
Follow the water

FOLLOW THE LIFE

⇒ • Solvent
• Biogenic elements
• Source of Free Energy

searches for life within our solar system commonly retreat from a search for life to a search for "life as we know it," meaning life based on liquid water, a suite of so-called "biogenic" elements (most famously carbon), and a usable source of free energy.

(Chyba & Hand, 2005, p. 34)

SIGA A VIDA

⇒ • Siga a água (Follow the water)
- Siga o carbono
- Siga o nitrogênio
- Siga o fósforo
- Siga a energia
- Siga a entropia
- Siga a informação
- Siga o significado

A água é essencial para a vida como conhecemos

H_2O

A água também pode ser essencial para a vida em outros pontos do Universo

Afinal, há água por toda parte no Universo

- H_2O = Hidrogênio + Oxigênio
- Hidrogênio é o elemento mais abundante do Universo e o mais simples (só um próton)
- Oxigênio (seis prótons e seis nêutrons) é o segundo elemento quimicamente ativo mais abundante
- Hélio (dois prótons e dois nêutrons) é o segundo elemento mais abundante mas não é quimicamente ativo

Relative abundances of chemical elements

Relative abundances of chemical elements (O=100) The abundances are in number (decreasing order) Sources: Lehninger 2000 (human body and Earth crust abundances); Asplind, Grevesse & Sauval 2004 (C, N, and O are solar photospheric values; the other elements are solar system meteoritic values)		
Human Body	Earth Crust	Cosmic
H 247	O 100	H 21 900
O 100	Si 59.6	O 100
C 37.3	Al 16.8	C 53.7
N 5.49	Fe 9.6	N 13.2
Ca 1.22	Ca 7.5	Mg 7.41
P 0.86	Na 5.3	Si 7.10
Cl 0.31	K 5.3	Fe 6.17
K 0.24	Mg 4.7	S 3.16
S 0.20	Ti 1.1	Al 0.58
Na 0.12	H 0.4	Ca 0.43
Mg 0.04	C 0.4	Na 0.41

Água

Composta pelos dois elementos quimicamente ativos mais abundantes do Universo.

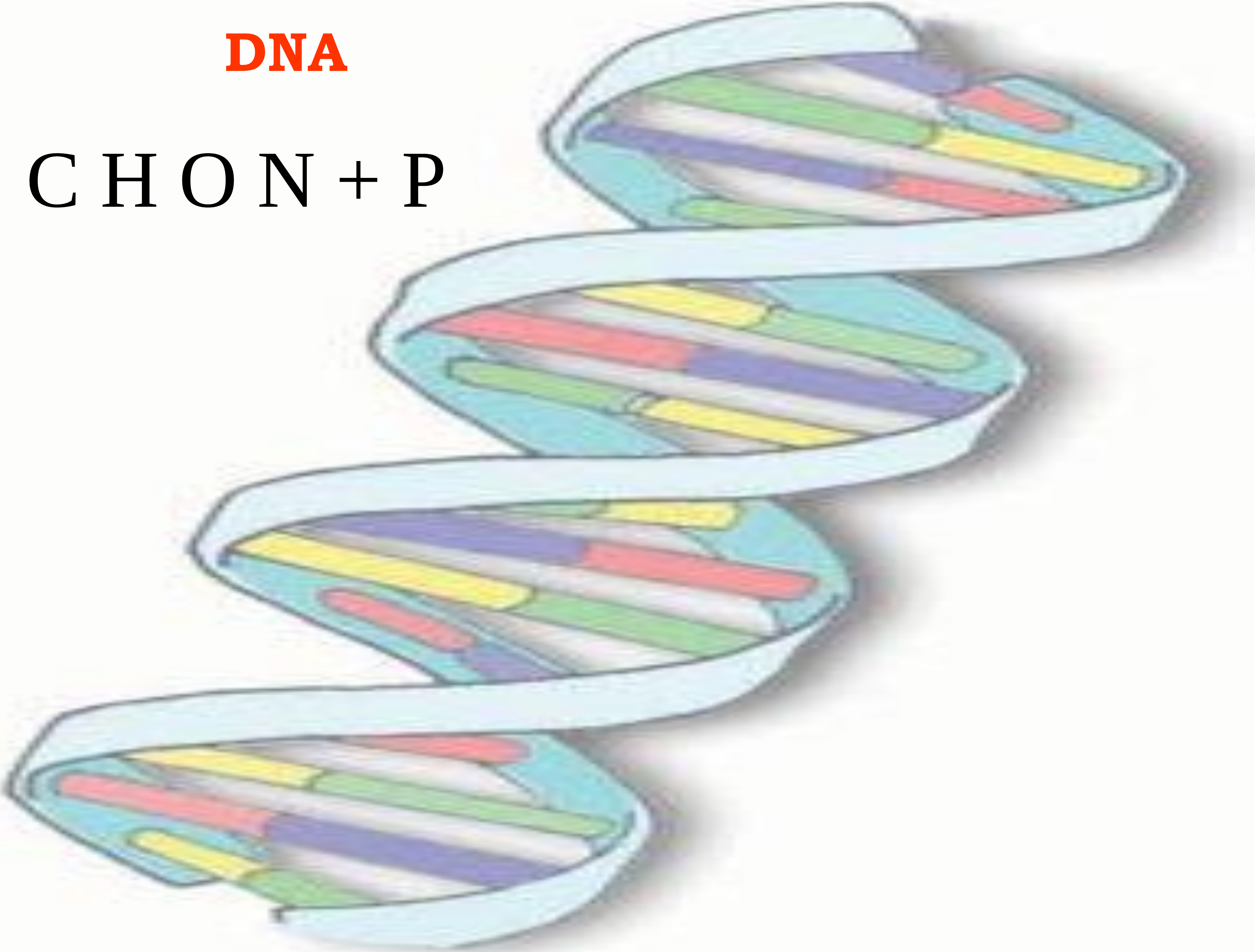
Principal componente dos cometas e dos seres vivos.

Assim, o Oxigênio e o Hidrogênio são os elementos principais de seres vivos terrestres e do Universo

Logo atrás vem o Carbono e o Nitrogênio.

DNA

C H O N + P



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O UNIVERSO
É ÚMIDO

Detecting Water through the PAH 6.2 line

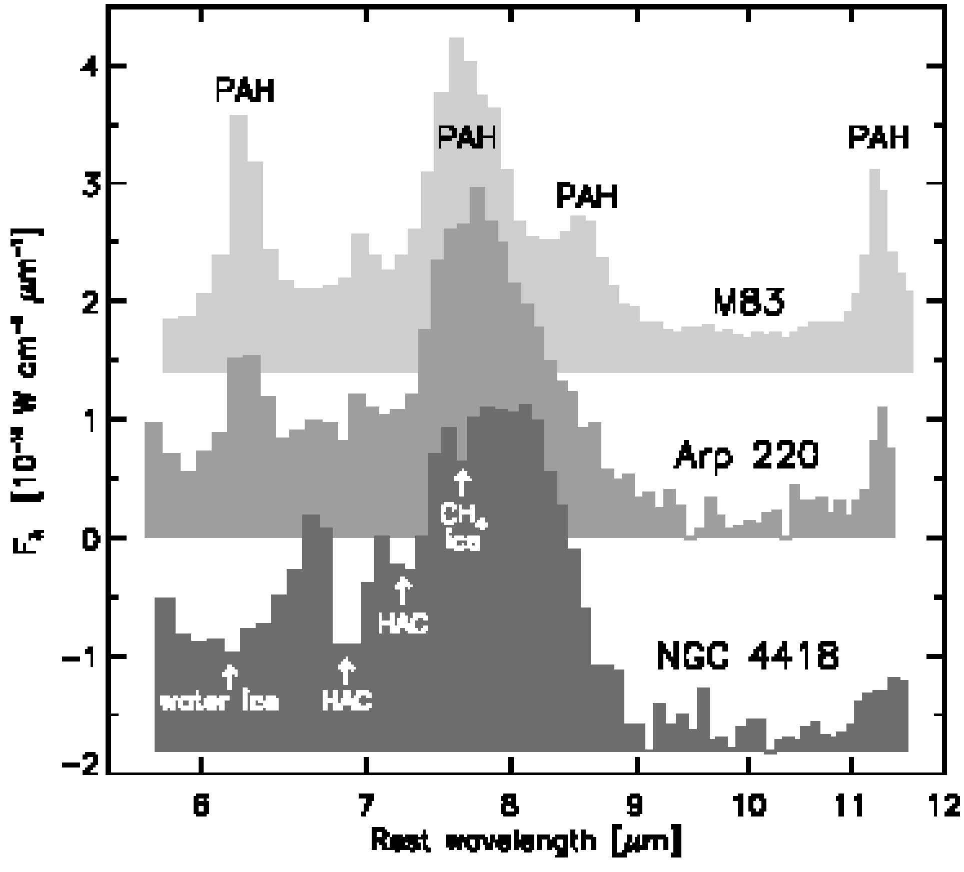
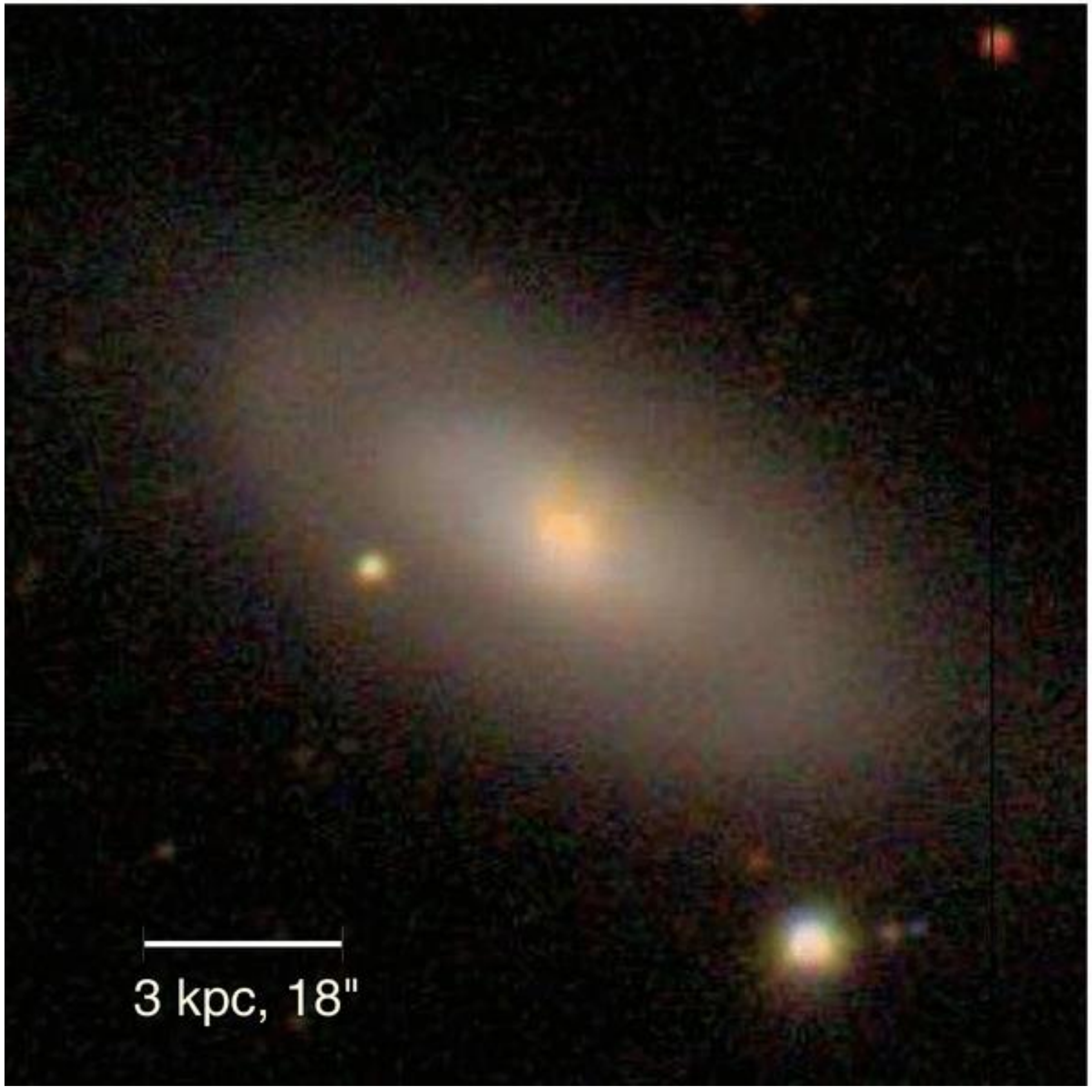
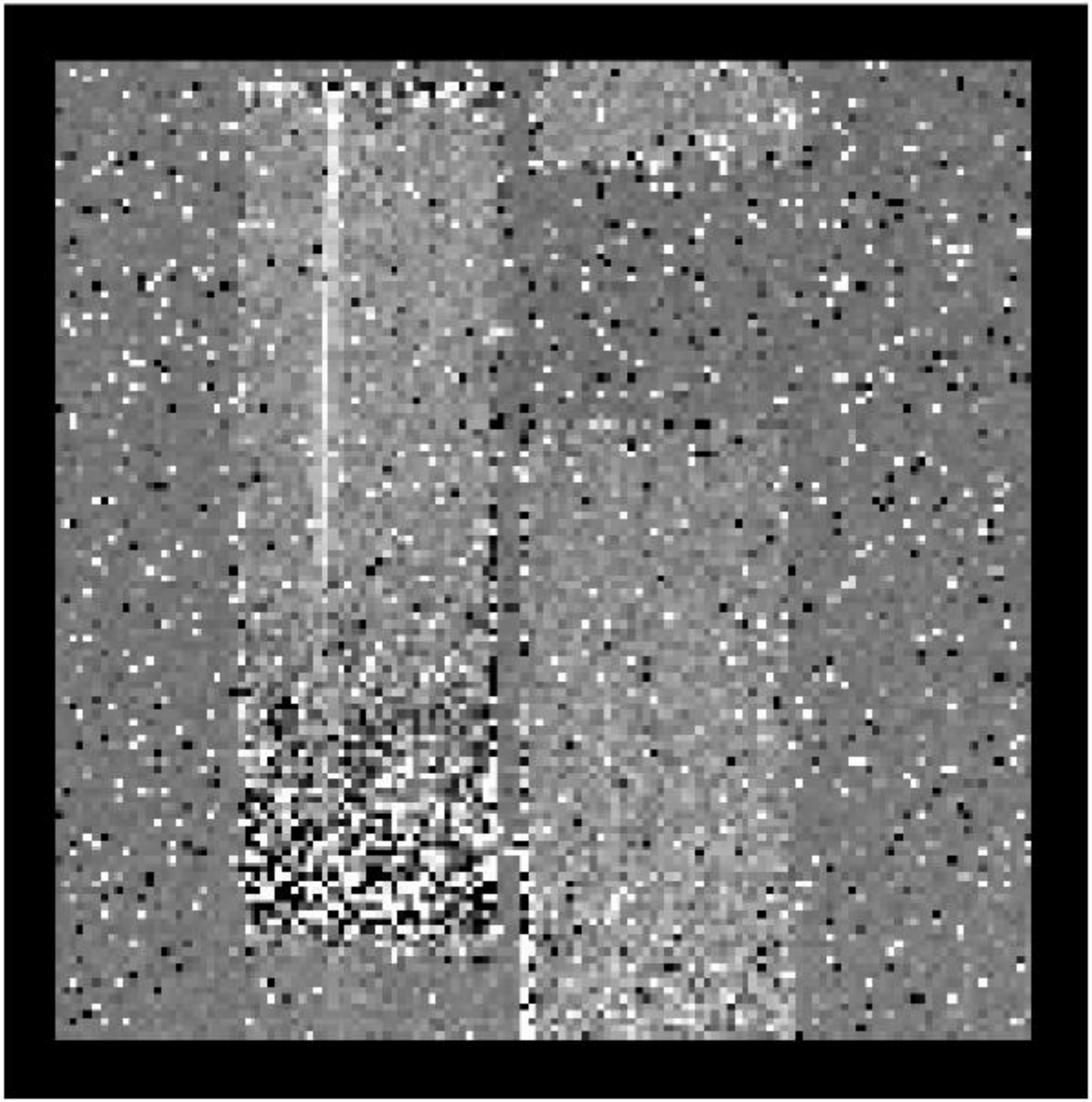


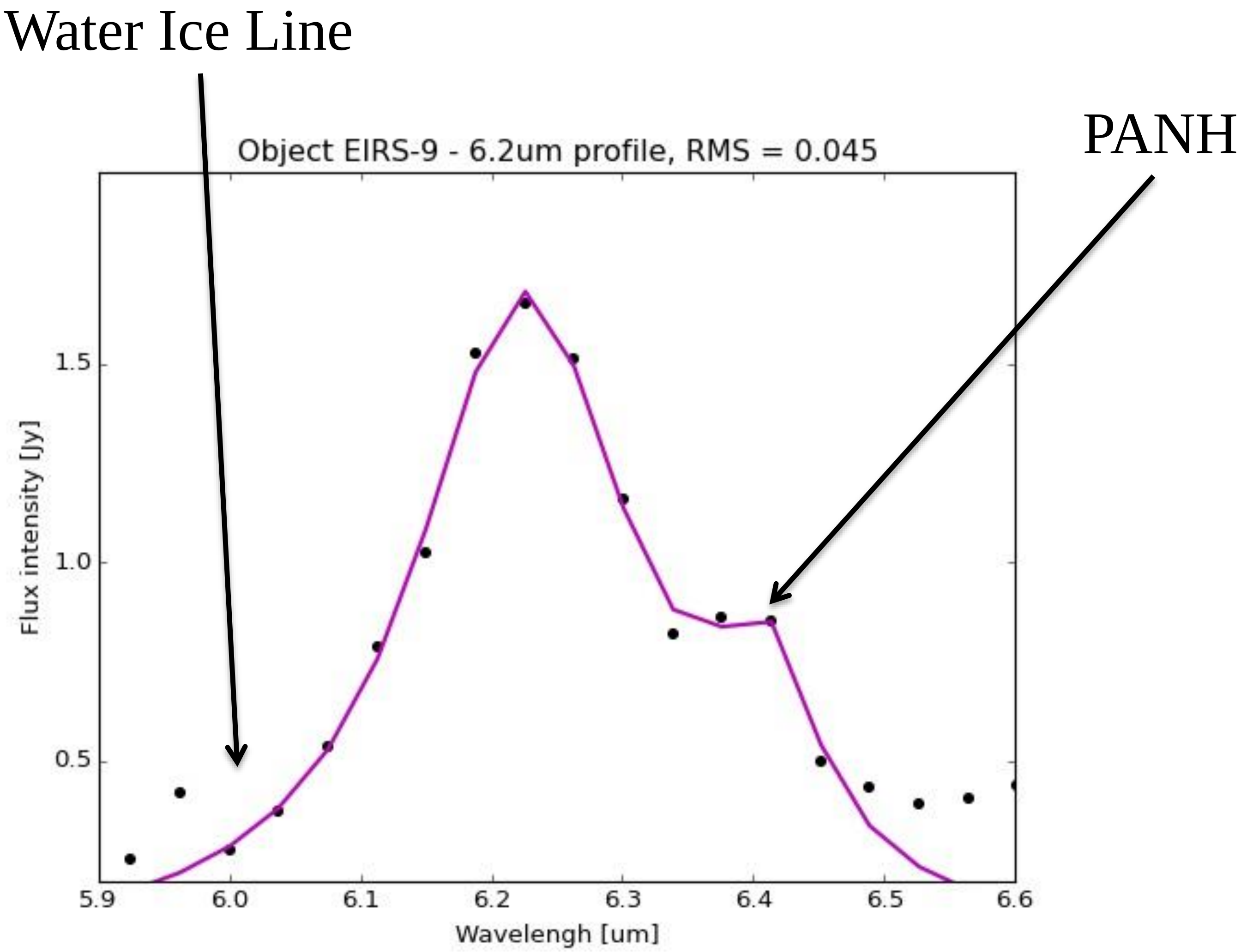
Fig. 2. A comparison of the ISO–PHT–S spectra of M 83, Arp 220 and NGC 4418. While the spectrum of M 83 is dominated by PAH emission bands, the spectrum of NGC 4418 is dominated by absorption bands of ices and silicates. The spectrum of Arp 220 shows characteristics of both. The spectra of M 83 and NGC 4418 have been scaled and offset.


