants, survive at an even smaller temperature interval. Is this the "normal" life?

OSUG

Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

IPAG

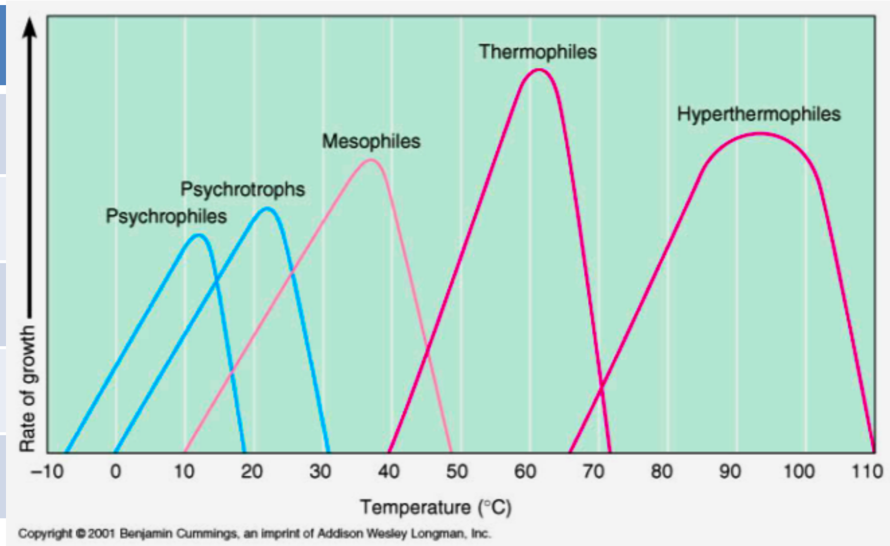
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER SCIENCES TECHNOLOGIE

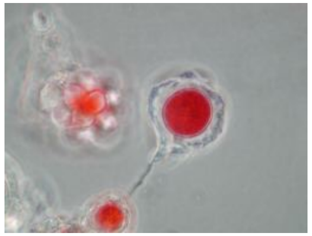
Terrestrial life and temperature

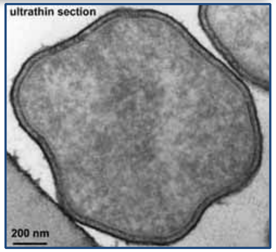
CLASSIFICATION OF THE LIVING BEINGS ACCORDING THE RANGE OF TEMPERATURE WHERE THEY SURVIVE AND THRIVE

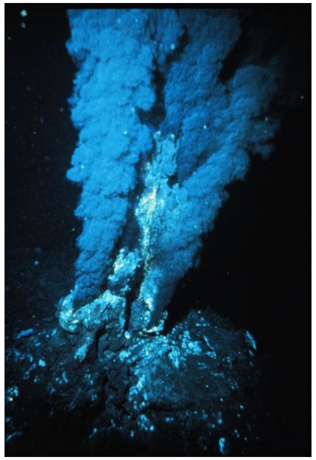
MICROORGANISMS	TEMPERATURE
PSYCHROPHILES	*-10 ÷ 20 ºC*
PSYCHROTROPHS	*0 ÷ 30 ºC*
MESOPHILES	*10 ÷ 50 ºC*
THERMOPHILES	*40 ÷ 70 ºC*
HYPERTHERMOPHILE	*> 80 ºC*



The microorganisms at the two extremes of the temperature distribution are called “**extremophiles**”.