3 kpc, 18"

Spitzer

Diâmetro: 0,85 m

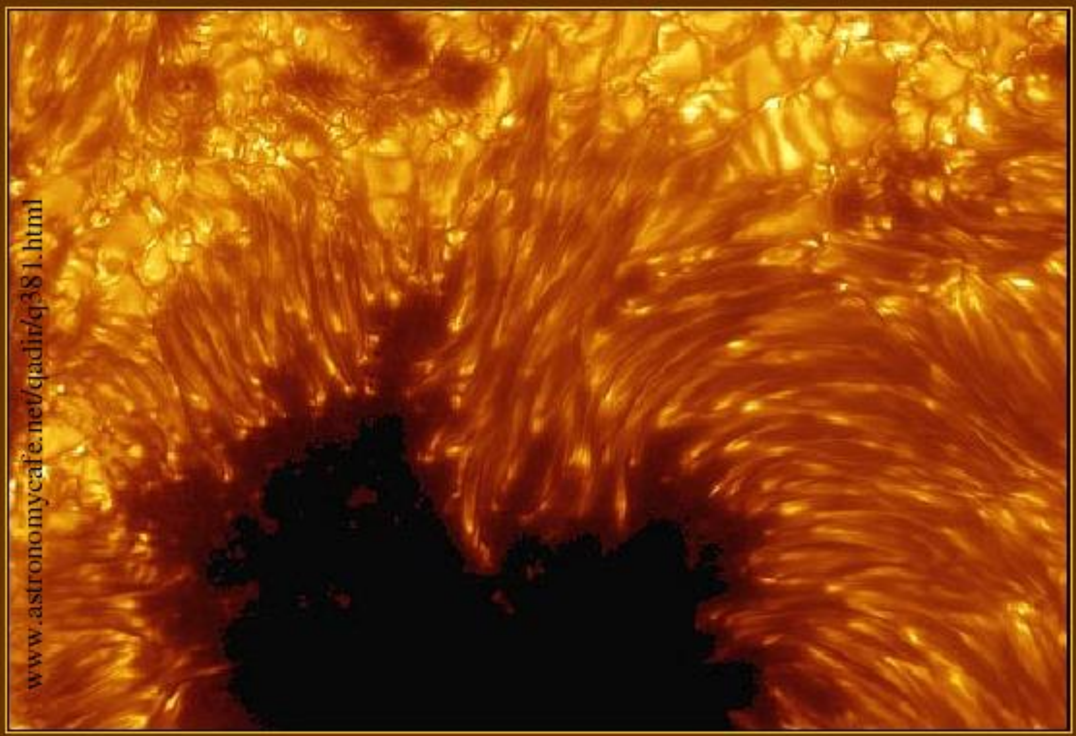



Water Ice Line
PANH
Object EIRS-9 - 6.2um profile, RMS = 0.045
Flux intensity [Jy]
1.5
1.0
0.5
5.9
6.0
6.1
6.2
6.3
6.4
6.5
6.6
Wavelengh [um]

z=1.83

O SISTEMA SOLAR
É ÚMIDO

SOL

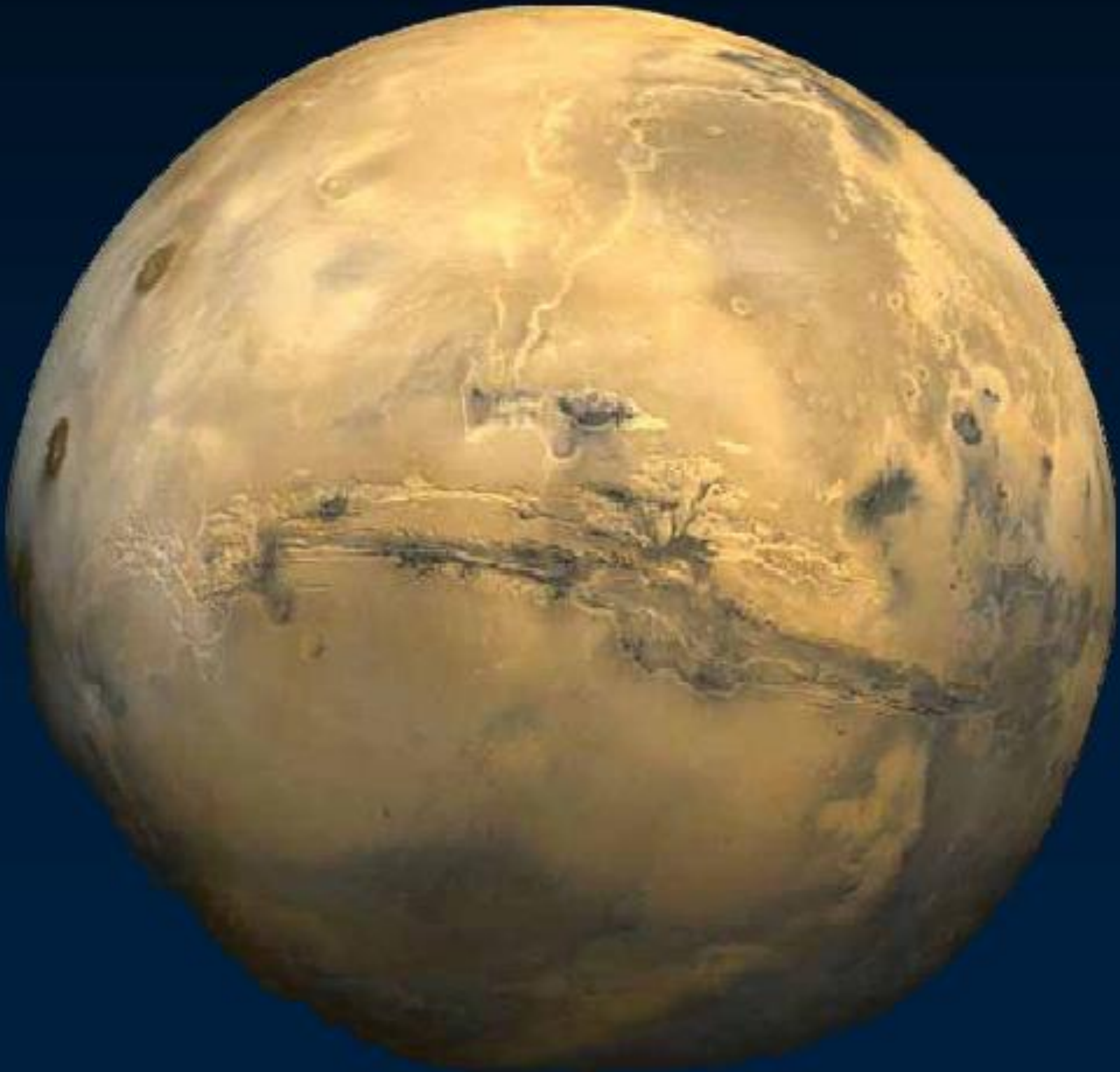


Regiões mais frias da atmosfera solar, cerca de 4.500 K

Na forma de vapor, a água está presente nas manchas solares. Elas causam uma espécie de efeito estufa. Moléculas de vapor de água são absorsores importantes nas atmosferas de estrelas frias, como a gigantes vermelhas variáveis.

O espectro da mancha na região espectral do infravermelho (entre 196 e 217 nanometros) é praticamente dominado por linhas de absorção pela água. Esta é a conclusão de Wallace e Livingston (NSO Tech. Rep. 92-001, 1992).

MARTE

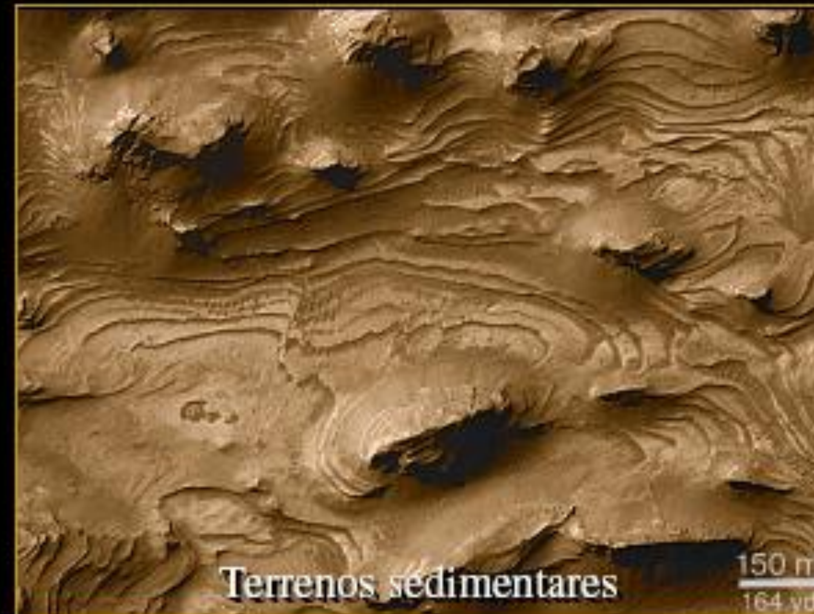


Água em Marte hoje

- A baixa pressão atmosférica impede água liquída na superfície

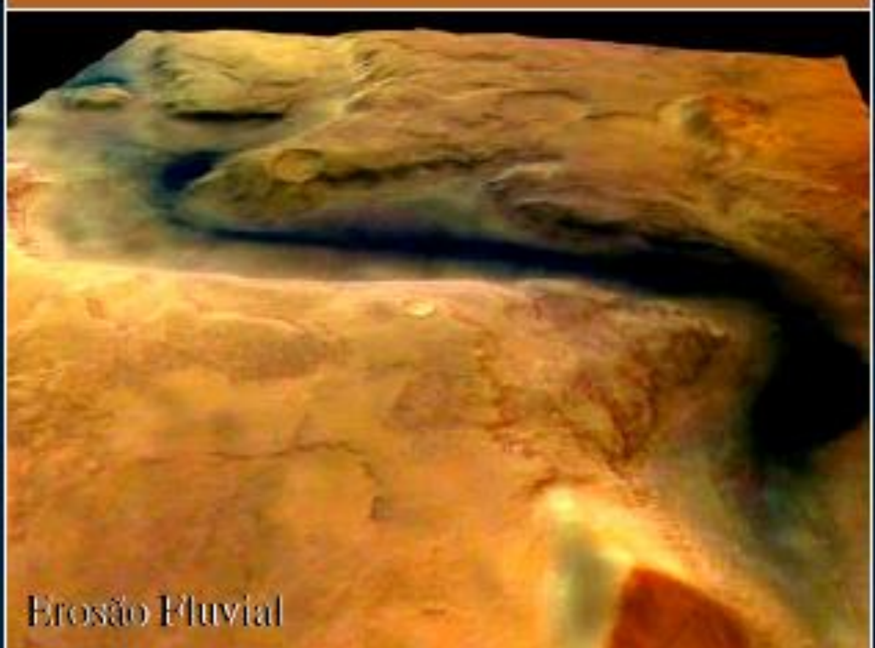
Vestígios de água em Marte

Já houve clima favorável à existência de água líquida na superfície. Eis algumas evidências:

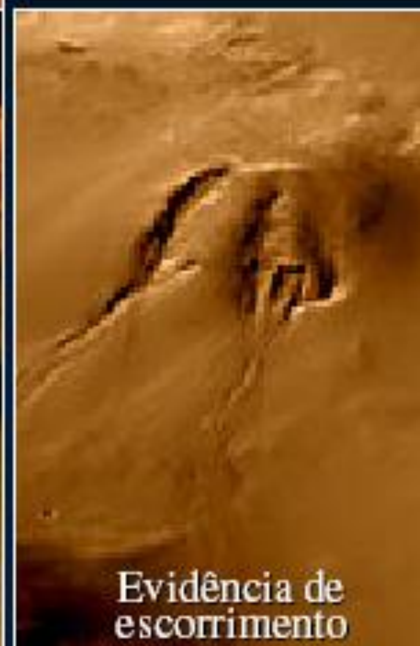


Terrenos sedimentares

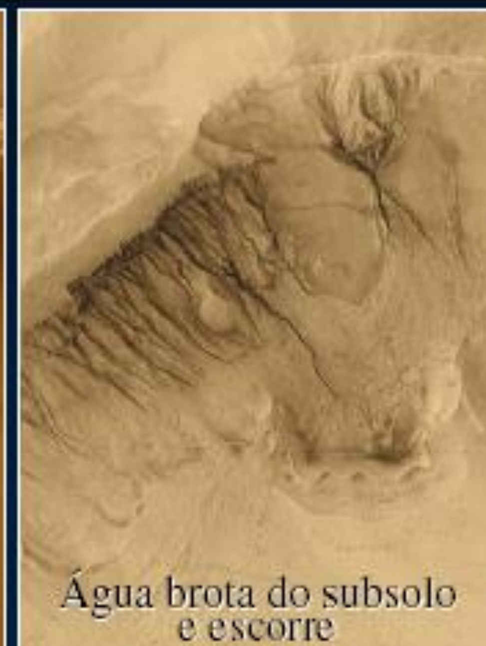
Vale Reull (41° S, 101° L), visto de 273 km acima do solo. Canal formado no passado por água corrente



Erosão Fluvial



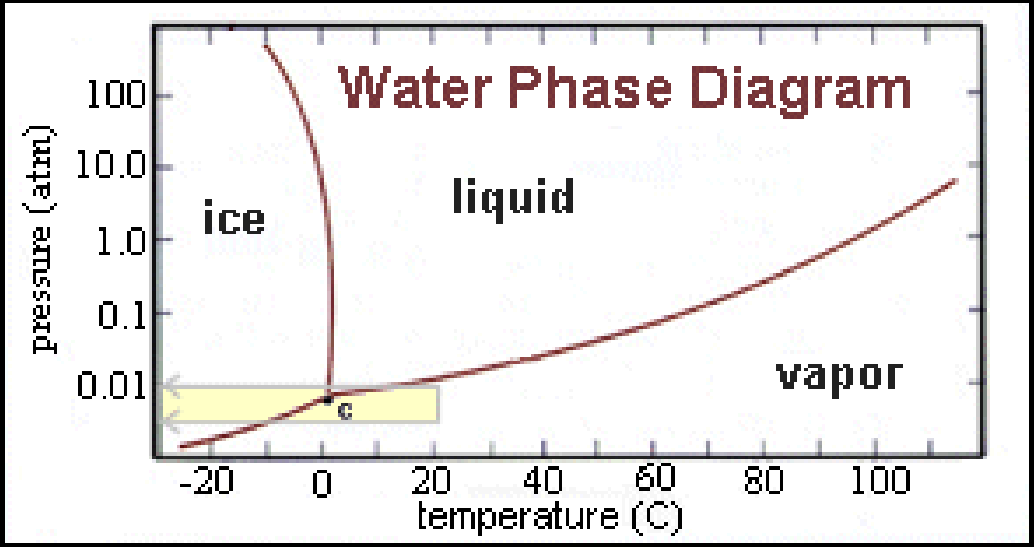
Evidência de escorrimento

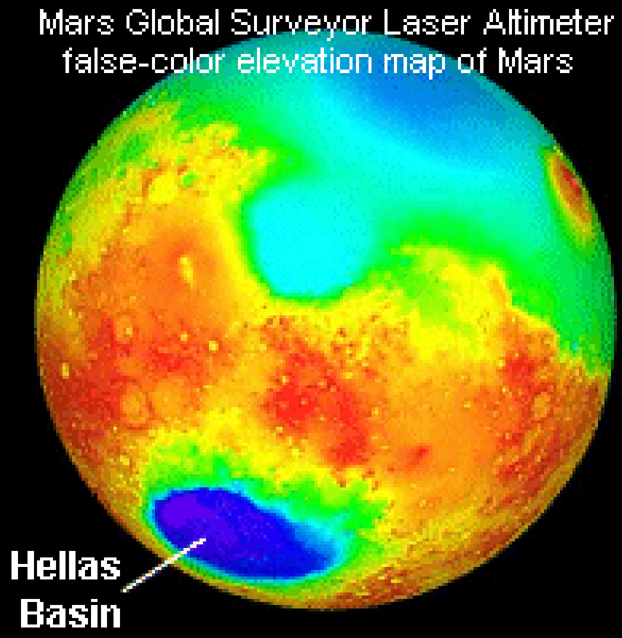


Água brota do subsolo e escorre

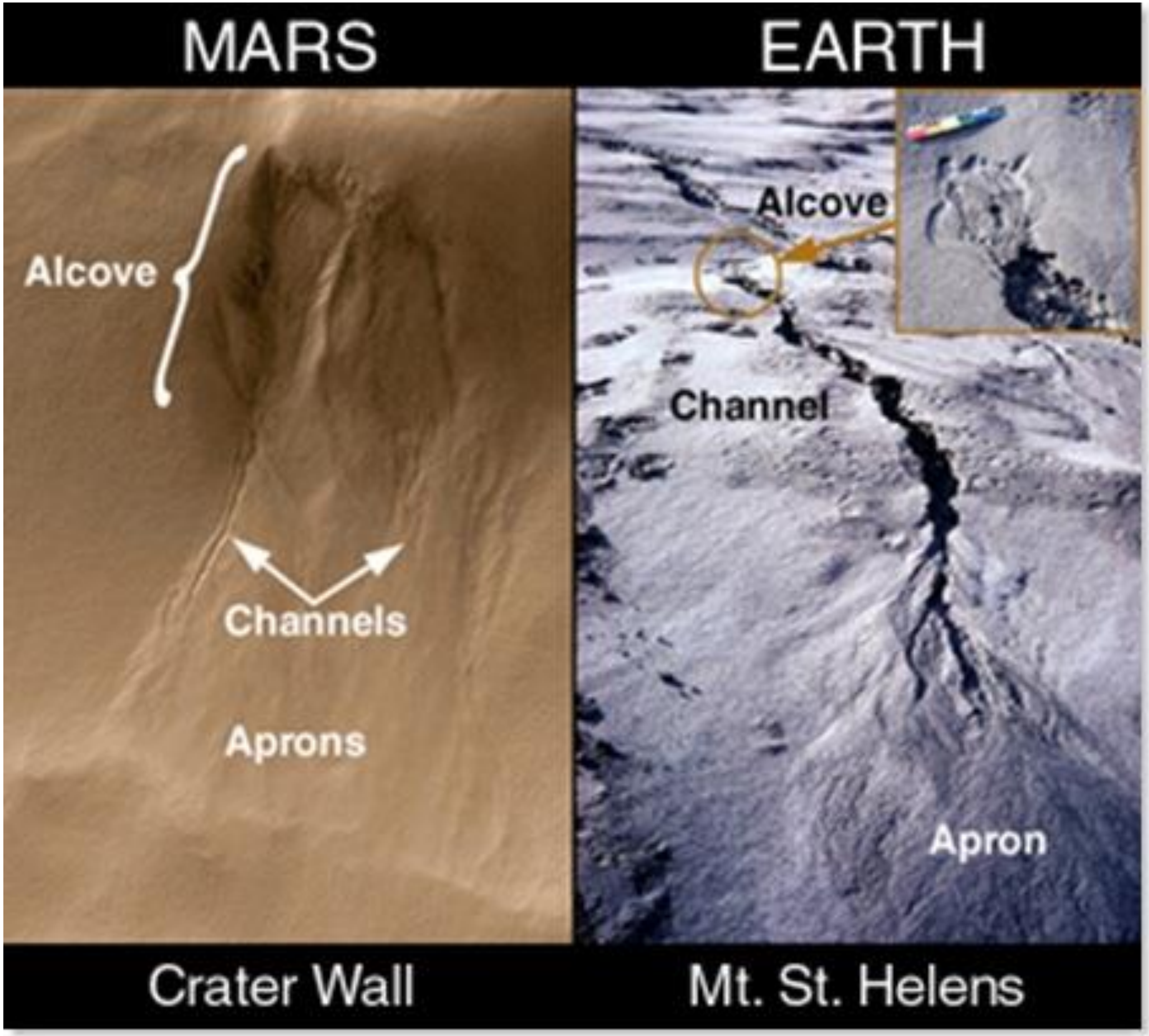
Água líquida em Marte hoje?

- Ponto Triplo da água: (T,p)=(271.16 K, 611.73 Pa)
- Pressão média em Marte: T= 600 Pa
- Pressão míxima: 30 Pa (Olympus Mons)
- Pressão máxima: 1150 Pa (Hellas Planitia)