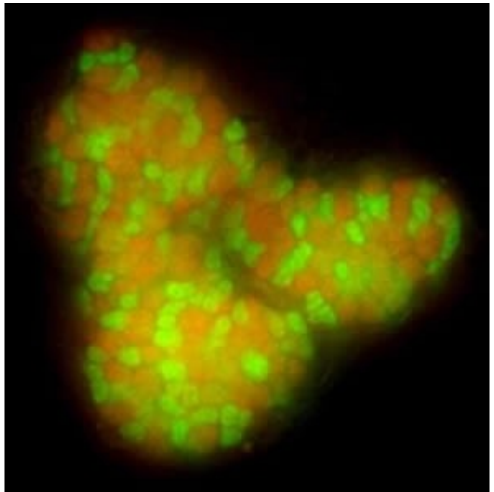




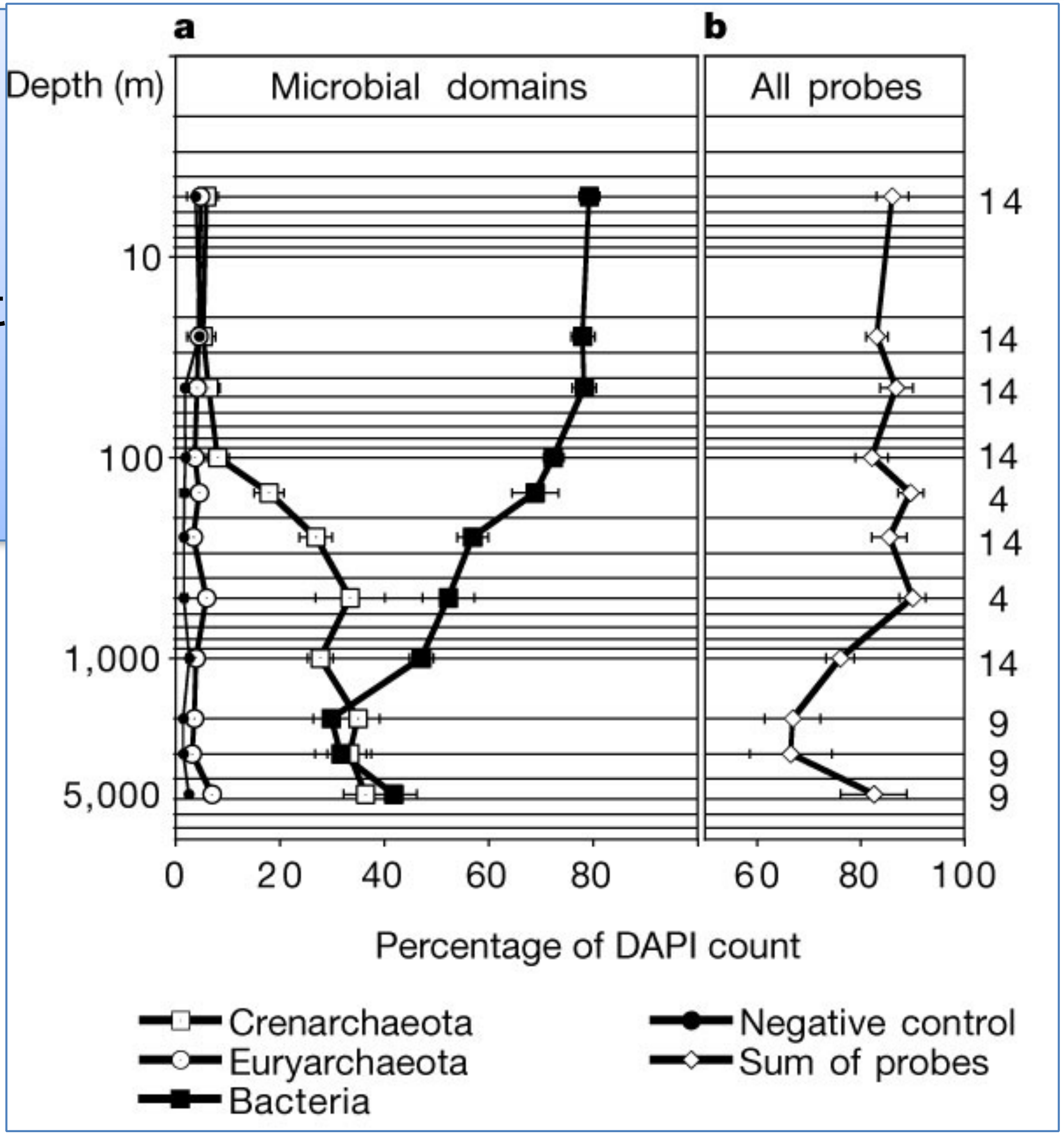


What is “normal” on Earth?

The majority of microorganisms live and thrive in the ocean floor. And, by the way, they live in symbiose so that it is extremely difficult to grow and study them in a laboratory.



Colony of bacteria (green) and archaea (red) in the ocean floor.



1. Life on Earth

1.3 Normal life on Earth

OSUG

C.Ceccarelli

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

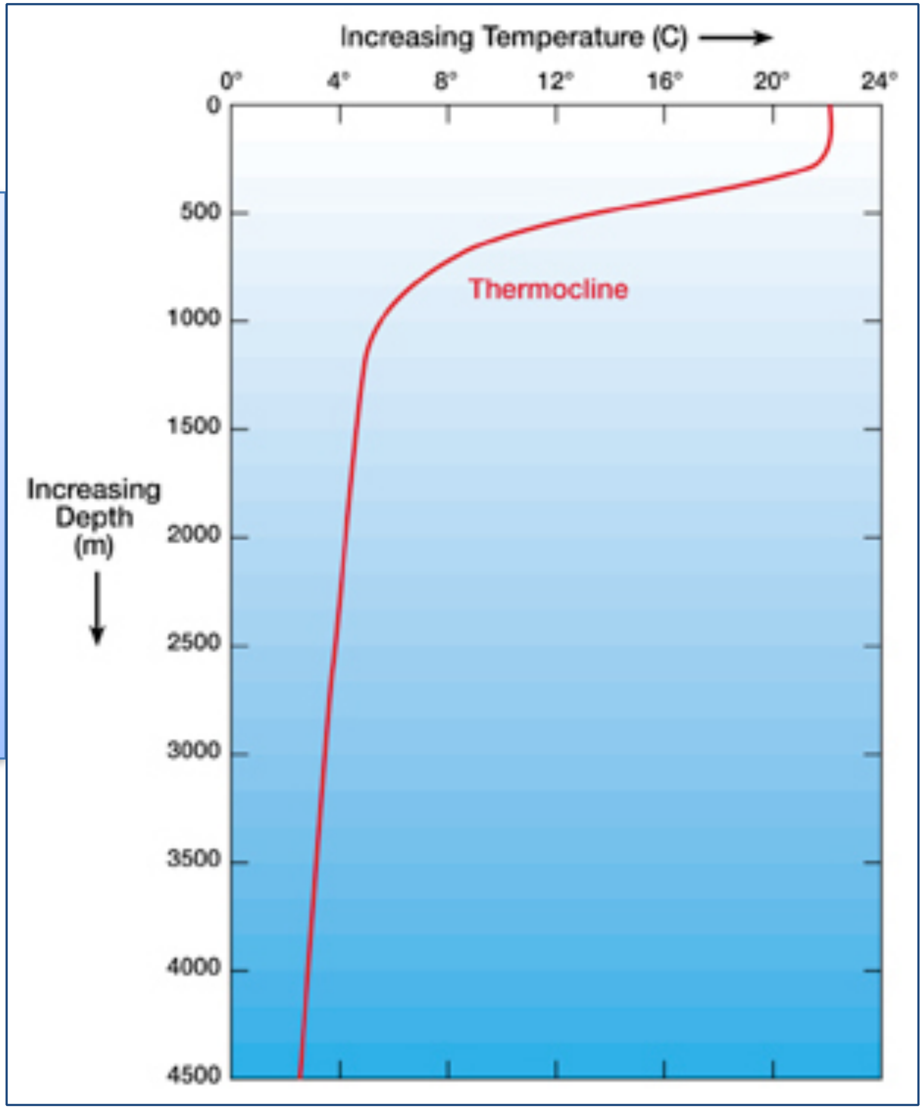
Université Joseph Fourier

What is “normal” on Earth?