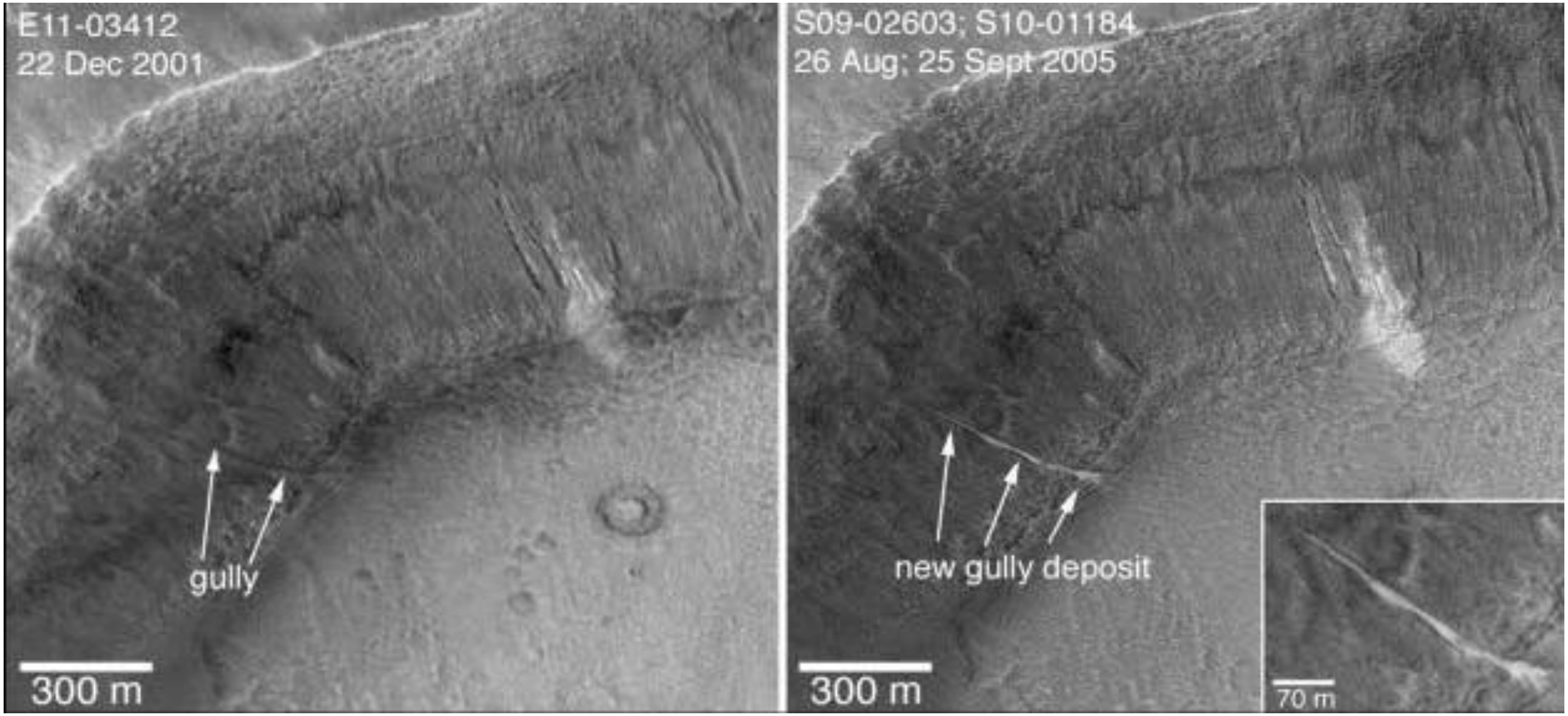




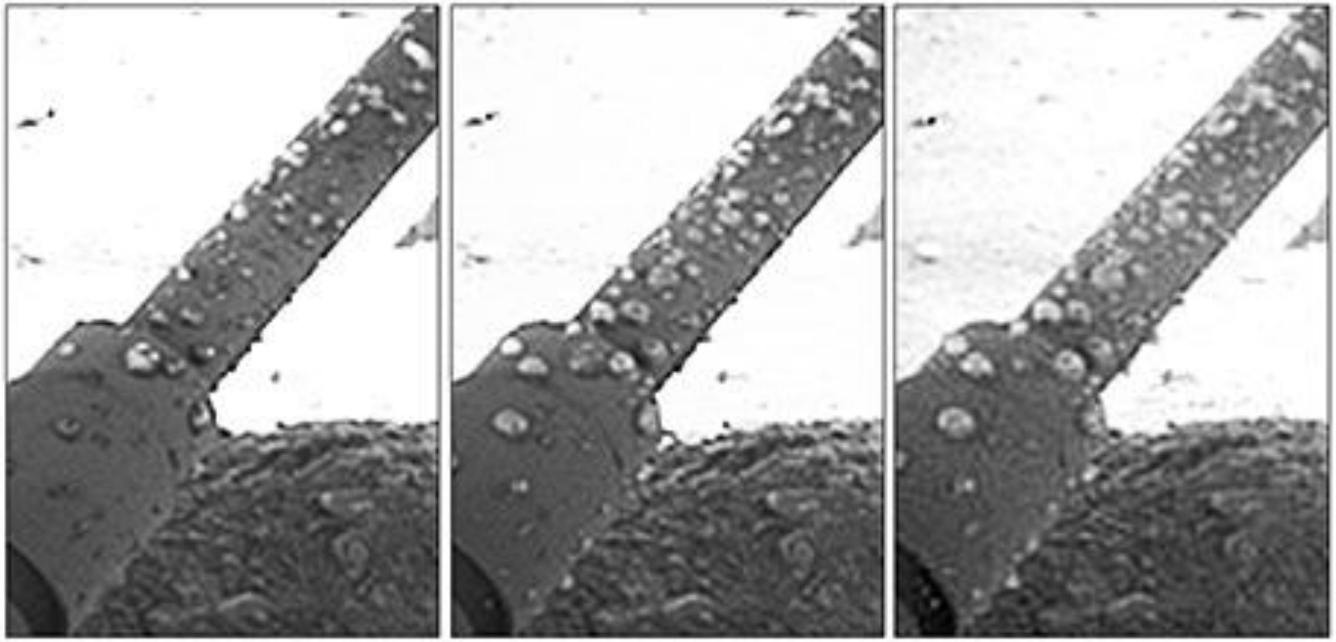
Water on Mars



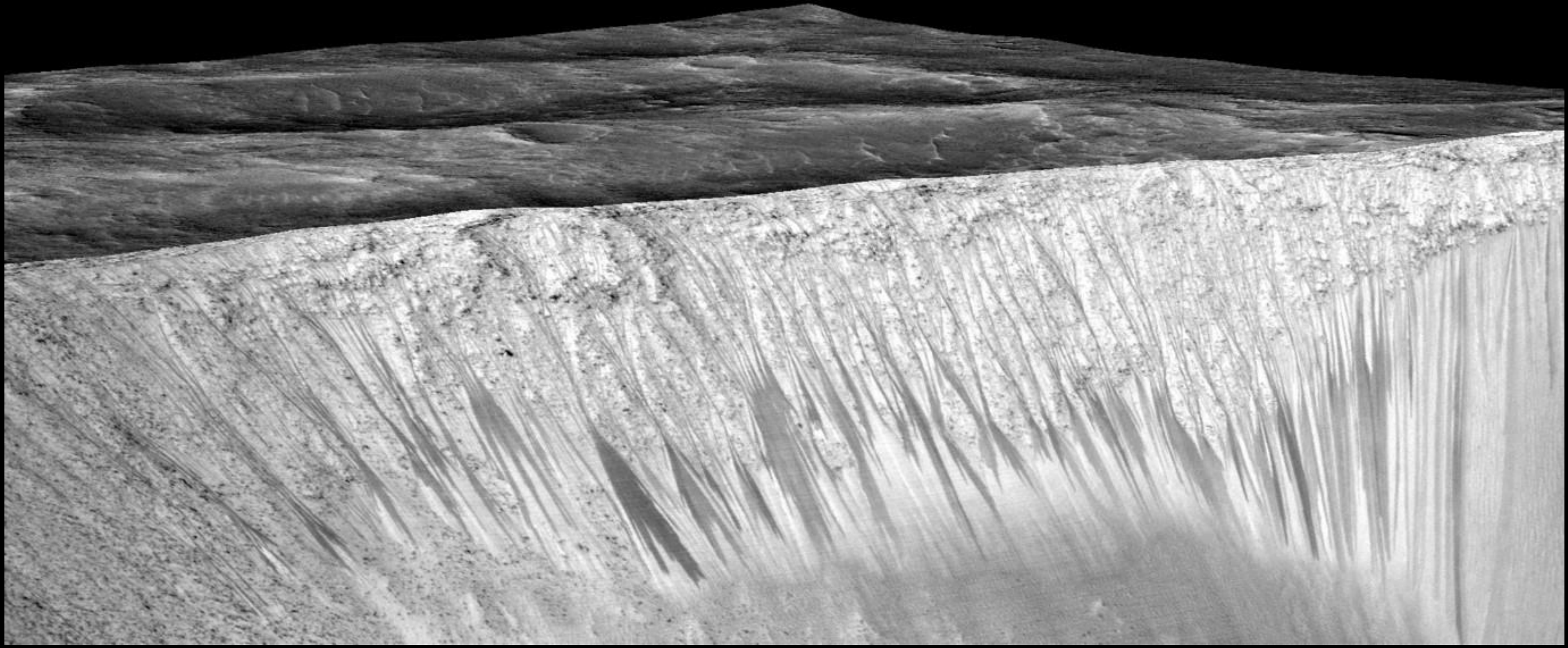
Water on Mars



Water on Mars



Water droplets collected on NASA's Phoenix lander



Cratera Garni

Descoberta água líquida em Marte!
(28/9/2015)

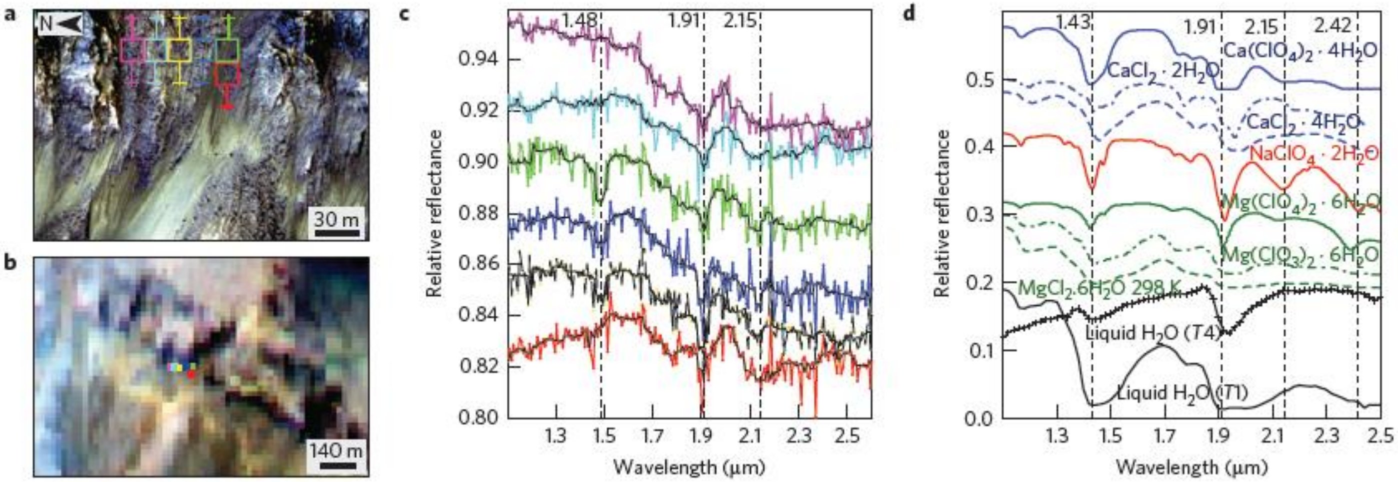


Figure 1 | Palikir crater RSL and spectral detection of hydration features. a, RSL on slope of Palikir crater ESP_024034_1380 (Infrared-Red-Blue/Green (IRB)) (L_S: 359 MY: 30). Coloured boxes show the location of the CRISM pixels with the uncertainty. **b**, Concurrent CRISM observation FRT0002038F (R: 2.53 μm, G: 1.51 μm, B: 1.08 μm) showing the same area as **a**. **c**, Spectra from coloured regions of interest shown in **a** and **b**. The observed data are plotted with coloured lines and the smoothed data in black lines. **d**, Laboratory spectra of various salts[17,28,29] and liquid water ($T1 = 1$ and $T4 = 4$ h into dehydration)[16].

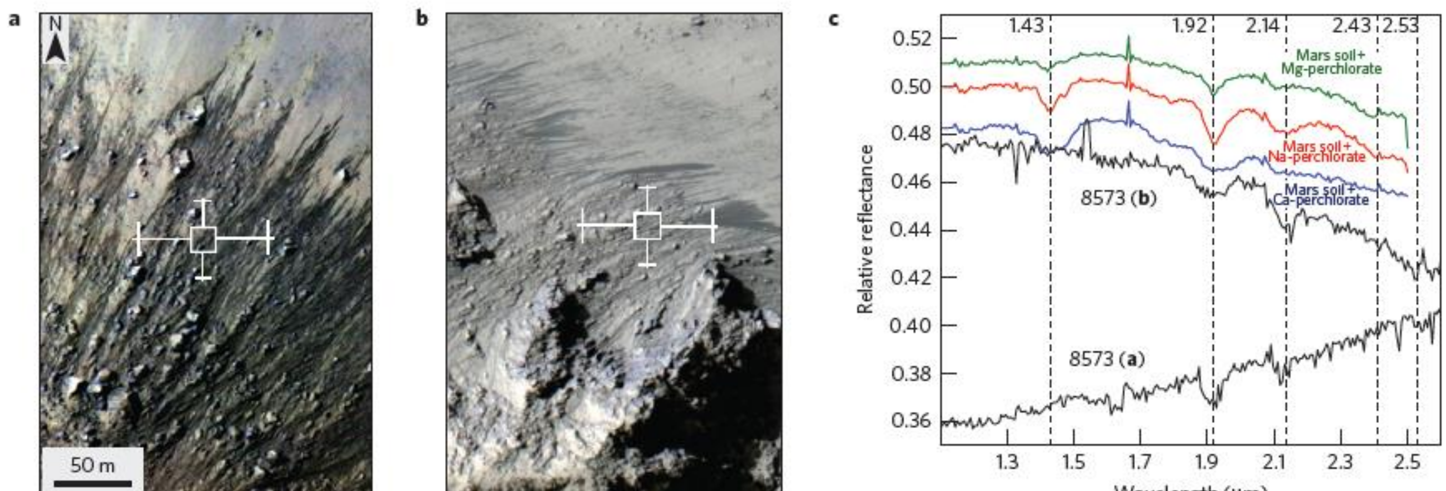
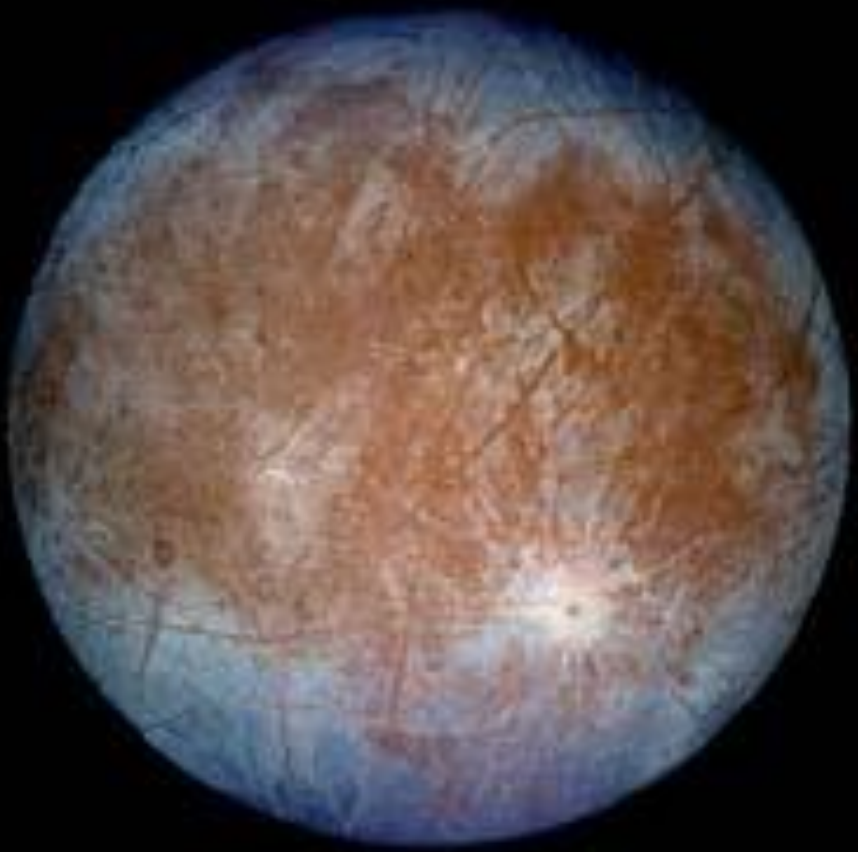
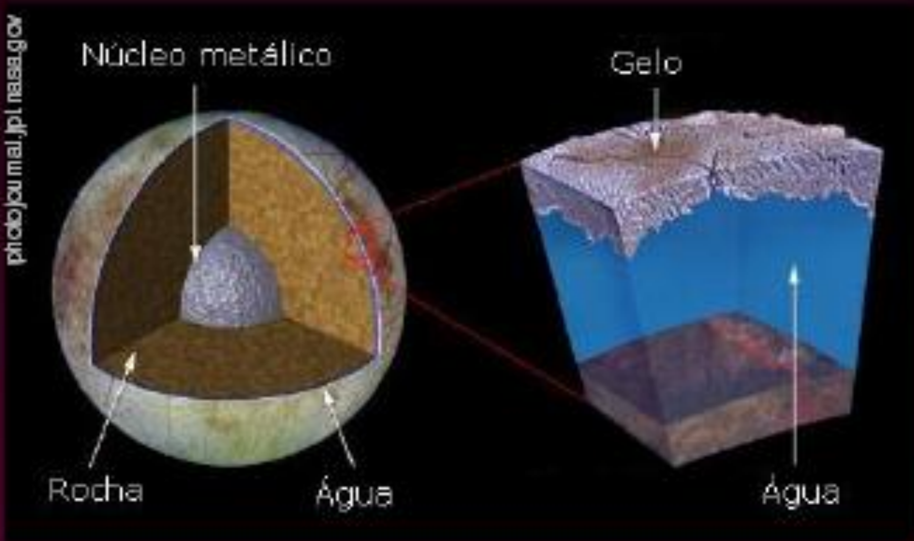


Figure 2 | RSL activity in the central peaks of Horowitz crater and associated CRISM spectra. a, RSL emanating from bedrock exposures at Horowitz crater's central peak. Part of HiRISE image PSP_005787_1475 (IRB) ($L_S = 334°$, MY 28). **b**, A different section of the same HiRISE image as **a**, showing RSL activity at a different peak (scale same as in **a**). In **a** and **b**, the white box with error bars shows the location of the CRISM pixels with the uncertainty. **c**, Black spectra correspond to the area in **a** and **b**, from CRISM observation FRT00008573. Coloured spectra are results from spectral mixing between the Martian soil and a variety of salts (specified in the figure).

Europa

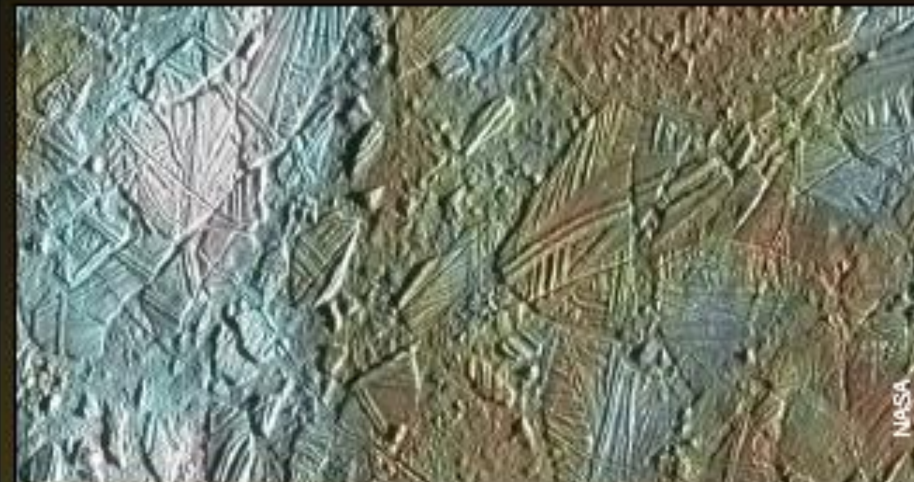




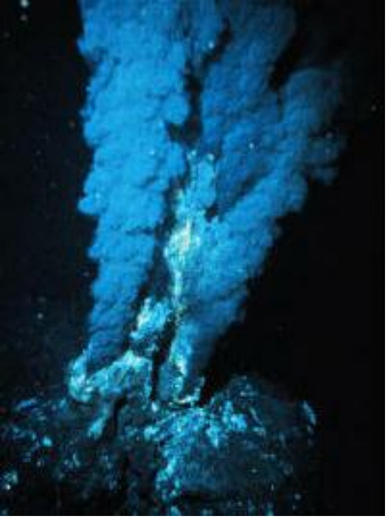
Europa, um dos maiores satélites de Júpiter, é um oceano cósmico. Abaixo de sua superfície congelada jaz um oceano de água líquida.

Em futuro próximo uma sonda visitará Europa.

Um explorador aquático deverá mapear o interior e procurar por alguma forma de vida.

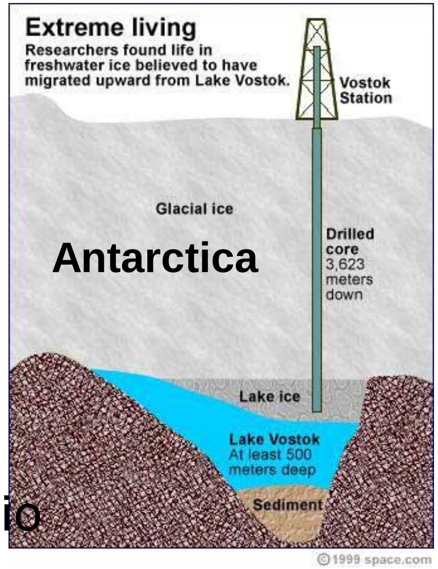


A crosta se fragmenta, os blocos de gelo flutuam na água, movem-se, e são fundidos em posições diferentes após o congelamento da água. Este fenômeno também se observa nas regiões polares da Terra.

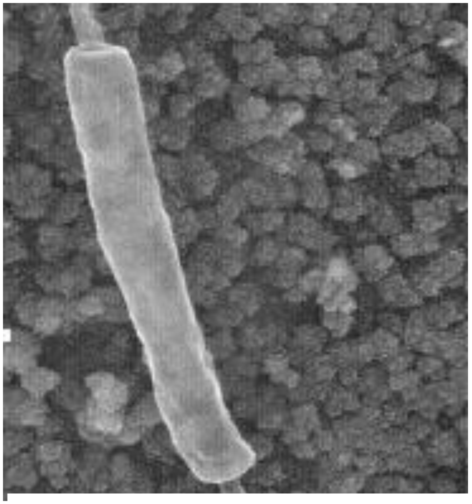


Hidrotermal vents

Extremófilos



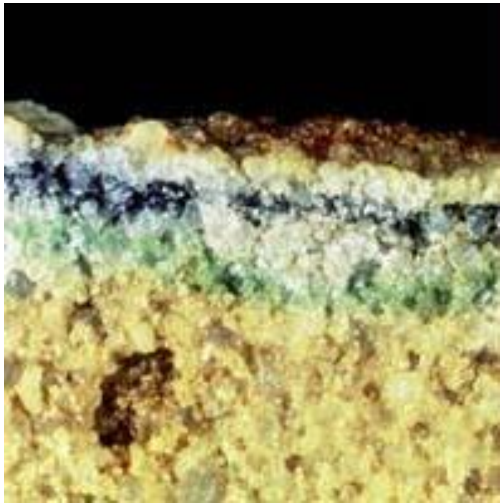
- Temperatura: -15° C < T < 230° C
- 0.06 < pH < 12.8
- 0 < Pressão < 1200 atm
- Seu metabolismo pode dispensar o oxigênio
- 20-40 milhões de anos de dormência
- 2 ½ anos no espaço, a –250 C, sem nutrientes, água and expostos a radiação (*Strep. Mitis*)



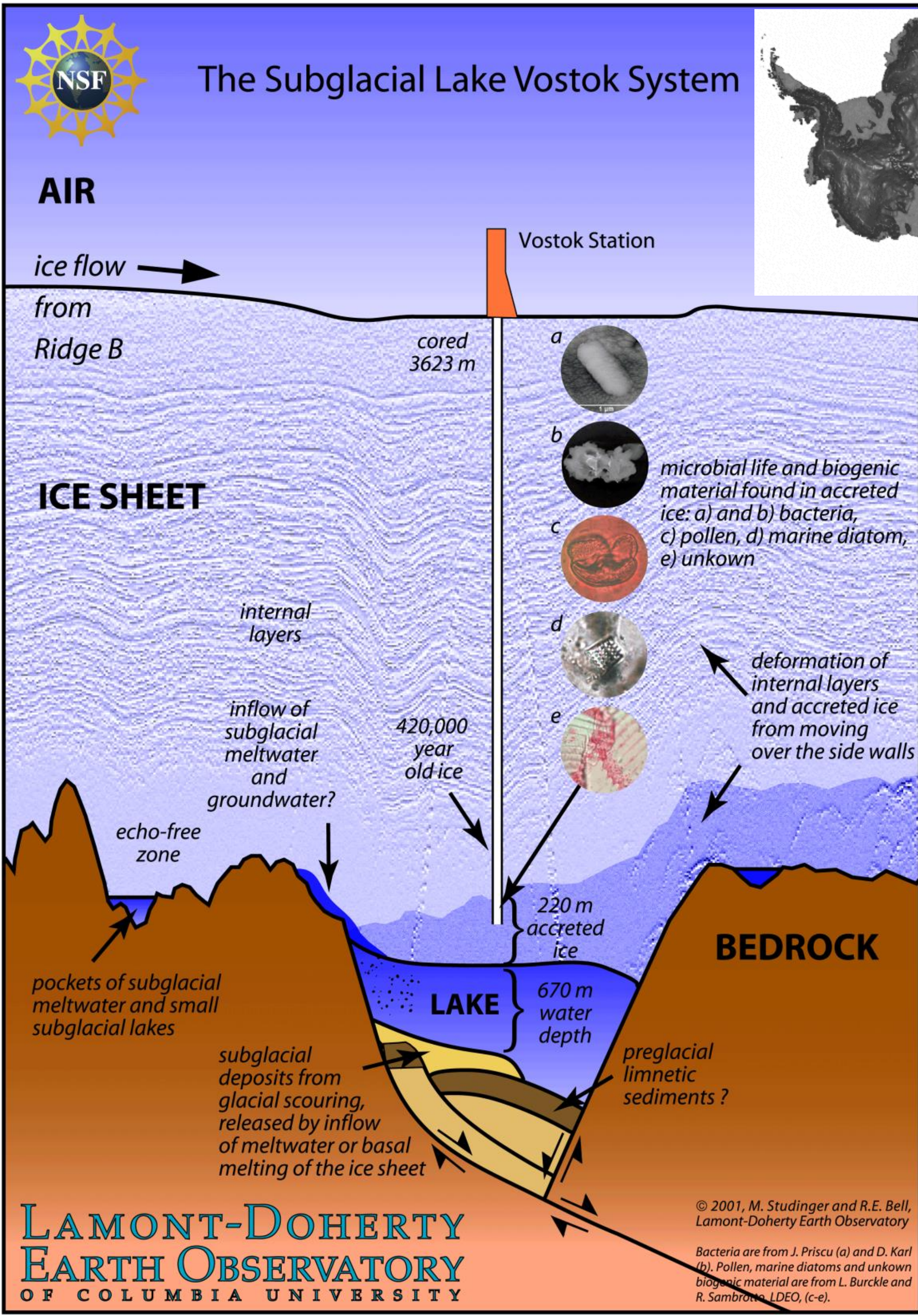
Thermophile bacteria

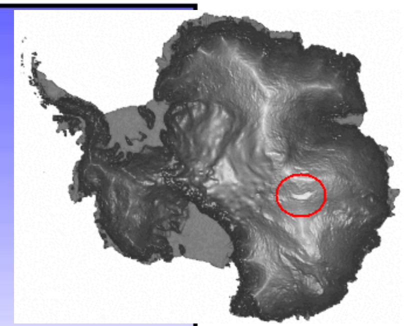
Hot geisers and volcans

Criptoendoliths

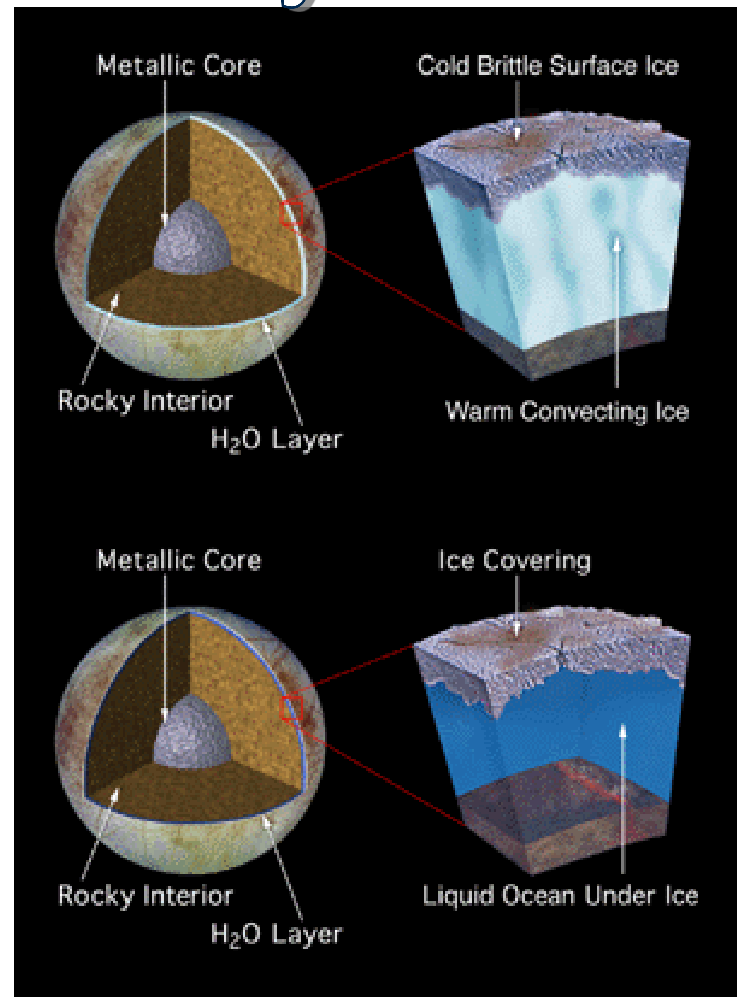


Life in subglacial systems



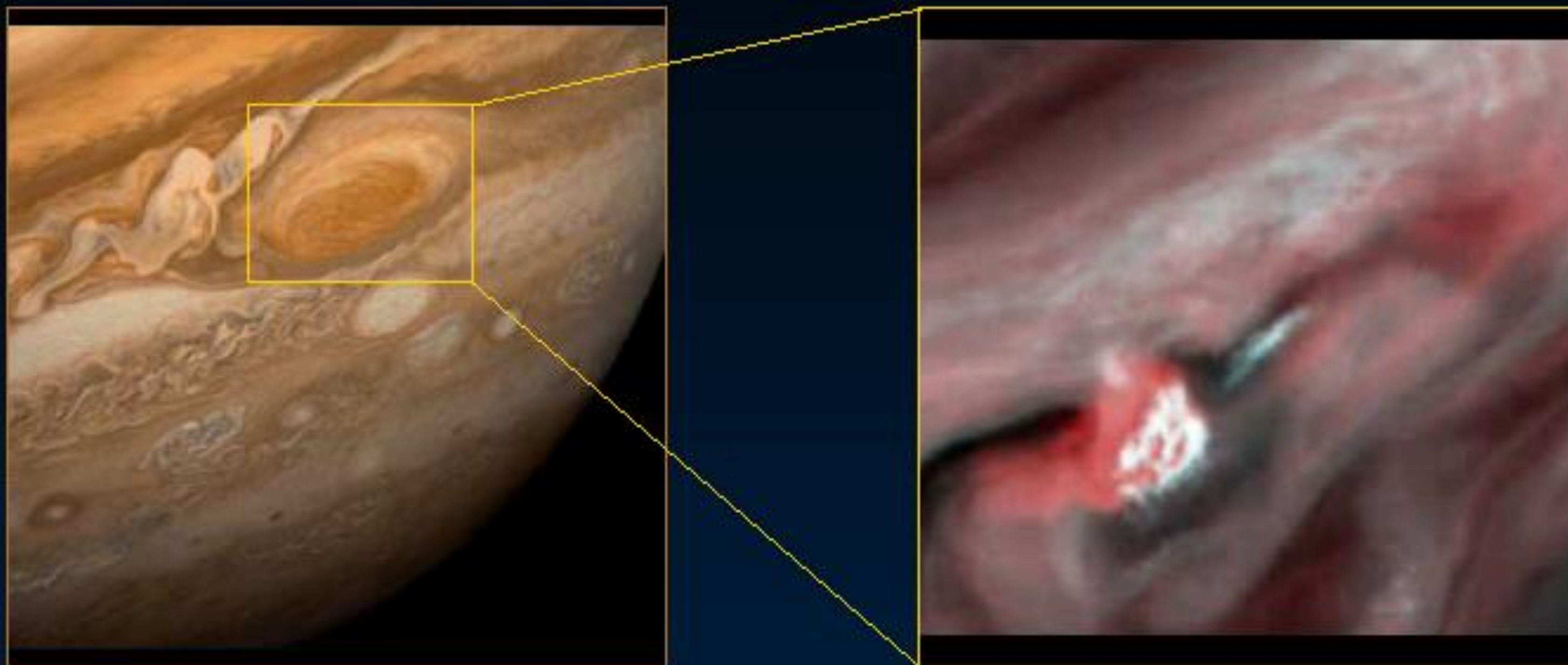


Europa

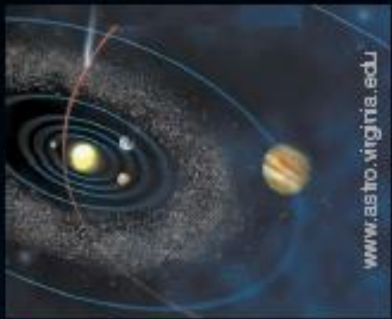


Kuhn

Tempestade de nuvem d'água em Júpiter?



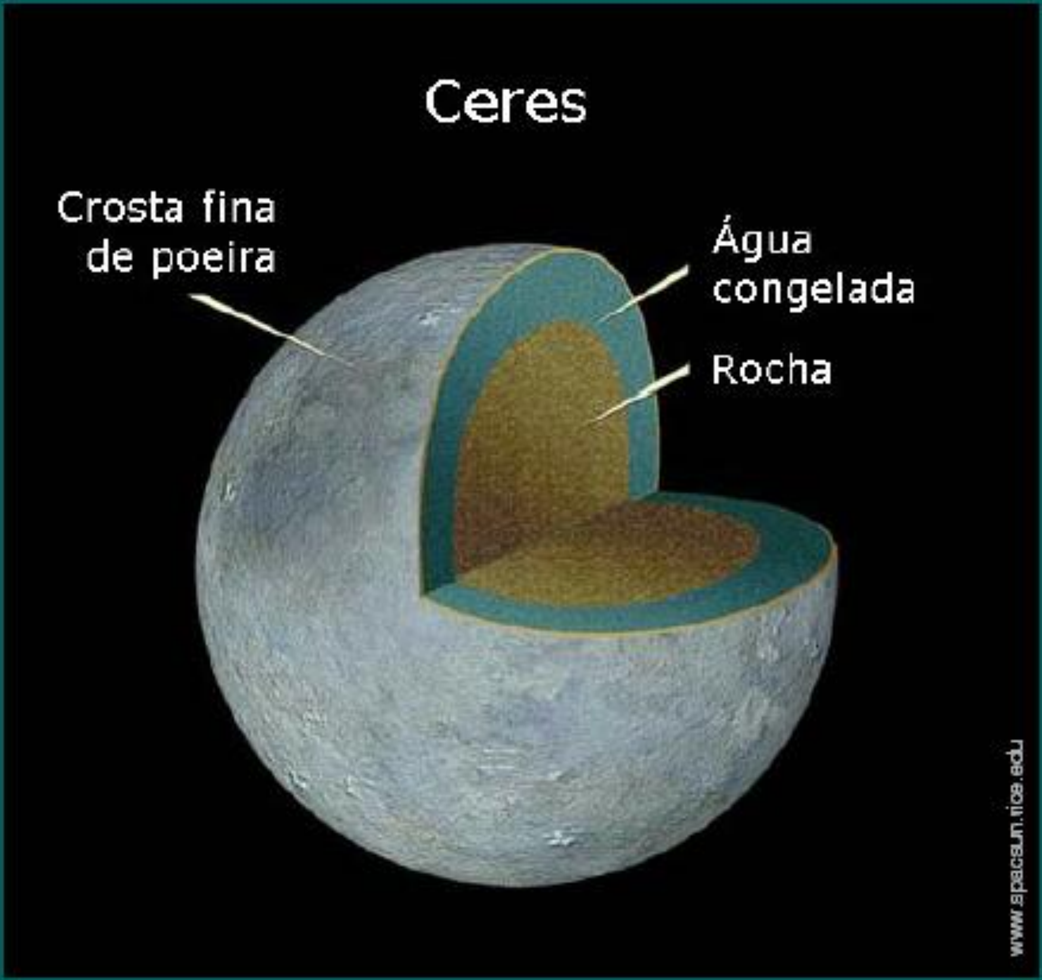
Uma tempestade convectiva à noroeste da Grande Mancha Vermelha é vista na imagem à direita. A área branca no centro é uma nuvem espessa de amônia, de baixa pressão (pouco menor que a do nível do mar) e bem mais elevada que as nuvens vizinhas. A região vermelha é a que contém água e representa a base dessa coluna tempestuosa.



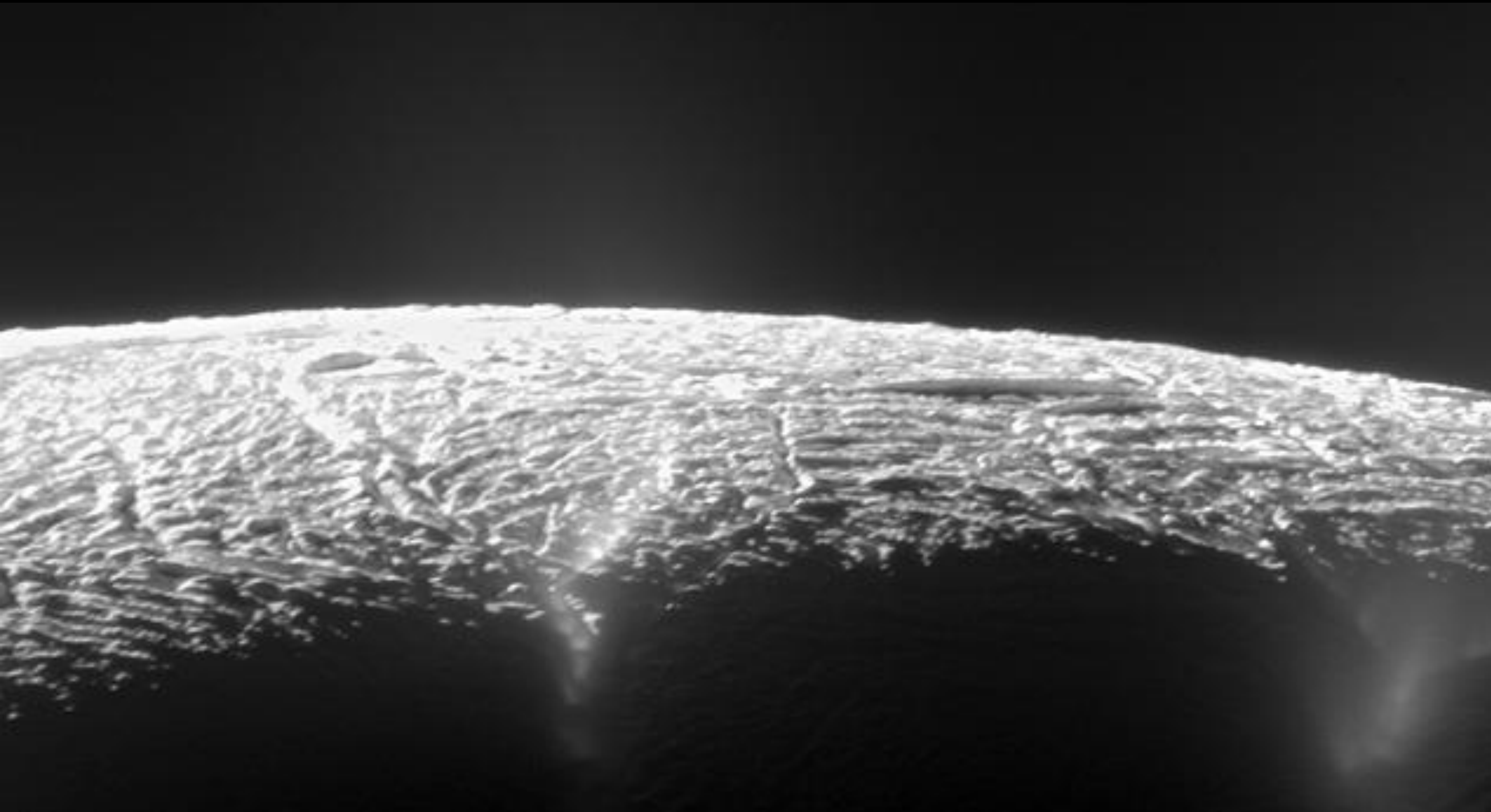
Planetas-anões podem conter água

Antes de agosto de 2006 Ceres era o maior asteróide do Cinturão, localizado entre Marte e Júpiter, agora ele é o menor planeta-anão. Com seus quase 930 km de diâmetro, ele pode conter cerca de 25% da massa total do Cinturão. Estudos recentes indicam a possibilidade de ele possuir um manto espesso rico em água. Se essa água representar um quarto da massa do manto, Ceres pode conter mais água doce que a Terra.

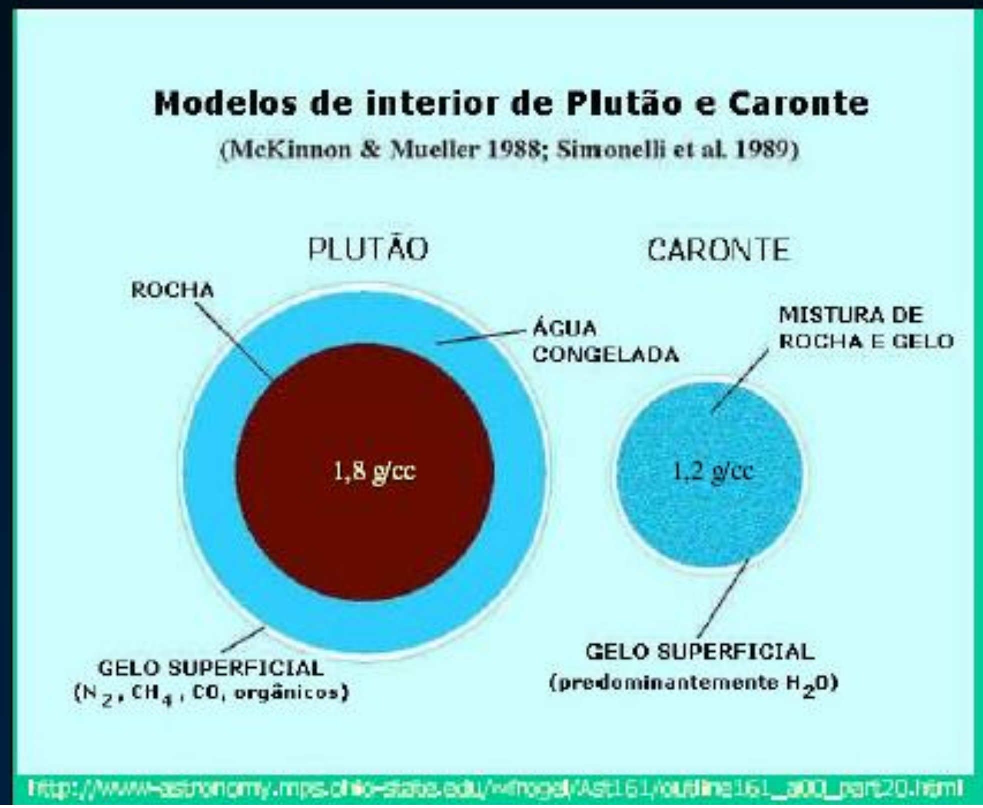
O volume total de água na Terra é cerca de 1,4 bilhão de km³, sendo 41 milhões de km³ de água doce. Ceres pode conter 200 milhões de km³ de água doce.



Enceladus

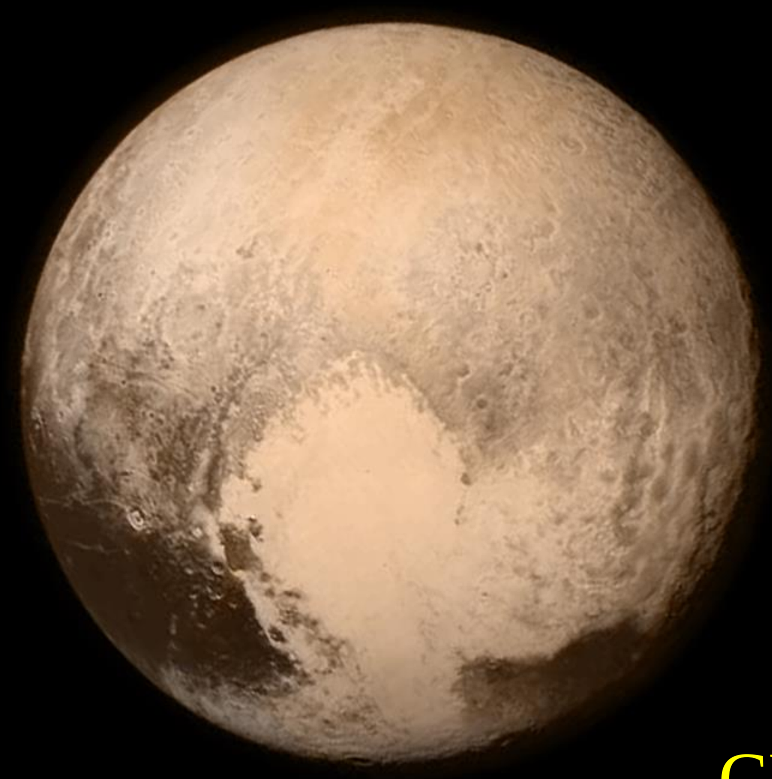


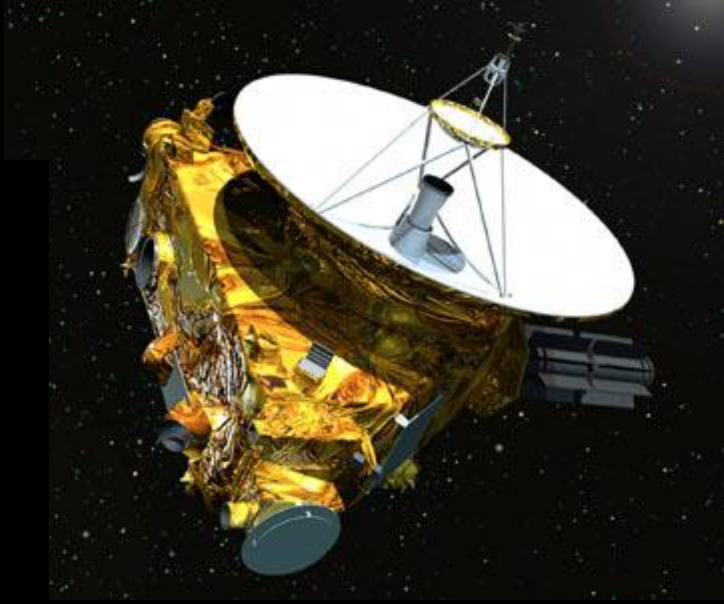
A dupla Plutão e Caronte é de uma região rica em água congelada