1. Life on Earth

1.3 Normal life on Earth

The temperature of the 90% of ocean water is less than 5°C (between -1 et 4°C).
=> The majority of marin microorganisms live and thrive in cold environments, which are extreme only from the human point of view.



For the majority of microorganisms, which constitute the majority of the biomass, it is us who are extreme!

C.Ceccarelli

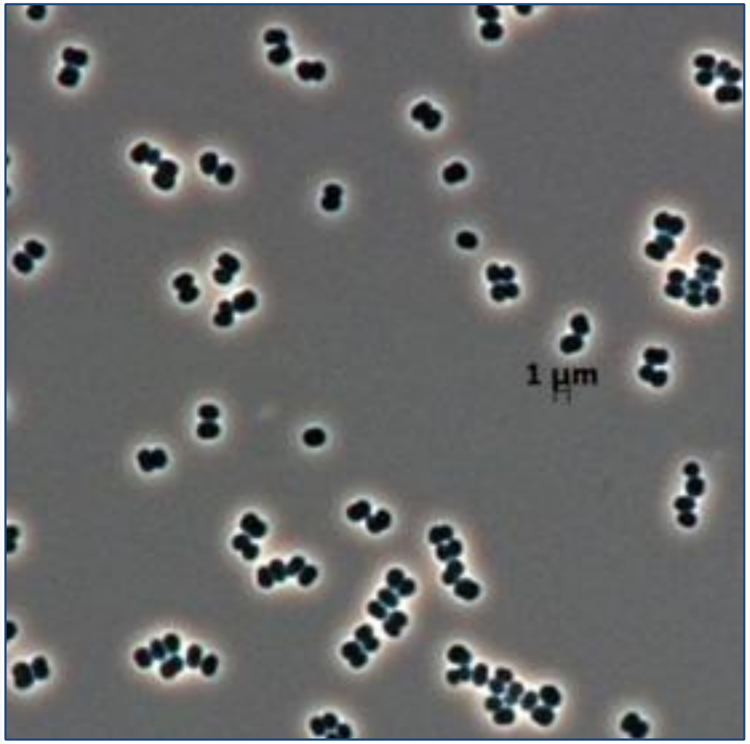
OSUG

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER

Herschel discovers a new bacterium

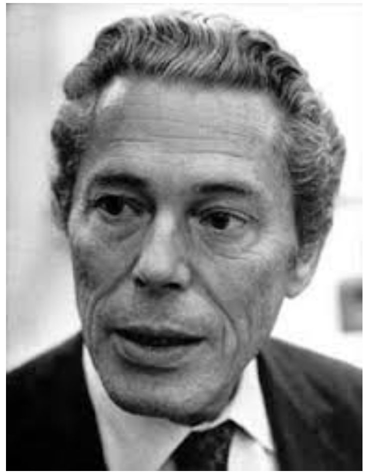
In 2009, ESA discovered a new bacterium, called *Tersicoccus phoenicis*.
It was discovered not in space, of course, but in the clean room (at the Guiana Space Center) where the Herschel payload was assembled.
Soon after, it was also recognised to have been found in the clean room where the NASA Phoenix Lander was assembled (at the Kennedy Space Center).



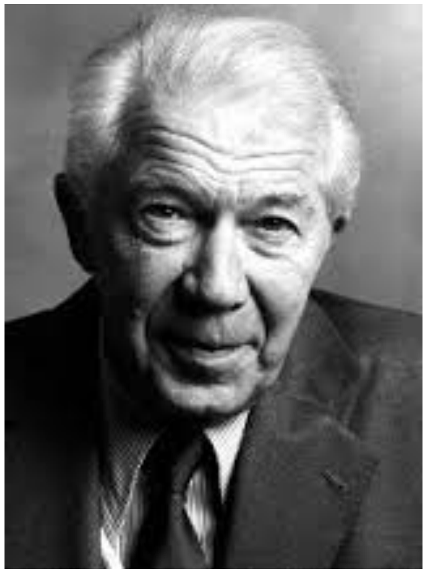
Where does this bacterium, which resists the sterilisation of the clean rooms, come from and why is it found only there?
A possible answer is that is that this extremely resistant bacterium flourishes in the clean rooms because its competitors are dead.

1.4 HAZARD or COSMIC IMPERATIVE ?

J. Monod: Life is only the results of natural processes by "pure chance"
(e.g. Le hazard et la necessité; 1970).



OR



C. De Duve: Life is an obligatory manifestation of matter, written into the fabric of the universe, and that there must be many sites of life, perhaps even intelligent life sometimes, in many parts of our galaxy and in others
(Phyl.Trans.RoyalSoc. 2011).

OSUG

Observatoire des Sciences de l'Univers de Grenoble

C.Ceccarelli

IPAG

Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER

1.4 HAZARD or COSMIC IMPERATIVE ?

Terrestrial life uses what is at its disposition. From this point of view, life is a mere consequence of chemistry: there are no reasons that it is restricted to Earth…

	HAZARD	*COSMIC IMPERATIVE*
USE OF COSMIC ELEMENTS	*0*	*1*
EFFICENCY	*0*	*1*

HAZARD or COSMIC IMPERATIVE ? cont.