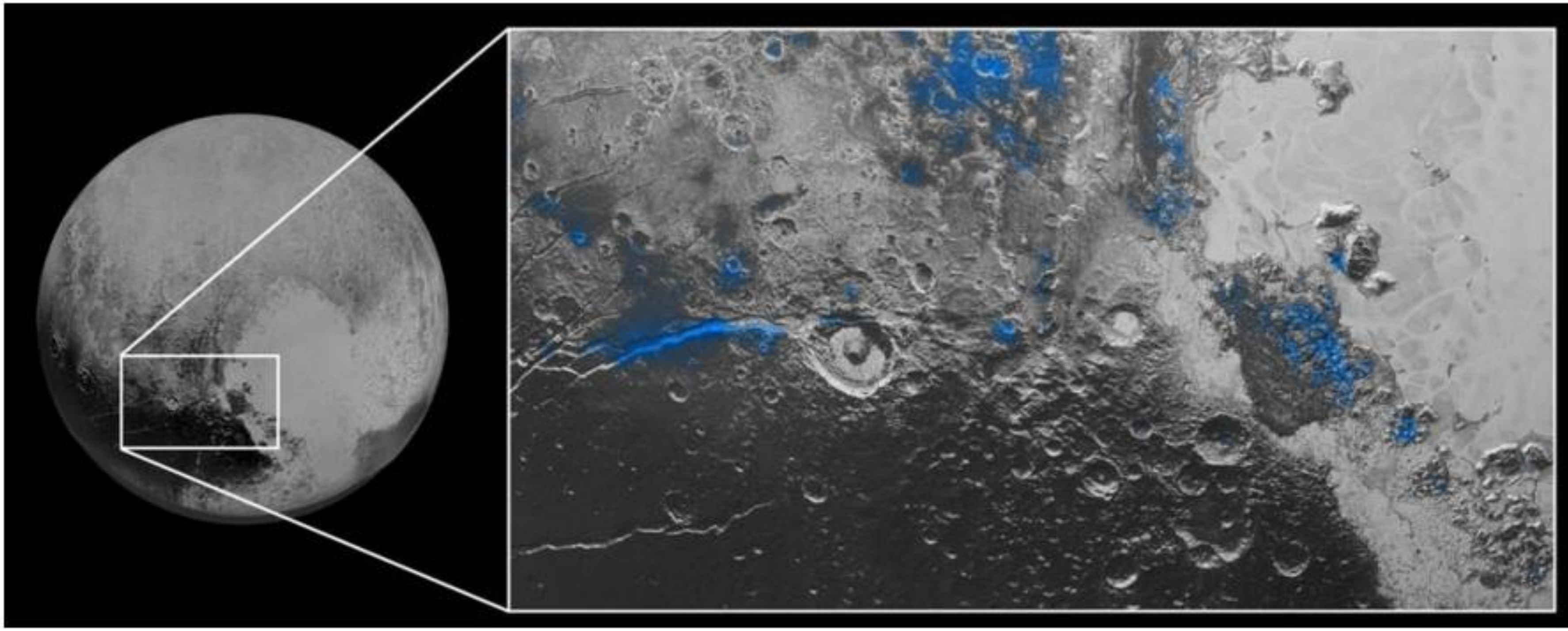
PLUTÃO

New Horizons





CLOSEST APROXIMATION
12.500 km
2015/07/15 00:52 GMT



Water Ice on Pluto: Regions with exposed water ice are highlighted in blue in this composite image from New Horizons' Ralph instrument, combining visible imagery from the Multispectral Visible Imaging Camera (MVIC) with infrared spectroscopy from the Linear Etalon Imaging Spectral Array (LEISA). The strongest signatures of water ice occur along Virgil Fossa, just west of Elliot crater on the left side of the inset image, and also in Viking Terra near the top of the frame. A major outcrop also occurs in Baré Montes towards the right of the image, along with numerous much smaller outcrops, mostly associated with impact craters and valleys between mountains. The scene is approximately 280 miles (450 kilometers) across. Note that all surface feature names are informal.
Credits: NASA/JHUAPL/SwRI

Os cometas são feitos praticamente de água

Composição química básica:

80% de H_2O,

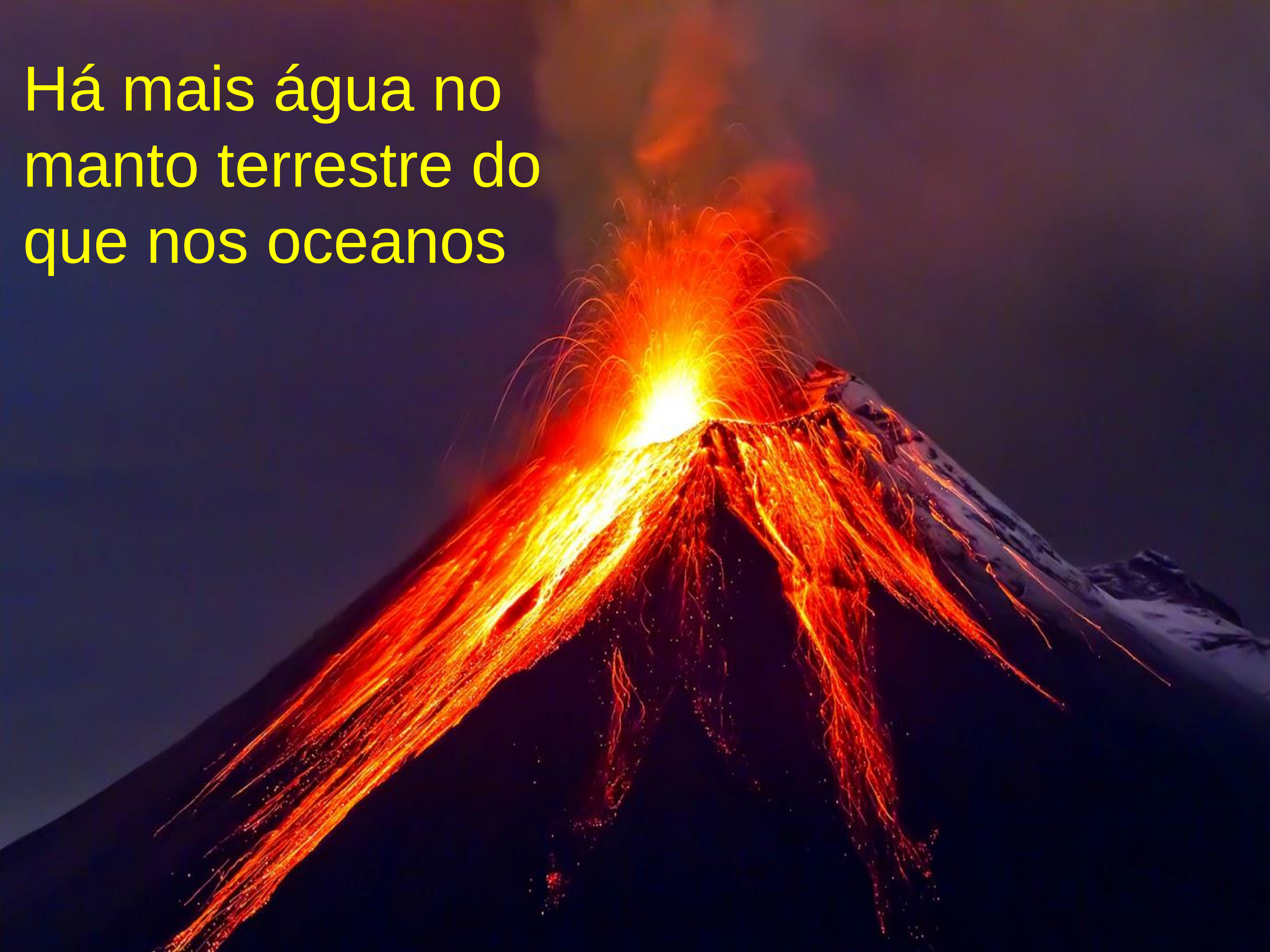
16% de CO,

4% de CO_2

e traços de

NH_3 e CH_4

A Terra é o "Planeta Água"?


Há mais água no
manto terrestre do
que nos oceanos

Super Terras e Planetas-Oceano

Liquid Water

- H_20 is the combination of the two most abundant chemical elements in the Universe
- H_20 is the most abundant tri-atomic molecule in the Universe (requires stars)
- liquid H_20 is much less common (a narrow range of pressure and temperatures)
- liquid H_20 requires planetary environments
- highest boiling temp= 650 K (high pressures)

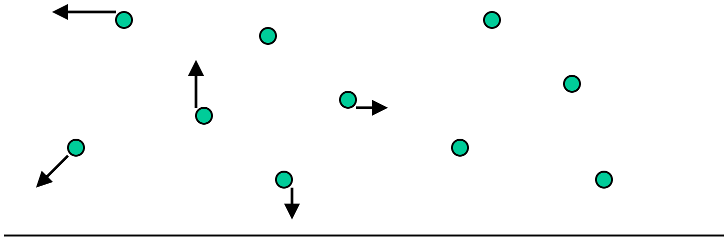
Três Estados da Água

- Na Terra, a água pode estar presente nos seus três estados: gelo (sólido), água líquida (líquido) e vapor d’água (gasoso)
- Pressão e Temperatura controlam qual é o estado dominante em um particular ambiente planetário

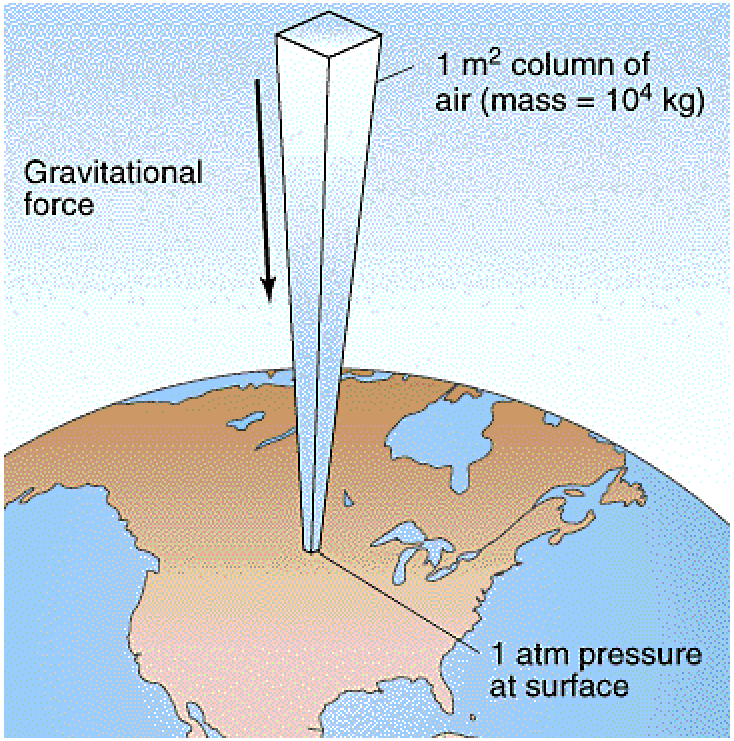


Pressão Atmosférica

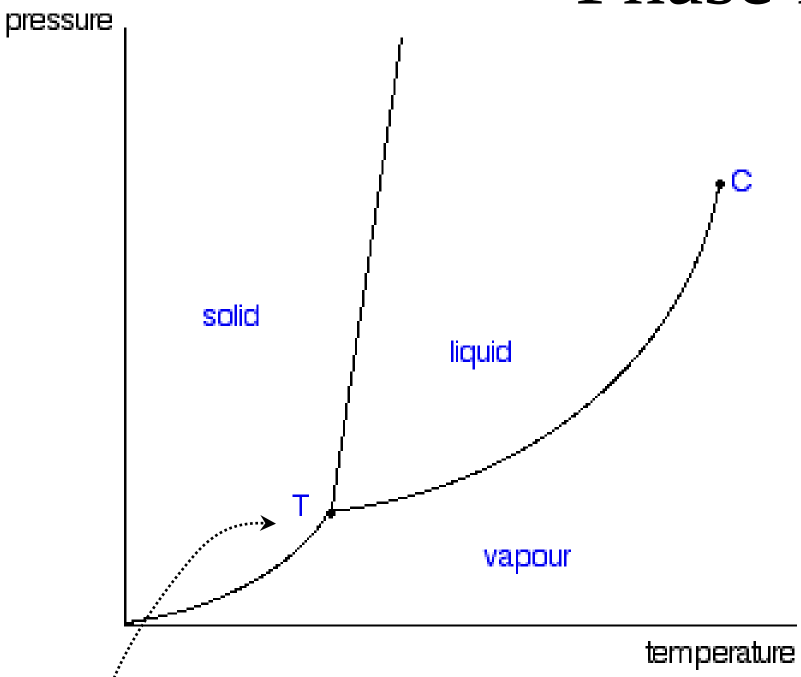
No nível do mar: 1 atmosfera = 101 325 Pa = 101.325 kPa = 1.01325 bar

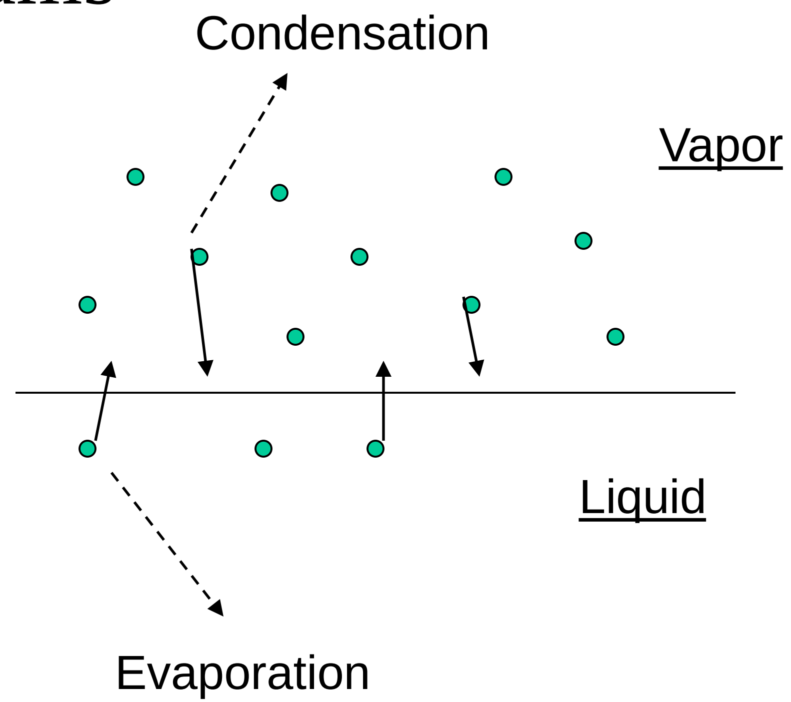


A pressão é devida ao impacto das moléculas na superfície



Phase Diagrams



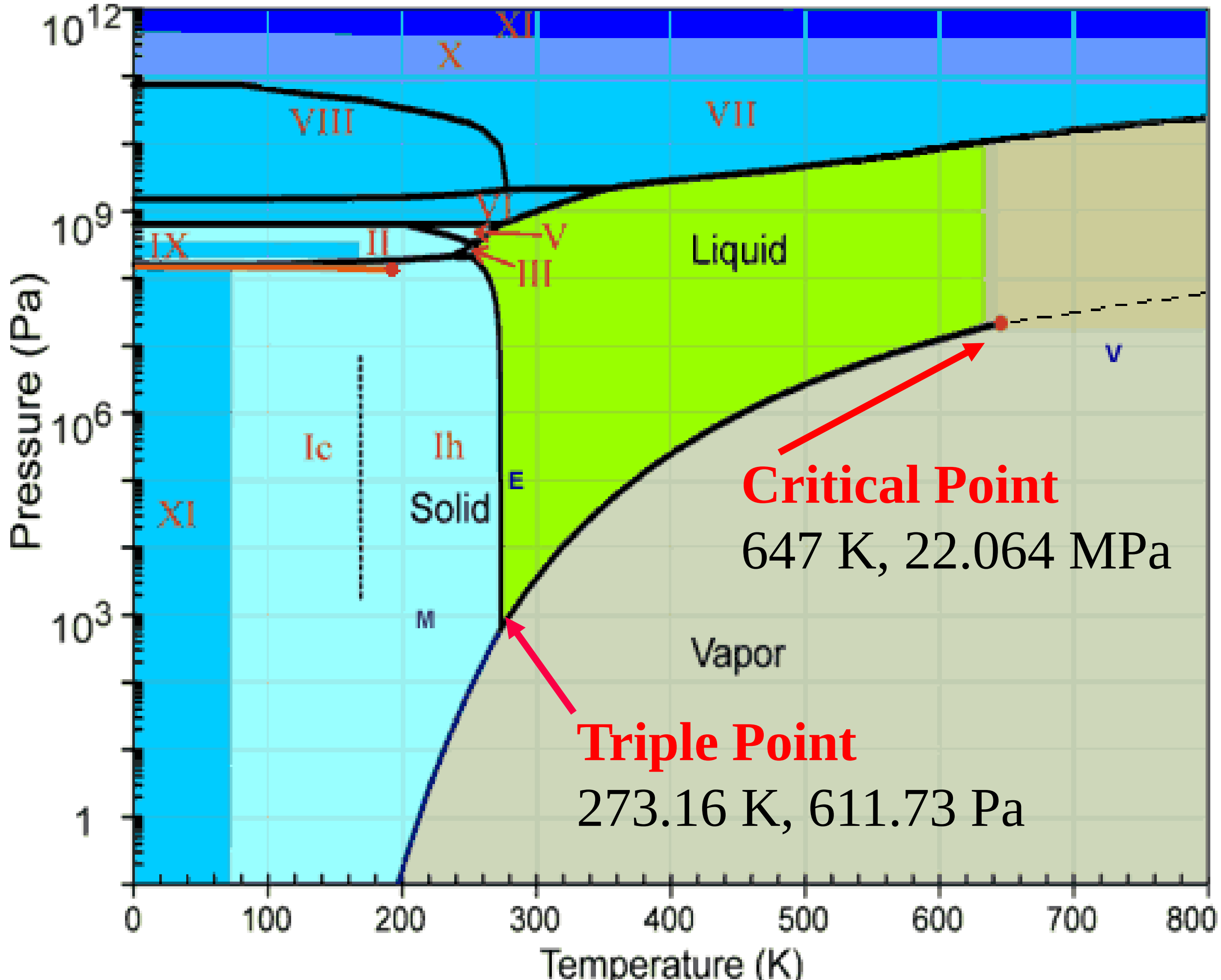


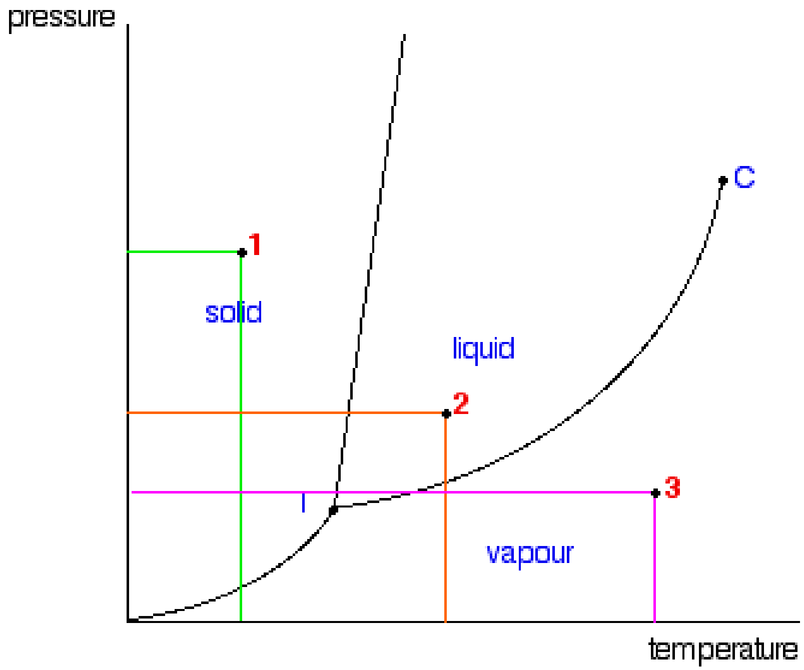
At some point Condensation = Evaporation – liquid and vapor phases are in Equilibrium – saturation curve

T – triple point of a substance is the temperature and pressure at which three phases (gas, liquid, and solid) of that substance may coexist in thermodynamic equilibrium

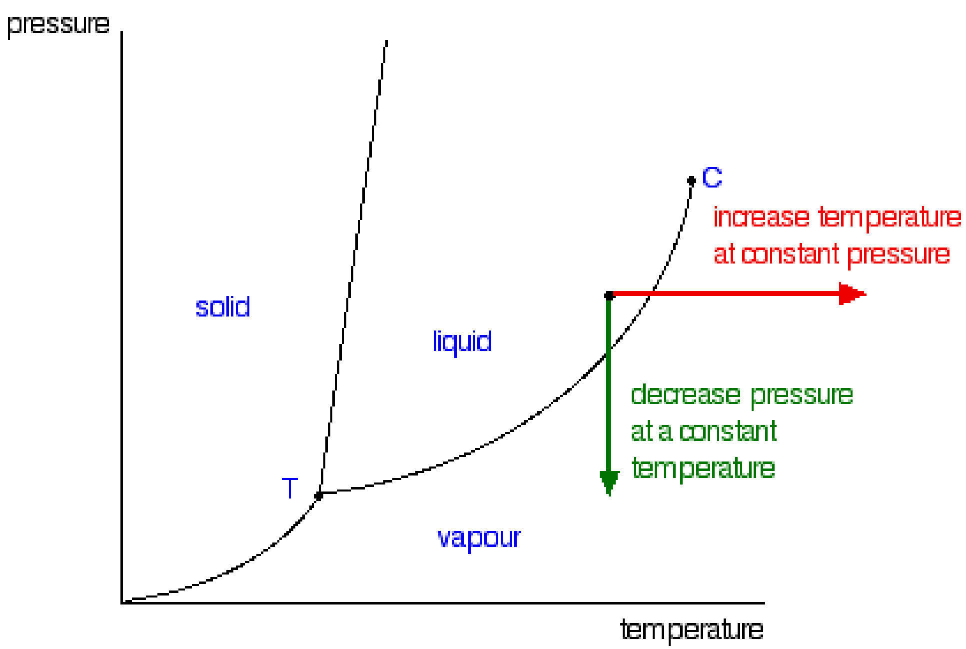
C – critical point – liquid phase cease to exist

Phase Diagram for Water





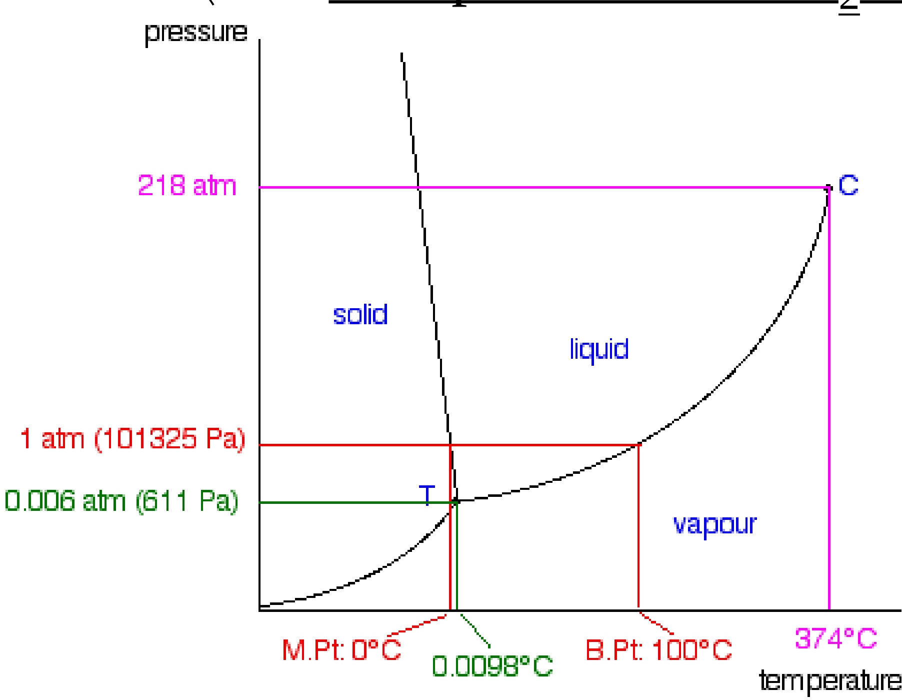
1. Conjunto de condições (1) – fase sólida
2. Conjunto de condições (2) – fase líquida
3. Conjunto de condições (3) – fase gasosa



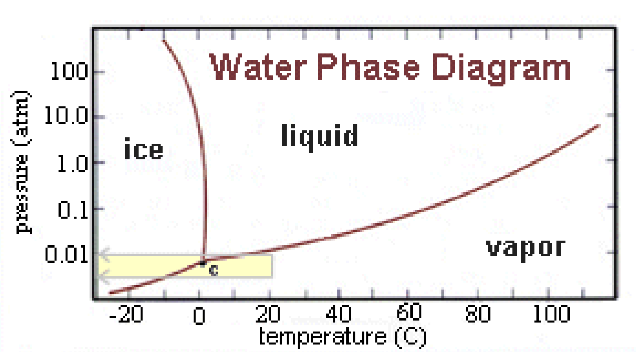
Pode-se fazer um líquido ferver ou aumentando sua temperatura ou diminuindo sua pressão

Não pode haver H_2O líquido abaixo de 0.006 atm (Marte)
Não pode haver CO_2 líquido abaixo de 5 atm – gelo seco

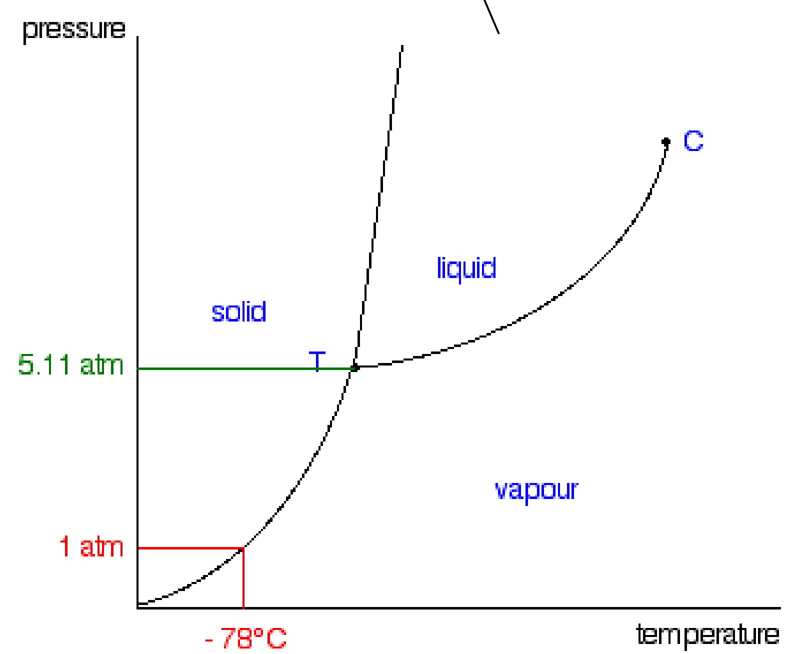
H_2O



Separatriz sólido-liquido
do H_2O inclinada para a direita
⇒ gelo da H_2O mais leve que a líquida
do CO_2 inclinada para a direita
⇒ gelo do CO_2 mais denso que o líquido



CO_2

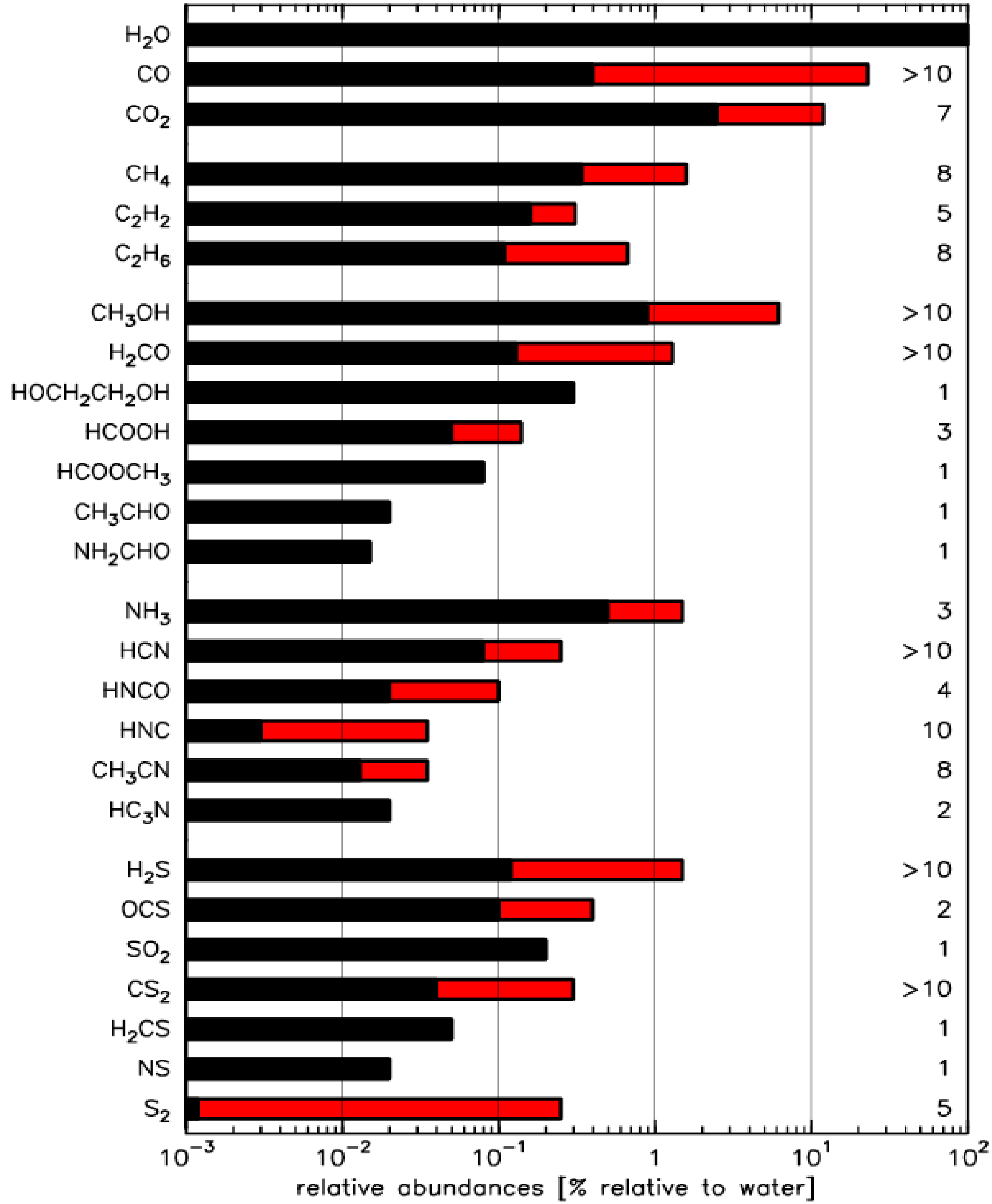


ALTERNATIVE BIOSOLVENTS?

Evidence for chemical diversity

Diversity among Oort cloud comets

No systematic differences between Oort cloud and « Kuiper belt » comets



Crovisier 2005

Phase transition properties of possible biosolvents

Substance	Melting Point (K)	Boiling point (K)	Temperature range for liquid (K)*	Triple point temperature (K)	Triple point pressure (Pa)
Water (H_2O)	273.15	373.15	100	237.16	611.73
Carbon monoxide (CO)	68	81.64	13	68.13	15400
Carbon dioxide (CO_2)	-	-	-	216.58	518500
Ammonia (NH_3)	195.42	239.81	44	195.40	6076
Methane (CH_4)	91.	111.	20	90.67	11690
Acetylene (C_2H_2)	-	-	-	192.4	128250
Ethane (C_2H_6)	101.	184.6	84	91.6	1.1
Methanol (CH_3OH)	176.	337.8	162	175.5	0.14
Formaldehyde (H_2CO)	156.15	254.05	98	187.66	42.4
Hydrogen sulfide (H_2S)	190.85	212.87	22	187.66	23200

*at 1atm pressure (101.325 kPa)

Water: Pros & Cons

- It is easily done: it is a tri-atomic molecule and H and O are the first and third most abundant elements in the universe.
- It remains in liquid form for a relatively large temperature range (0 – 100ºC, under 1 atm); these limits could be extended under pressure and by the presence of dissolved salts.
  - ⇒This temperature range include temperatures high enough for chemical reactions to proceed at a relatively rapid pace, but not so high that collisions destroy important, large and fragile molecules.

Uma grande vantagem da H_2O – gelo flutua!

- Para a maior parte das substâncias, a fase sólida é mais densa do que a líquida
- O gelo é mais denso que a água líquida, e assim o gelo flutua
- Lagos e oceanos não congelam completamente
  – A vida pode sobreviver às glaciações

Uma outra vantagem da H_2O:
Alto Calor Específico

- **CALOR ESPECÍFICO DA H_2O:**

➢ **1 caloria (4,1868 Joules) para aquecer 1 g de H_2O em 1ºC.**

- **Isso significa que muita energia é necessária para aumentar a temperatura de uma dada massa de água; a energia é utilizada para superar a coesão das PONTES DE HIDROGÊNIO**

- **Assim, em um planeta com grande quantidade de água (como a Terra), variações da insolação só podem provocar PEQUENAS VARIAÇÕES NA TEMPERATURA DO PLANETA**

⇒GRANDE ESTABILIDADE TÉRMICA

- **O calor é armazenado nos oceanos no VERÃO e liberado de volta para a atmosfera no INVERNO.**

Water: Pros & Cons – Cont.

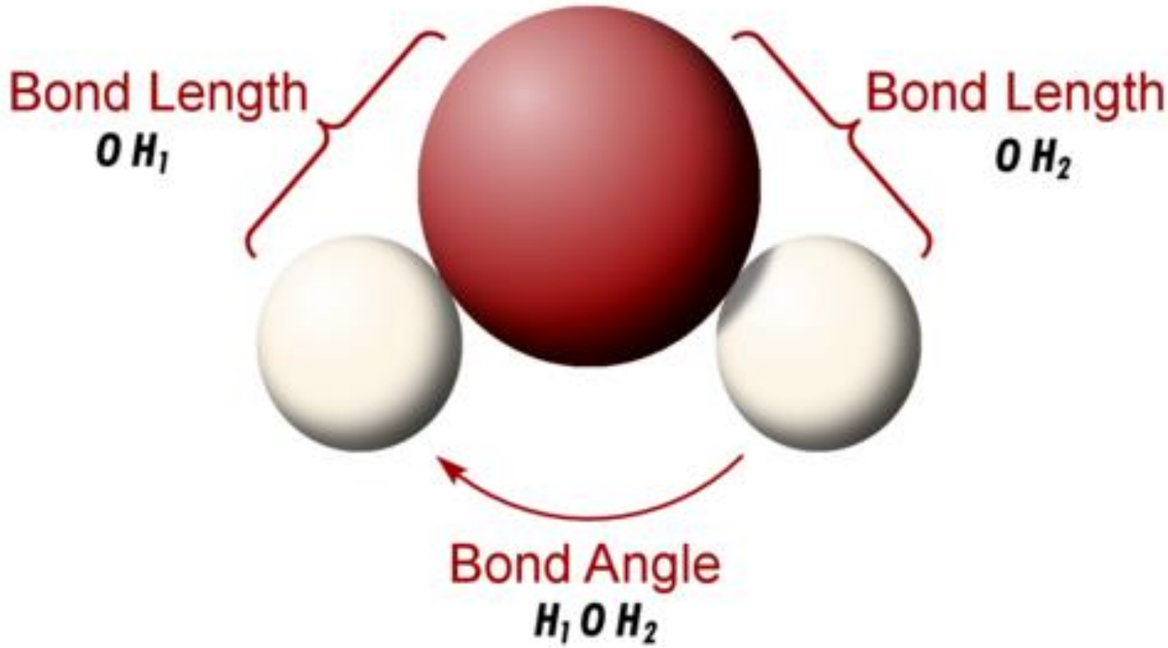
- Its ice is less dense than that of water so that ice floats. Having a frozen ice cap protects life below the ice and prevents freezing throughout all the bulk of the liquid. (eg. EUROPA)
- Water has a very large heat of vaporization and a large heat capacity. This means that the temperatures of a solution is stabilized by the thermal properties of water as a solvent and that water vaporization has a strong cooling effect (sweating).
- Water is a polar solvent so that it can discriminate between polar and non-polar molecules. Chemical discrimination results on the formation of mixed phases such as membranes, microenvironments and compartmentalization.
- Its relatively high viscosity protects living organisms from strong dynamical instabilities.
- The surface tension of water, twice that of ammonia and three times that of alcohol, exceeds the surface tension of any other liquid known.

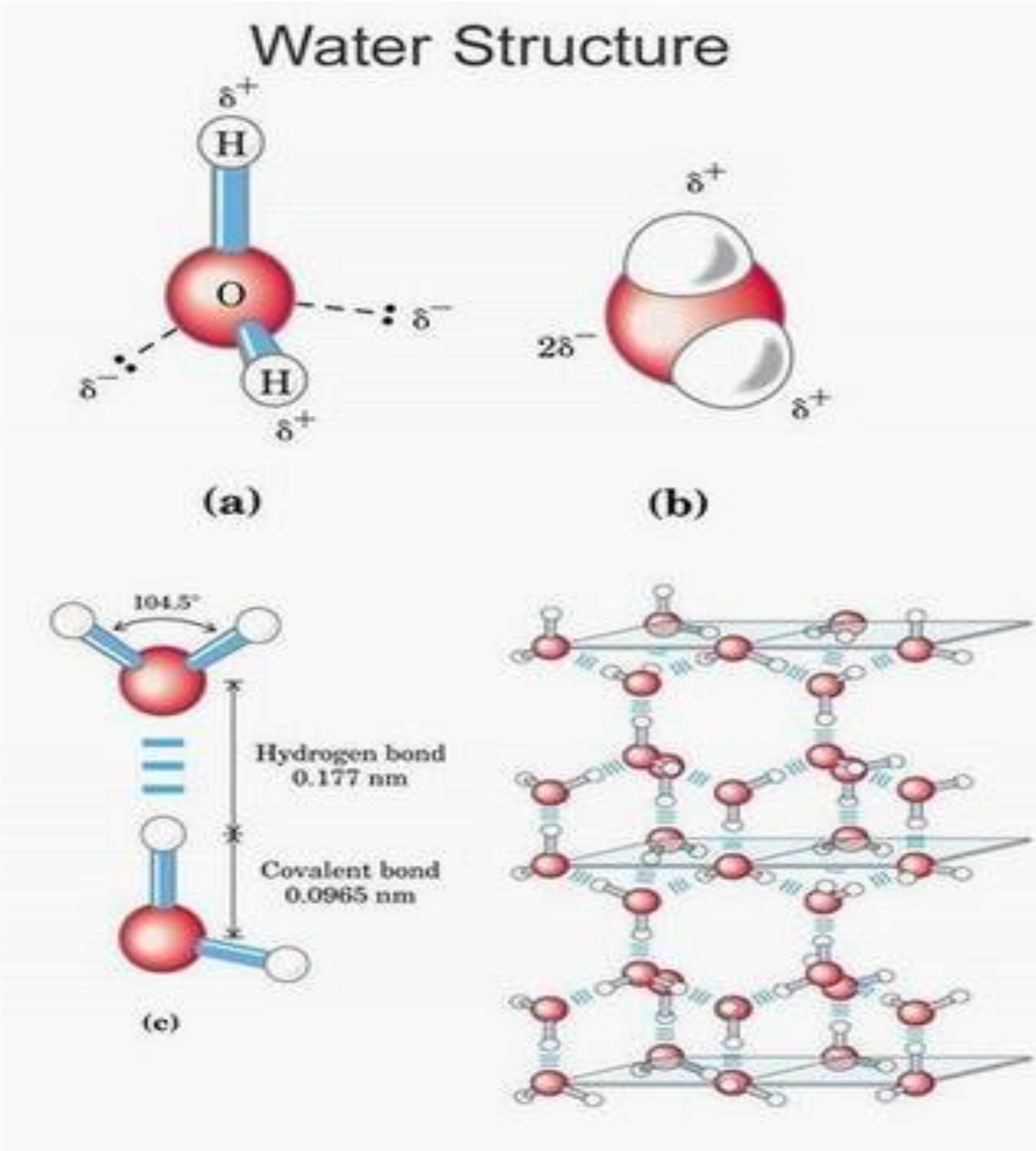
Water: Pros & <u>Cons</u>

- It is rather corrosive and reactive.
- It can hamper protein and nucleic acid concentrations
- Its ice is less dense than that of water so that ice floats. The high reflectivity of water ice could lead to thermal negative runaway conductive to global glaciations, that could turn into killing events.

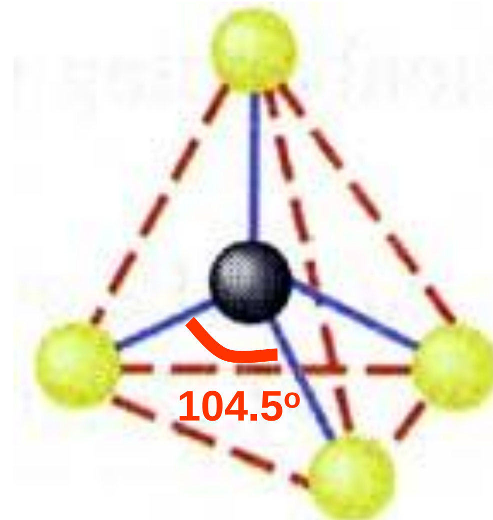
Estrutura da Água

ESTRUTURA da água





Water Structure
δ+
H
O
δ−
δ−
H
δ+
δ+
2δ−
δ+
(a)
(b)
104.5°
Hydrogen bond
0.177 nm
Covalent bond
0.0965 nm
(c)

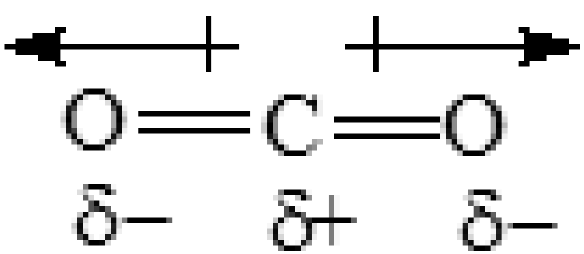


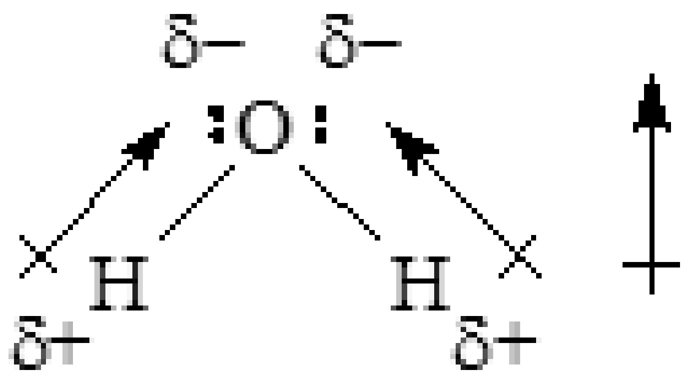
104.5°

Pontes de Hidrogênio

Molécula	Geometria	Momento dipolar (D)
H_2	Lineal	0
HF	Lineal	1.78
HCl	Lineal	1.07
HBr	Lineal	0.79
HI	Lineal	0.38
H_2O	Angular	1.85
H_2S	Angular	0.95
CO_2	Lineal	0
NH_3	Piramidal	1.47
NF_3	Piramidal	0.23
CH_4	Tetraédrica	0