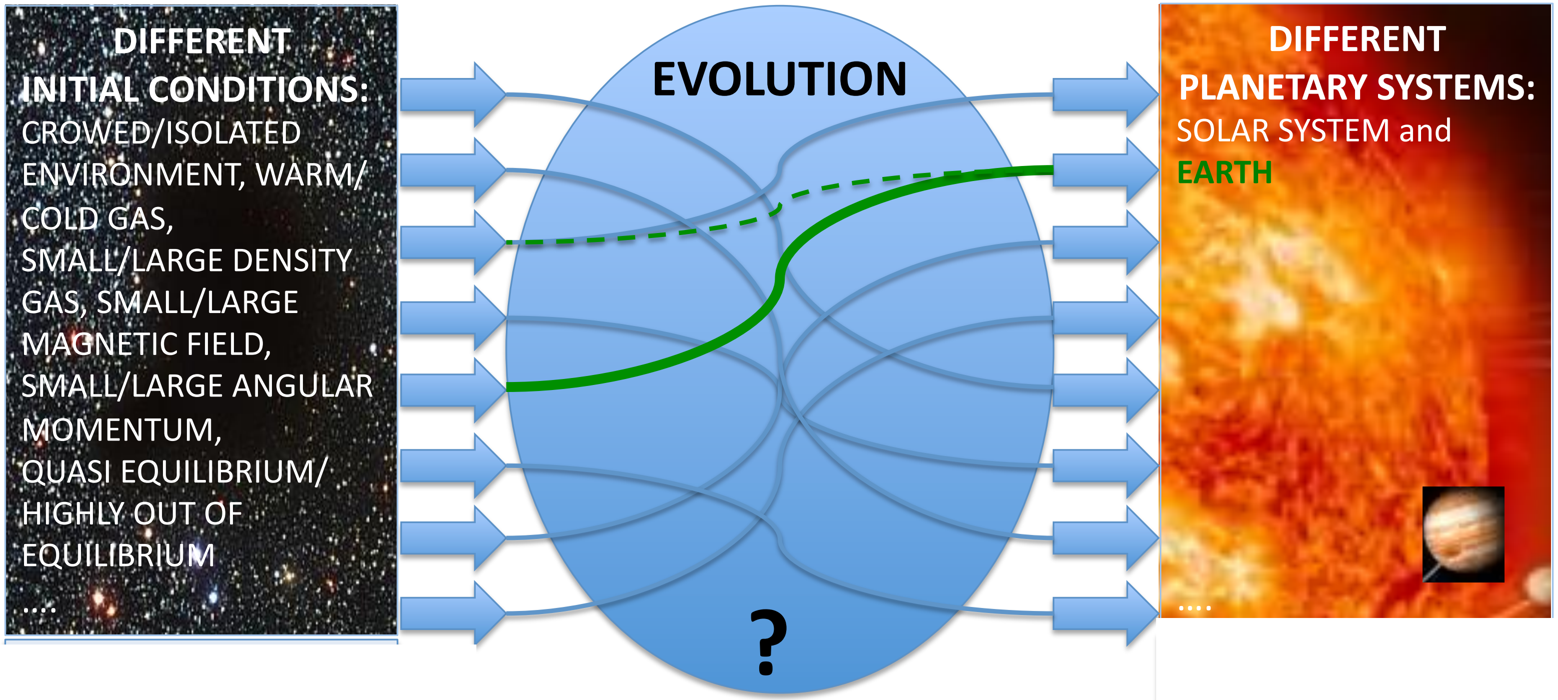
ANOTHER WAY TO ANSWER TO THIS QUESTION IS TO UNDERSTAND HOW WE ARRIVED HERE

WHAT HAPPENS TO THE TWO BASIC CONSTITUENTS, ORGANICS AND WATER?
DO WE HAVE ANY WAY TO RETRACE BACK WHAT HAPPENED TO THEM IN THE SOLAR SYSTEM?

1.5 A BRIEF OVERVIEW OF HOW WE ARRIVED HERE

C.Ceccarelli

THE SOLAR SYSTEM STARTED AS A COLD AND DENSE CLOUD OF DIFFUSE MATERIAL AND ENDED UP BECOMING A PLANETARY SYSTEM

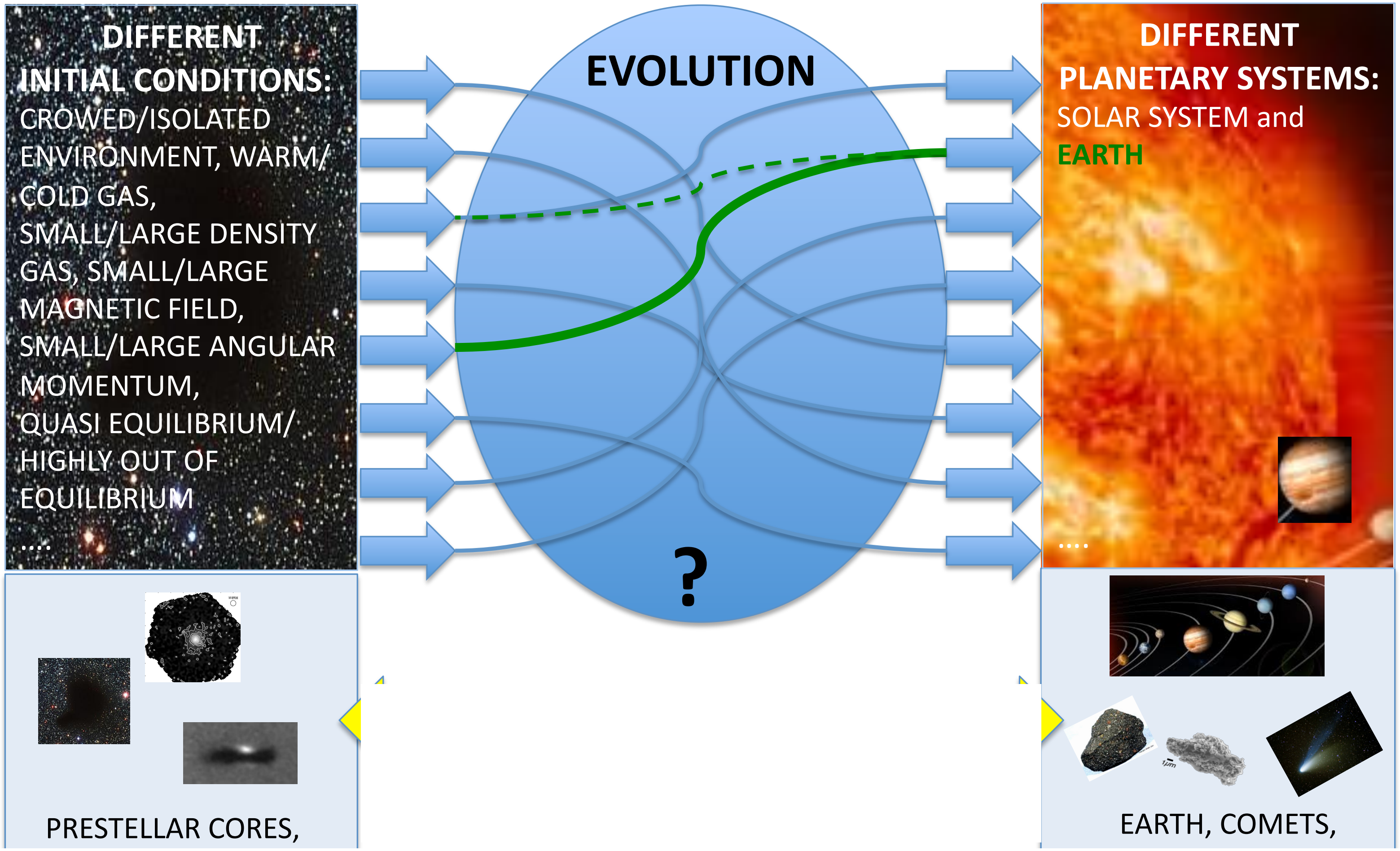


OF THE MANY POSSIBLE PATHS, WHICH ONE THE SOLAR SYSTEM FOLLOWED? AND WHY?

C.Ceccarelli

ON THE ONE HAND THE OBSERVATIONS OF PLANETARY SYSTEM CURRENTLY FORMING IN THE GALAXY

ON THE OTHER HAND, THE PLANETS, THE COMETS AND METEORITES WITH TRACES OF THE PAST EONS



FIND THE LINK, FOLLOW IT

OSUG

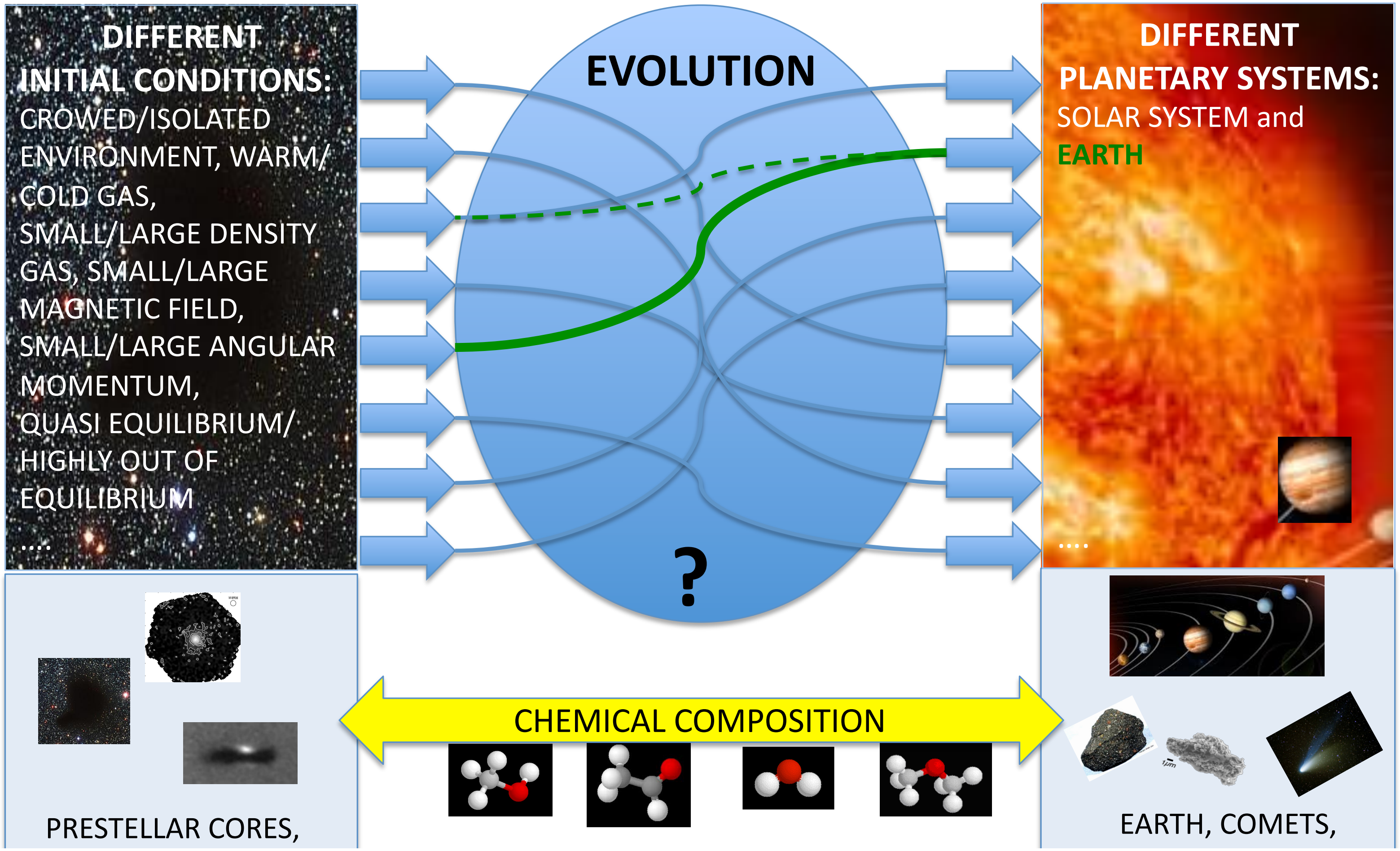
C.Ceccarelli

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER

ON THE ONE HAND THE OBSERVATIONS OF PLANETARY SYSTEM CURRENTLY FORMING IN THE GALAXY

ON THE OTHER HAND, THE PLANETS, THE COMETS AND METEORITES WITH TRACES OF THE PAST EONS



FIND THE LINK, FOLLOW IT
THE ASTROCHEMICAL WAY

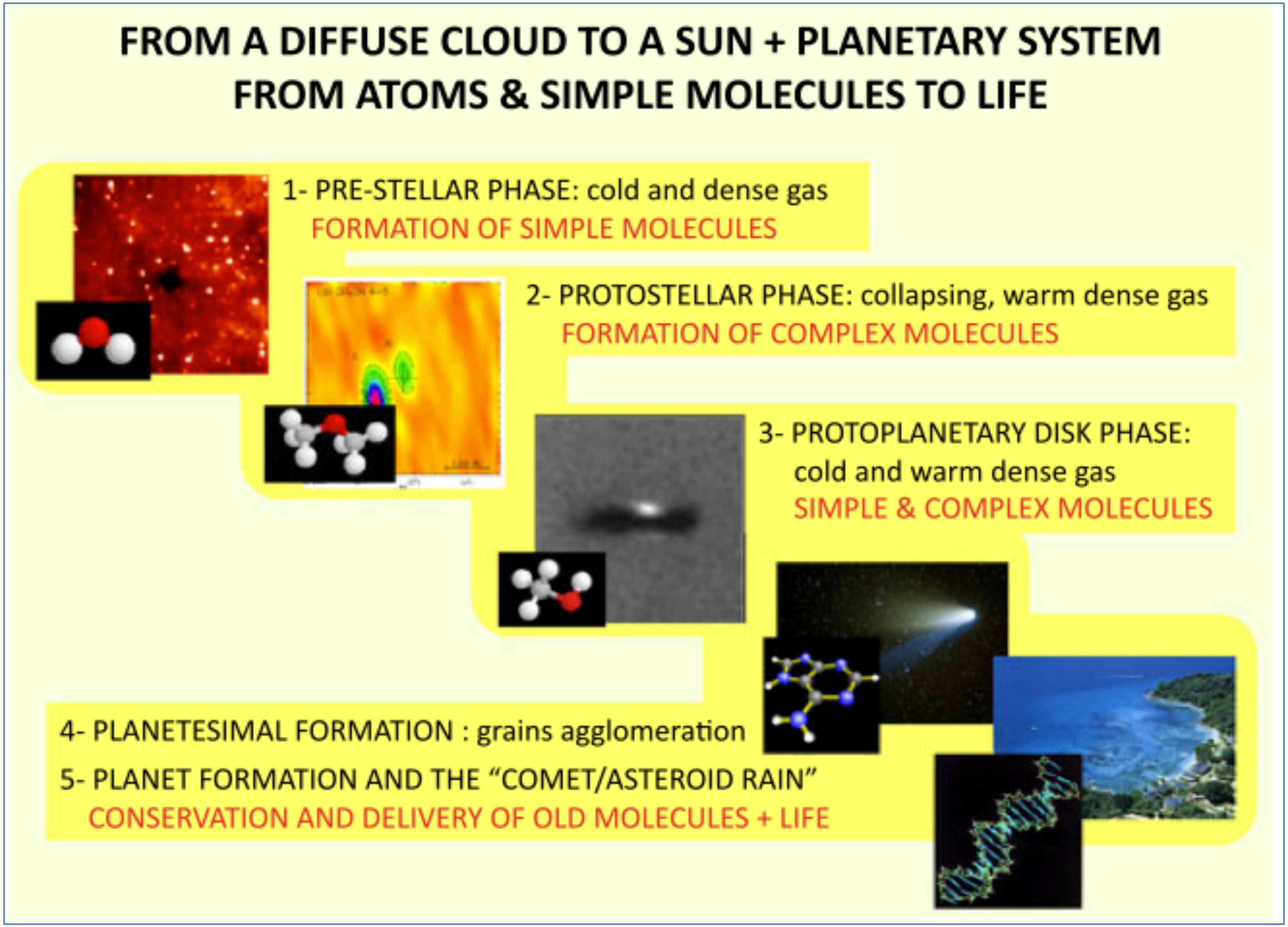
OSUG

C.Ceccarelli

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

UNIVERSITE JOSEPH FOURIER

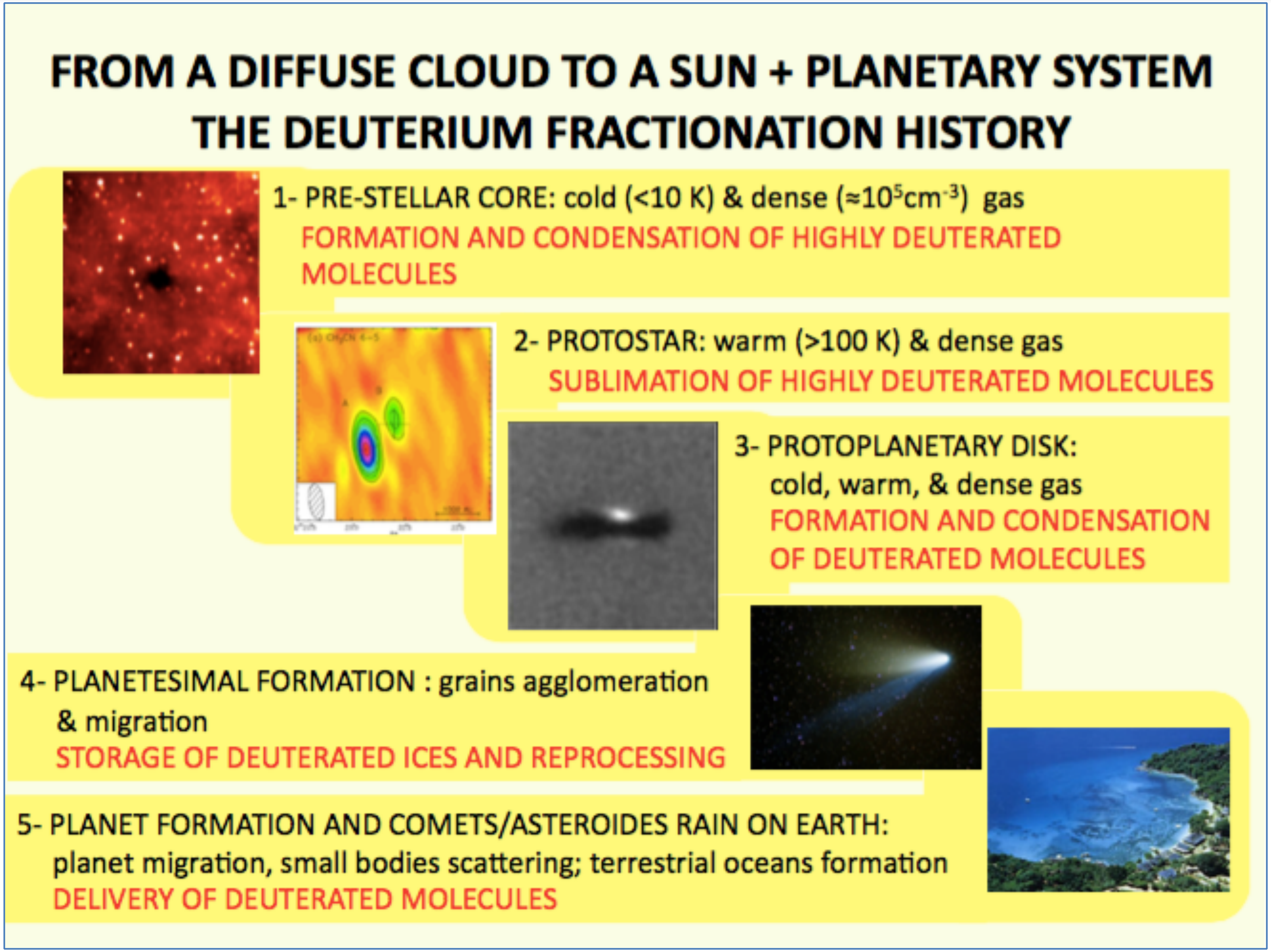
THE ASTROCHEMICAL WAY: ORGANICS



Caselli & Ceccarelli 2012, AAR

C.Ceccarelli

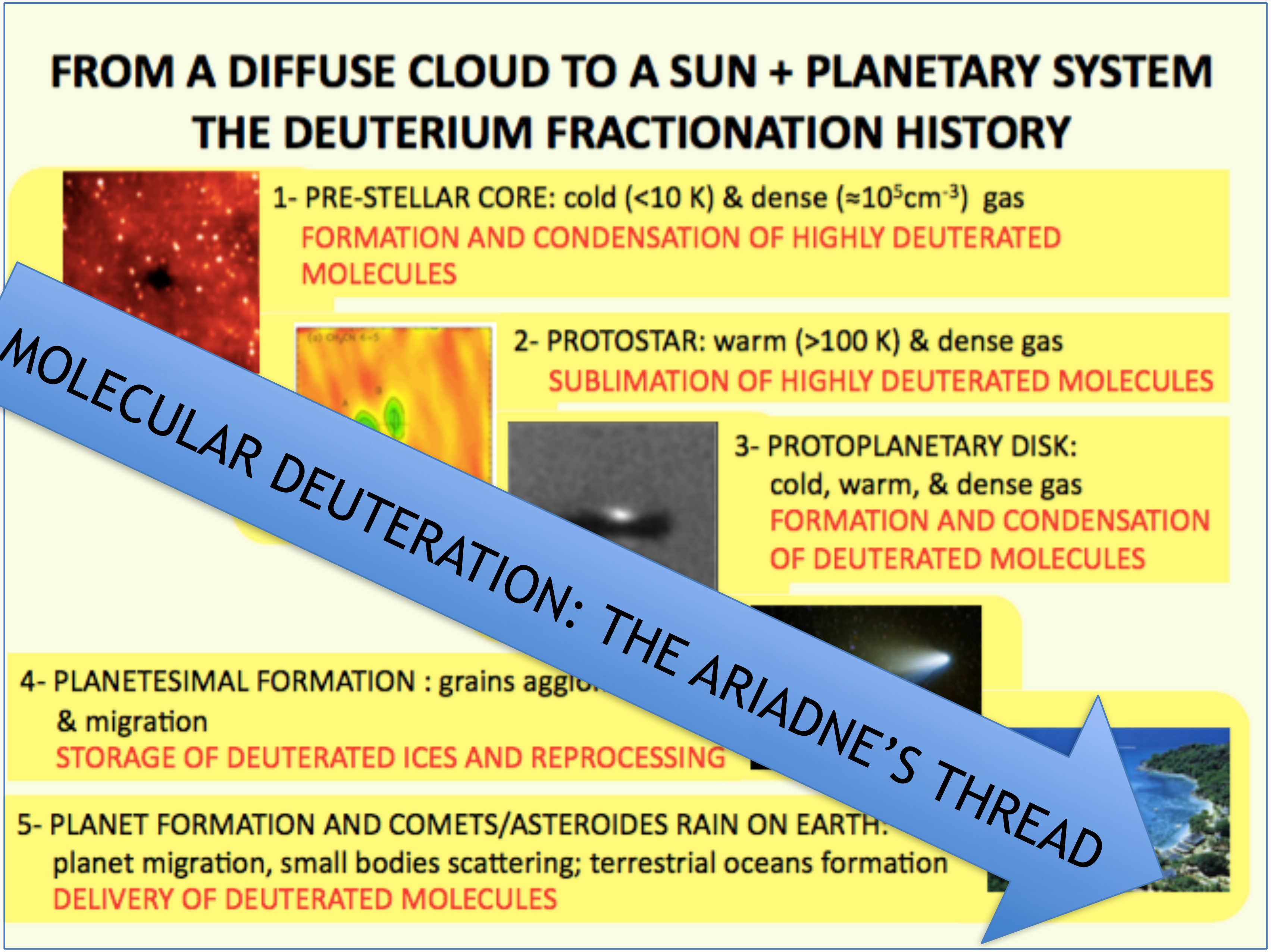
THE ASTROCHEMICAL WAY: DEUTERATION



Ceccarelli et al. 2014, PP6

Caselli & Ceccarelli 2012, AAR

THE ASTROCHEMICAL WAY: DEUTERATION

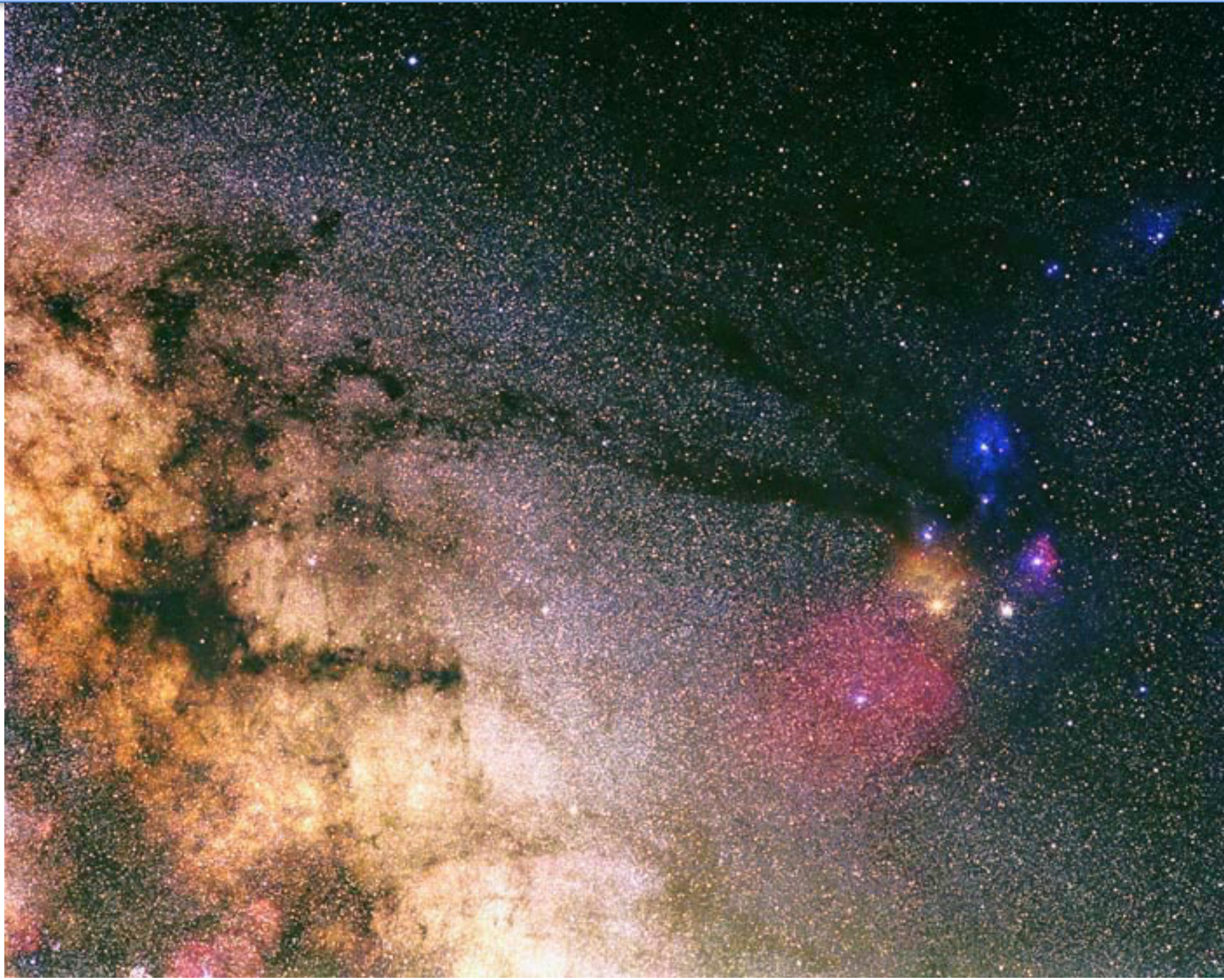


Ceccarelli et al. 2014, PP6

Caselli & Ceccarelli 2012, AAR

C.Ceccarelli

E quindi uscimmo a riveder le stelle



1. Life on Earth

1.5 Brief overview

OSUG

C.Ceccarelli

IPAG