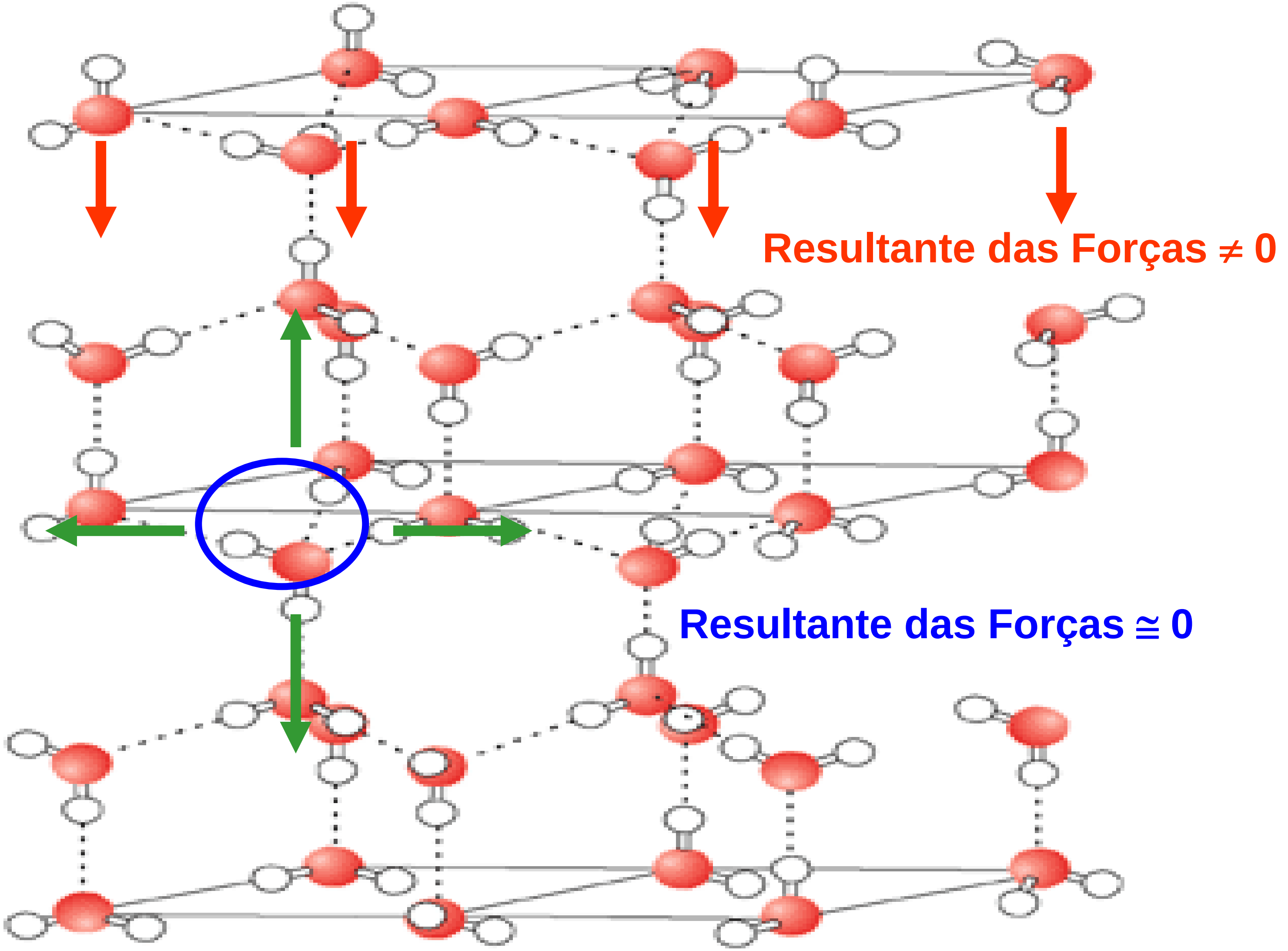
dipolo líquido = 0



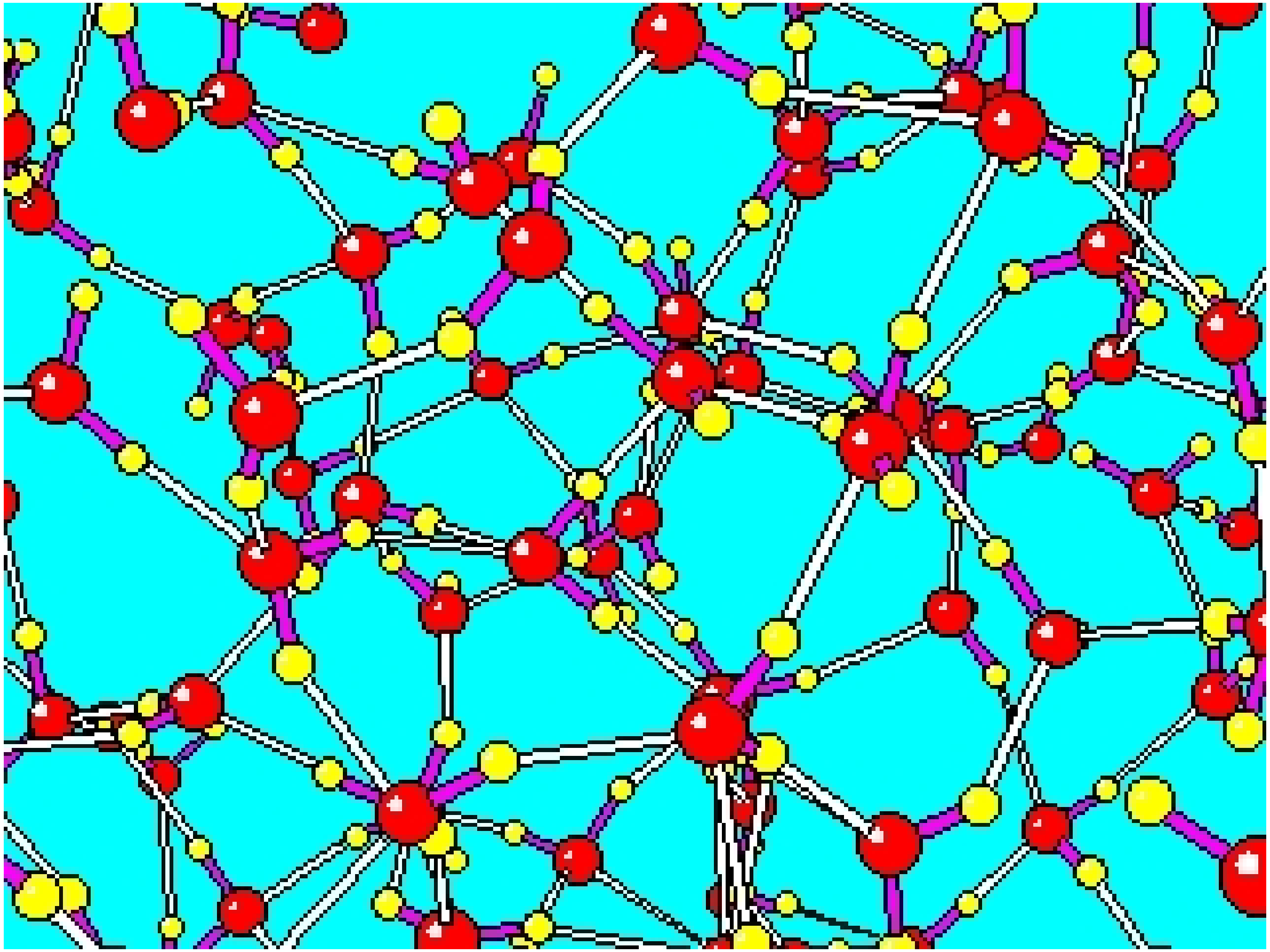


dipolo líquido = 1,85

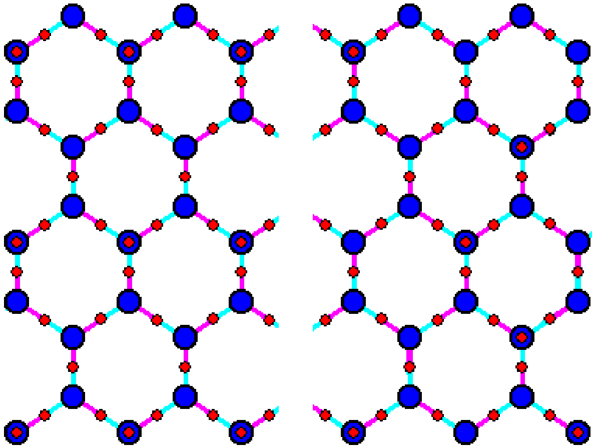
TENSÃO SUPERFICIAL



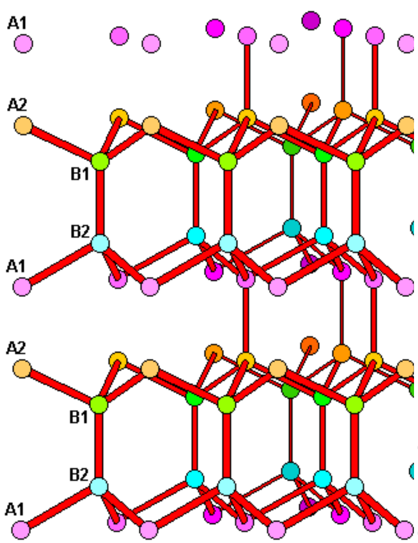
Na água líquida: grandes graus de liberdade entre as moléculas cria uma dinâmica entre as Pontes de Hidrogênio



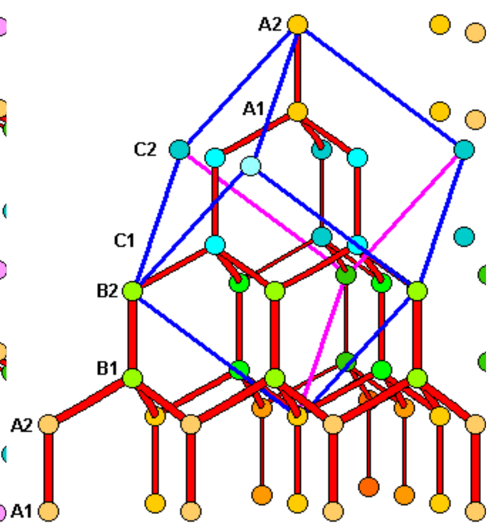
Organização no gelo

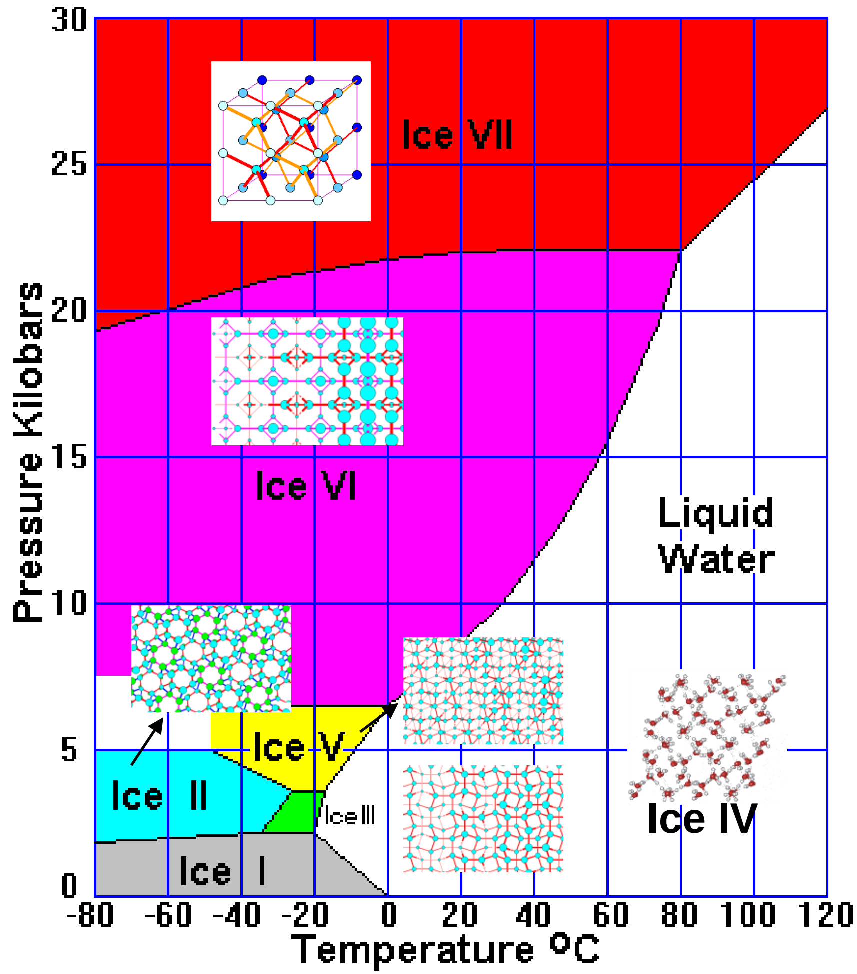


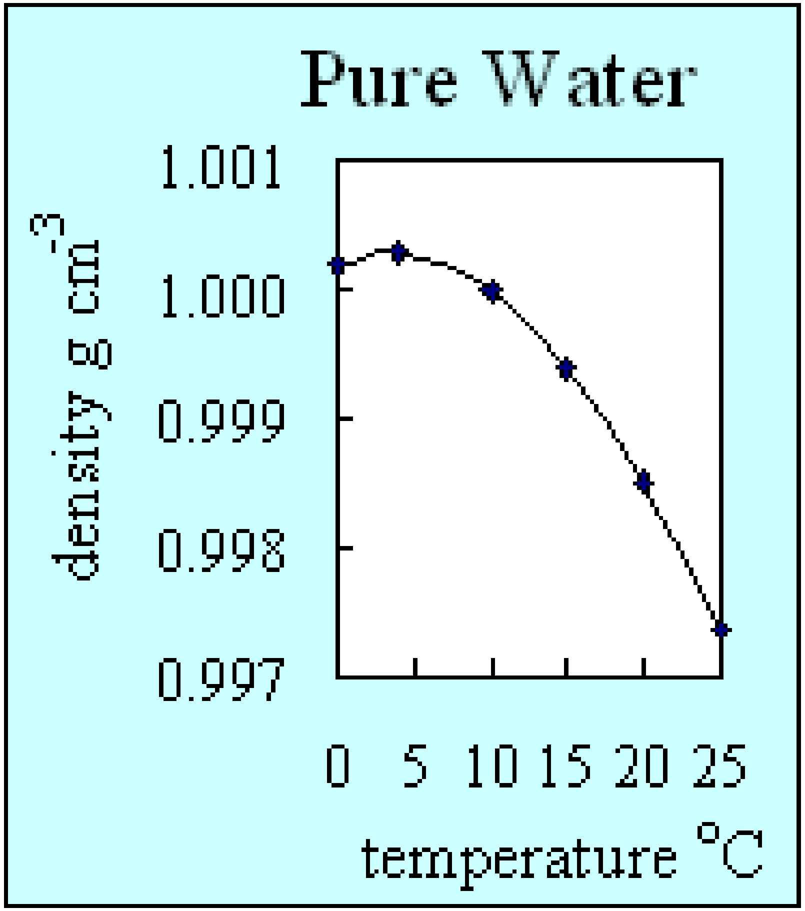
Ih

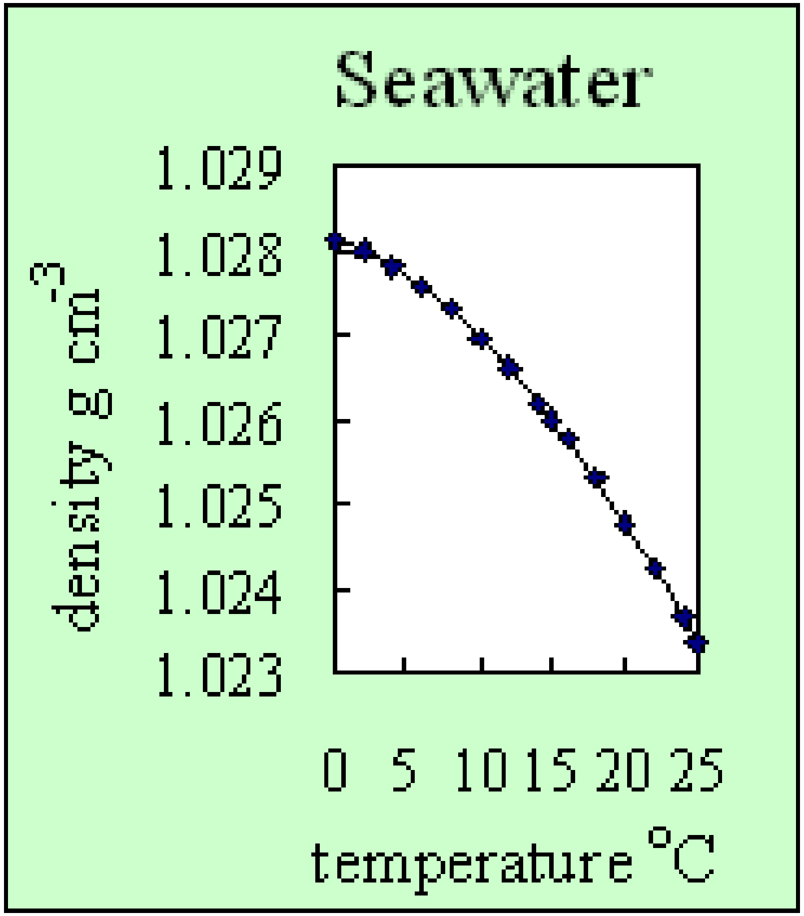


Ic





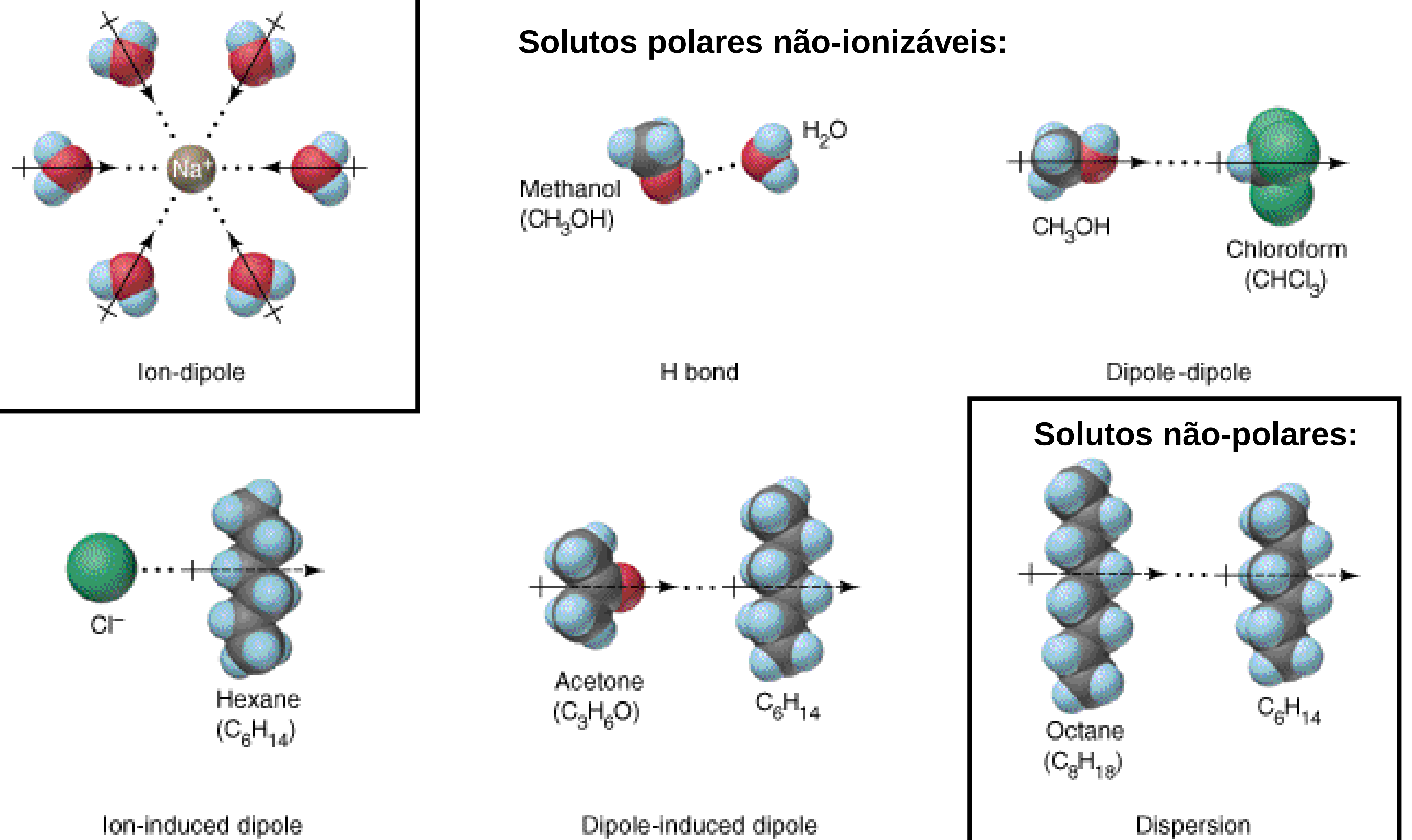

Pure Water
1.001
1.000
0.999
0.998
0.997
density g cm-3
0
5
10
15
20
25
temperature °C


Seawater
1.029
1.028
1.027
1.026
1.025
1.024
1.023
density g cm-3
0
5
10
15
20
25
temperature °C

Solutos ionizáveis:

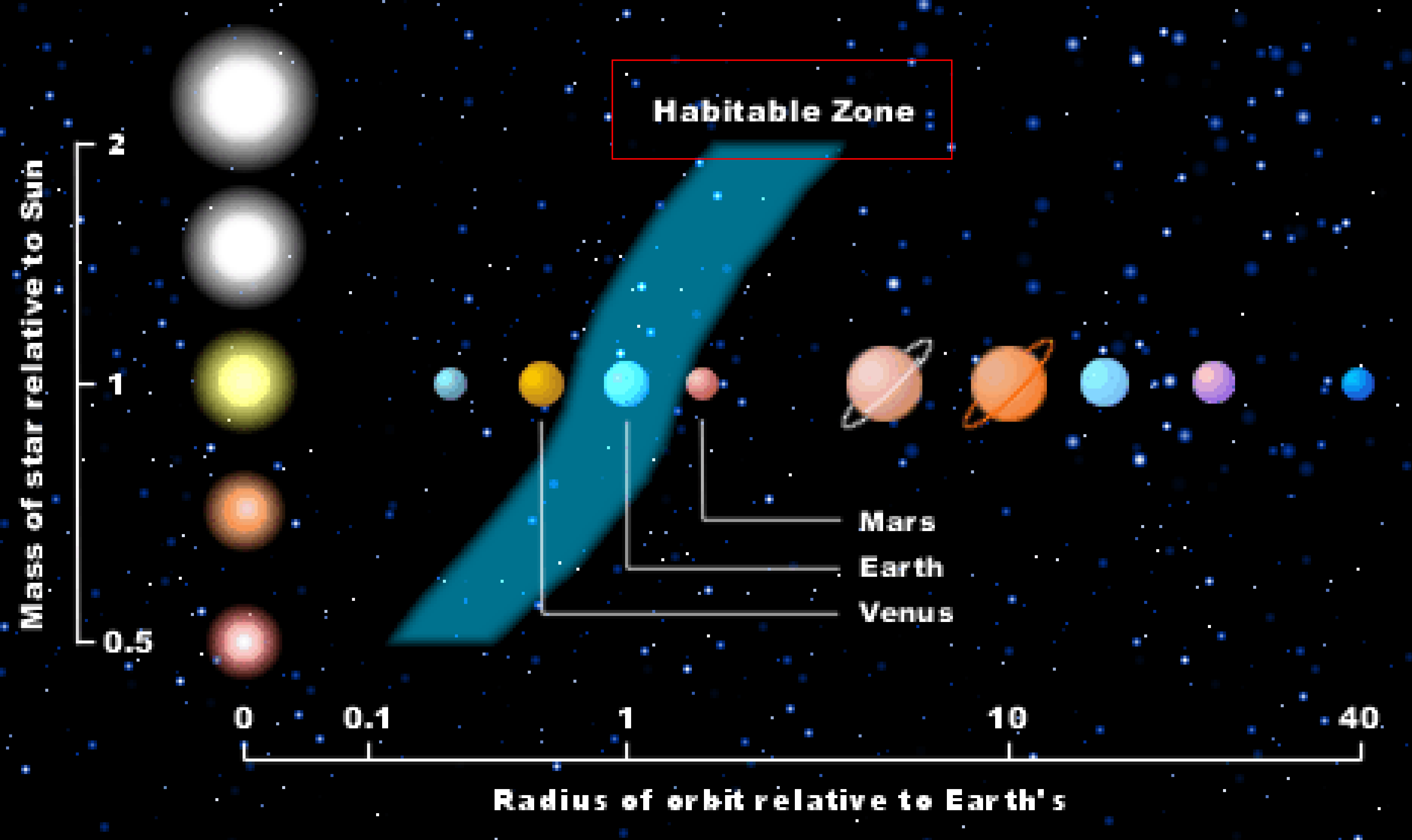
Solutos polares não-ionizáveis:

Solutos não-polares:



Zona Habitável Estelar

Distância certa da estrela ⇒ água líquida



A História da Cachinhos Dourados

Nem quente demais, senão ferve

Nem frio demais, senão congela

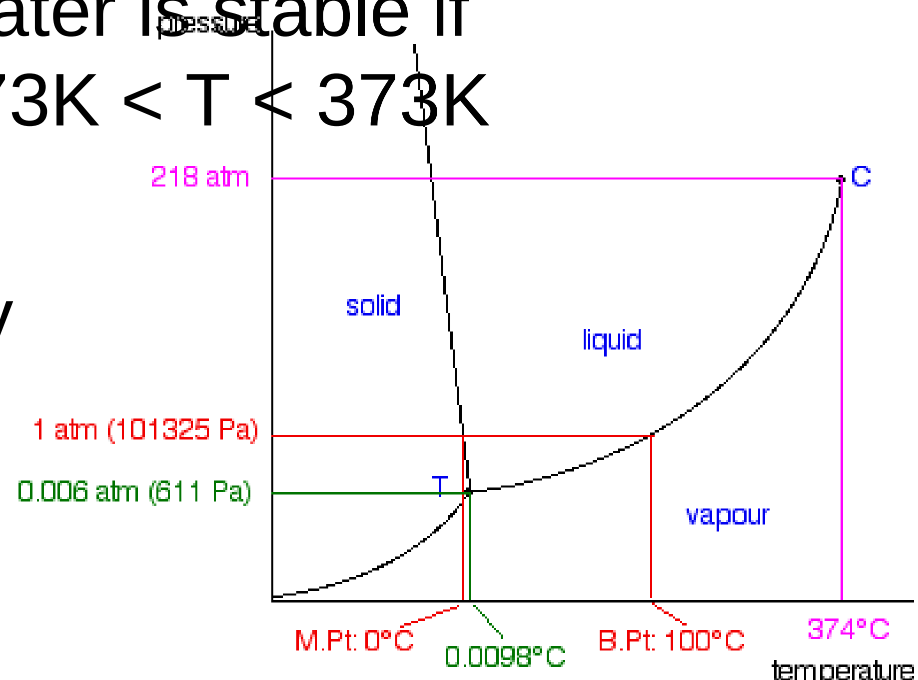
No Sistema Solar:

- Vênus sempre foi quente demais
- Marte, no passado, já esteve no ponto.
- A Terra em geral esteve no ponto, exceto em duas ocasiões de quase total congelamento

Habitable Zone

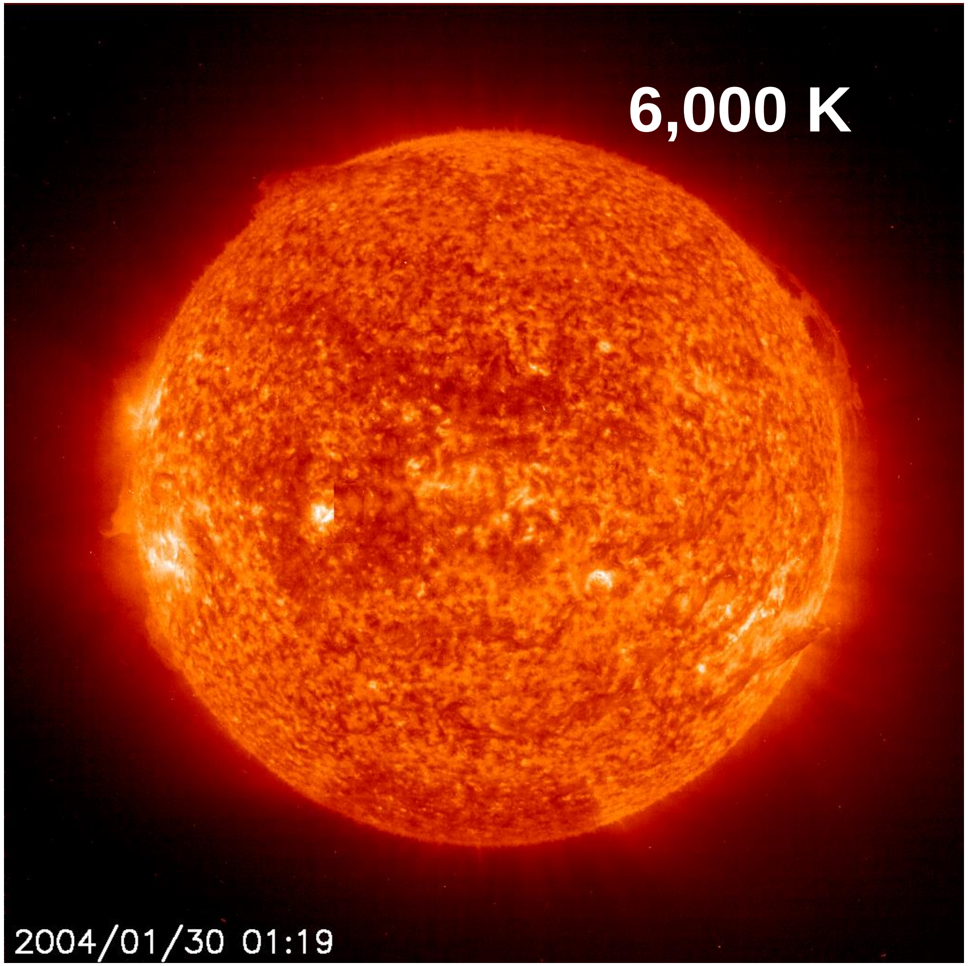
- A circumstellar habitable zone (HZ) is defined as encompassing the range of distances from a star for which liquid water can exist on a planetary surface.
- Under the present Earth's atmospheric pressure (1 atm = 101325 Pa) water is stable if temperature is 273K < T < 373K
- Planetary surface

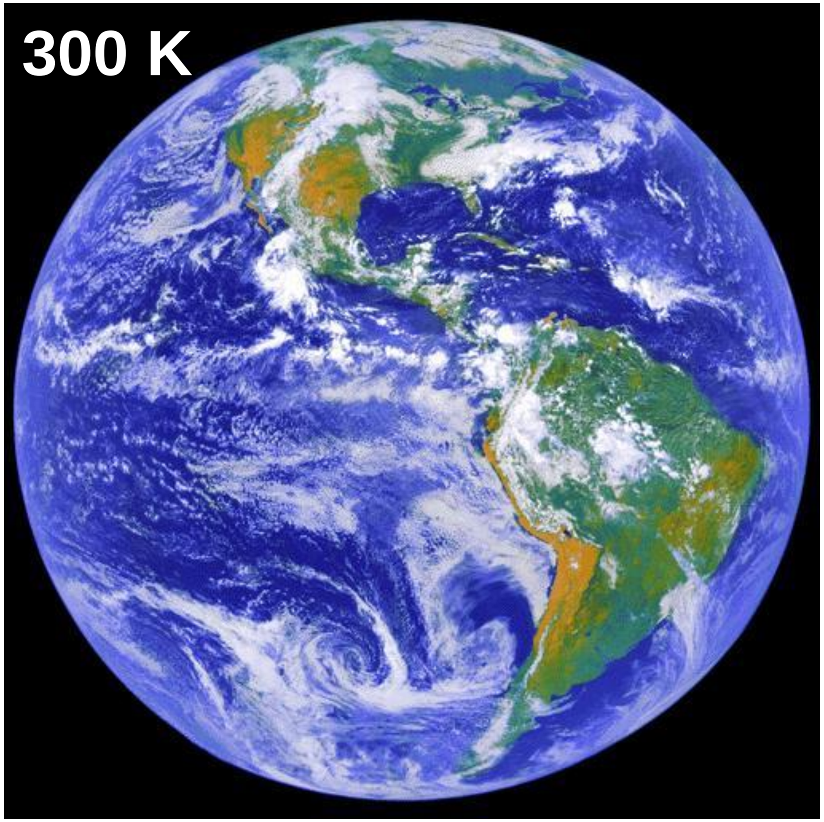
temperature (T) is the key



Example: Earth-Sun

The Earth's temperature (about 300K) is maintained by the energy radiating from the Sun.





Planetary Energy Balance

- We can estimate average planetary temperature using the Energy Balance approach

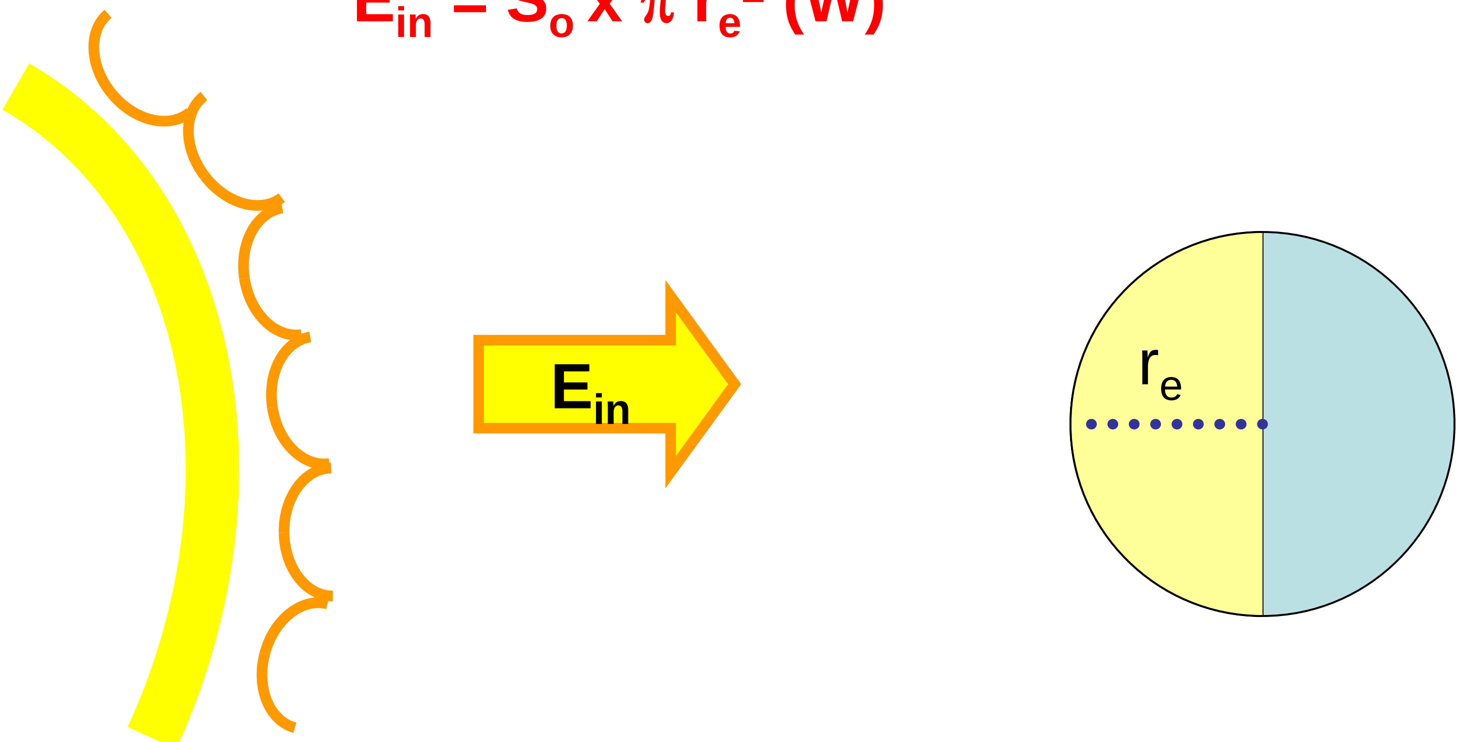
$$E_{in} = E_{out}$$

E_{in}

How much solar energy gets to the Earth?

Assuming solar radiation covers the area of a circle defined by the radius of the Earth (r_e)

$$E_{in} = S_o\ (W/m^2) \times \pi\ r_e^2\ (m^2)$$
$$E_{in} = S_o \times \pi\ r_e^2\ (W)$$



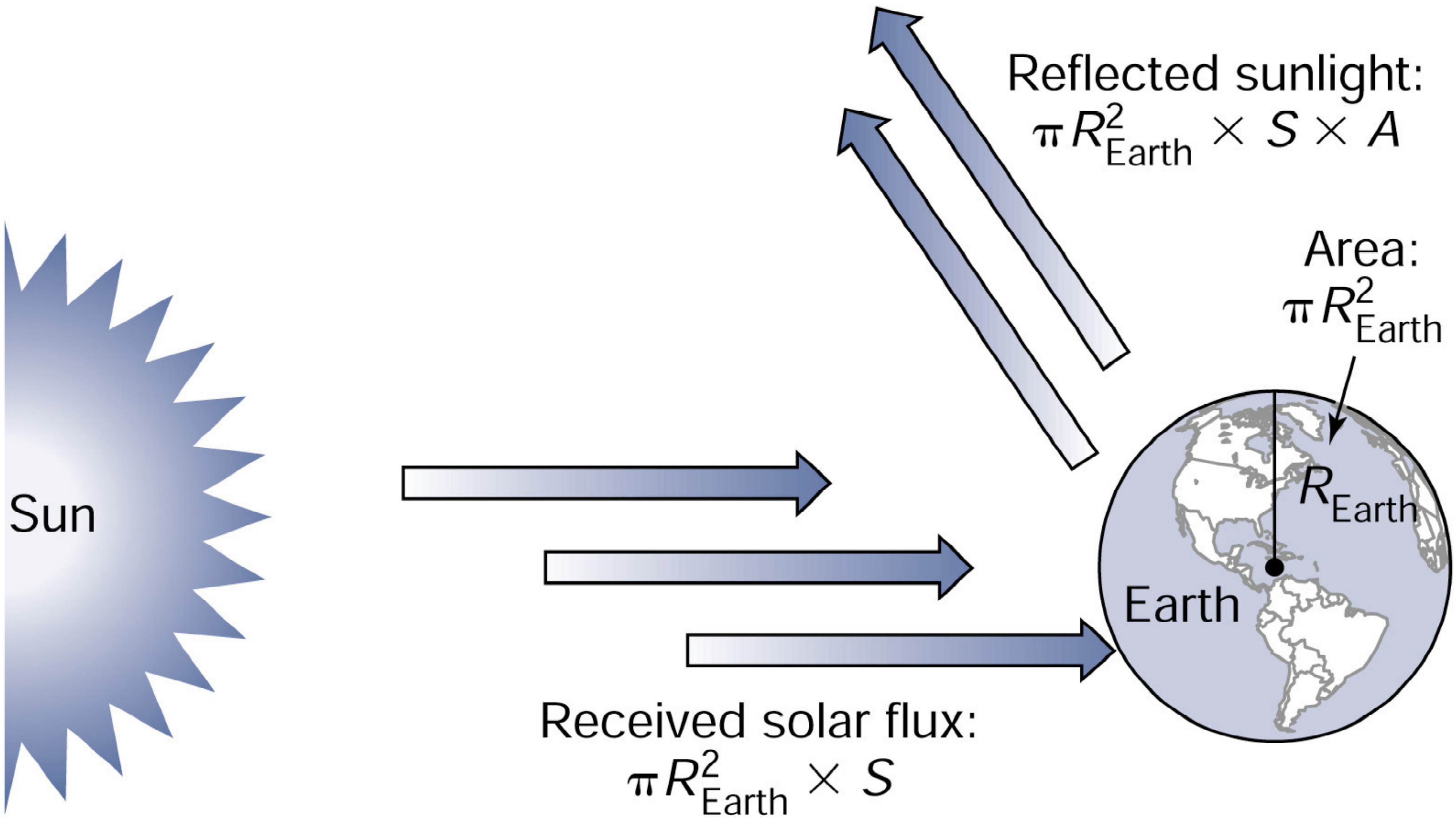
E_{in}

How much solar energy gets to the Earth's surface?

****Some energy is reflected away****

⇒ Albedo (A)

$$E_{in} = S_o \times \pi\, r_e^2 \times (1-A)$$

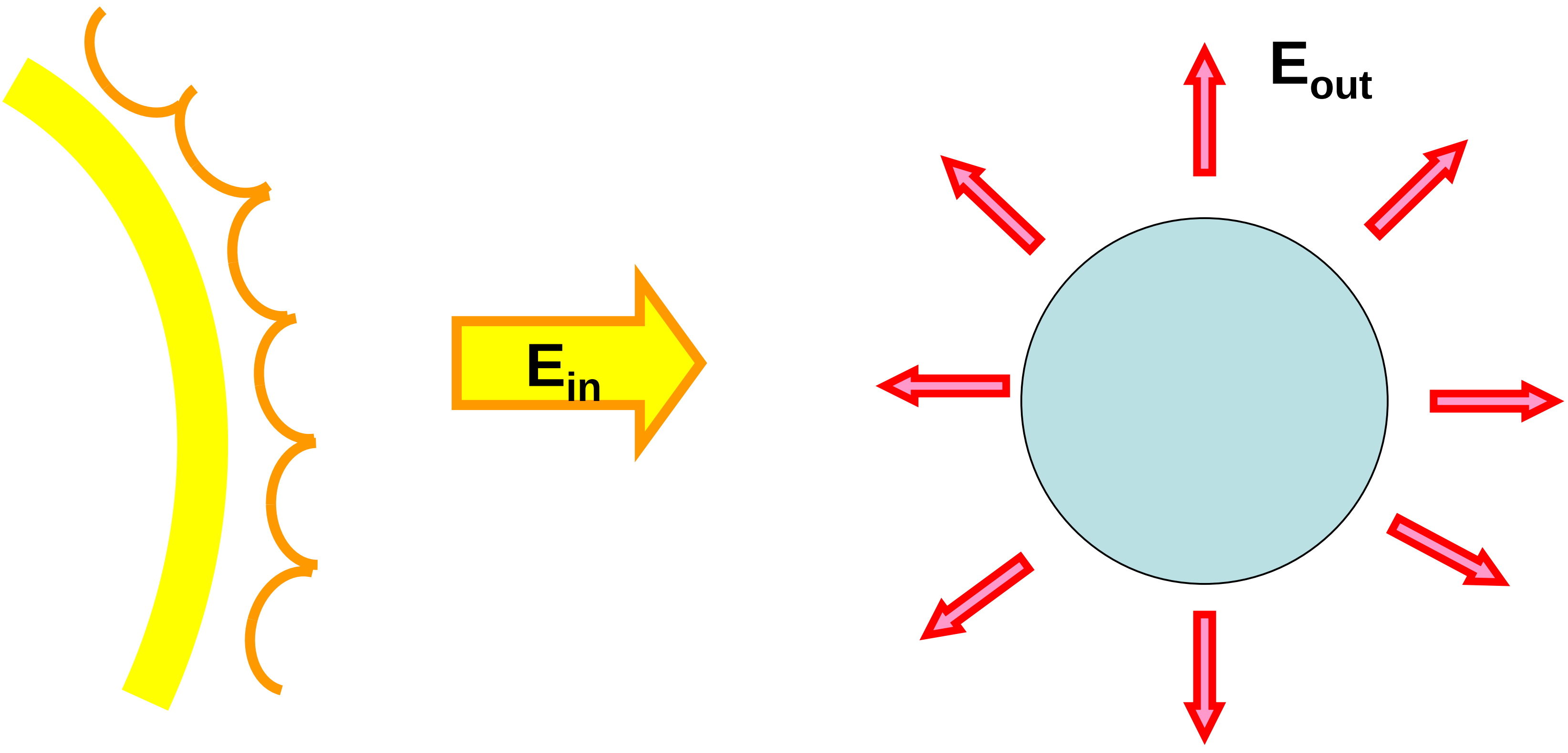


E_{out}

Energy Balance:

The amount of energy delivered to the Earth is equal to the energy lost from the Earth.

Otherwise, the Earth’s temperature would continually rise (or fall).



E_{out}

➡ *Stefan-Boltzmann law*

$$F = \sigma T^4$$

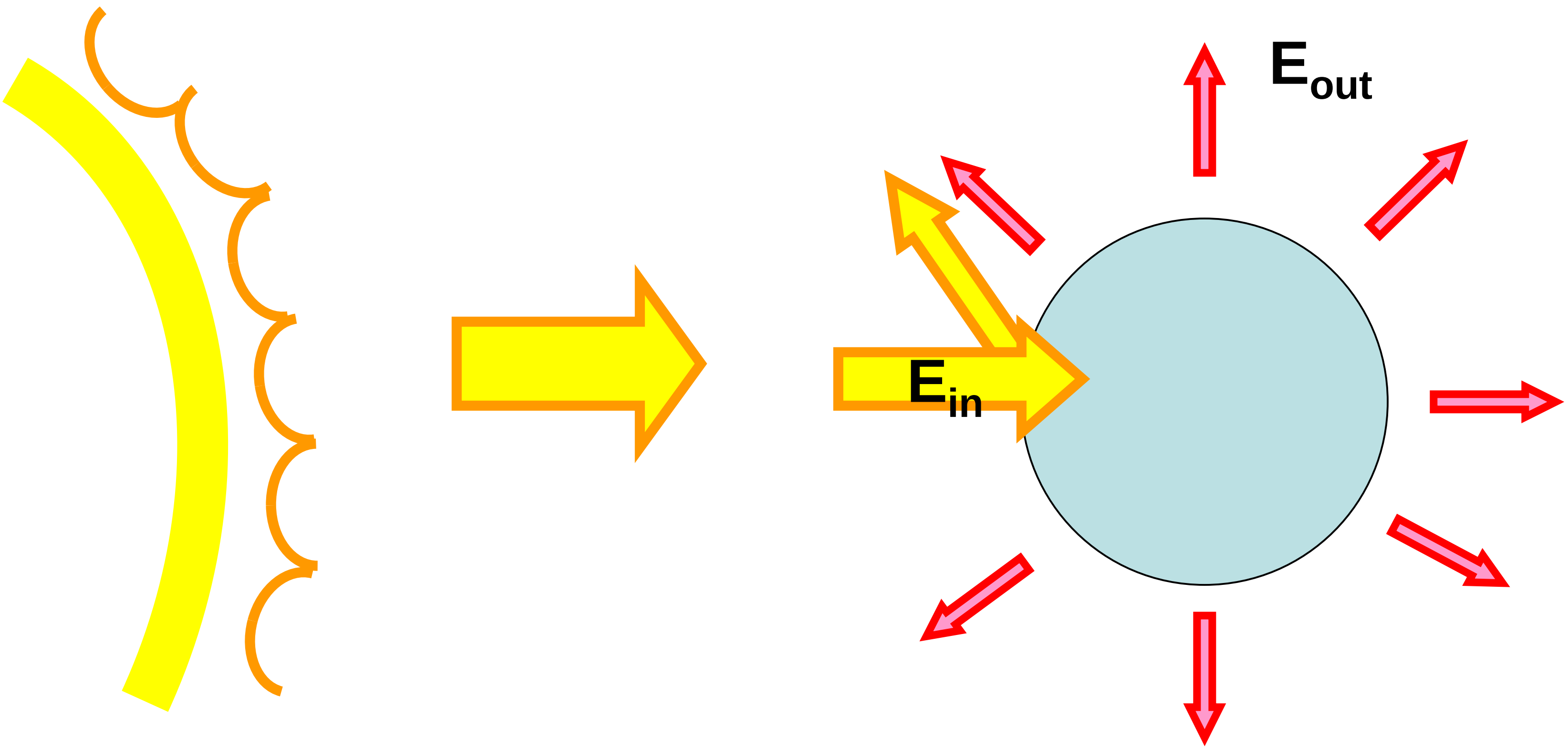
F = flux of energy (W/m^2)
T = temperature (K)
σ = 5.67 x 10^{-8} W/m^2K^4 (a constant)

Energy Balance:

$$E_{in} = E_{out}$$

$$E_{in} = S_o \, \pi \, r_e^2 \, (1\text{-}A)$$

$$E_{out} = \sigma \, T^4 (4 \, \pi \, r_e^2)$$

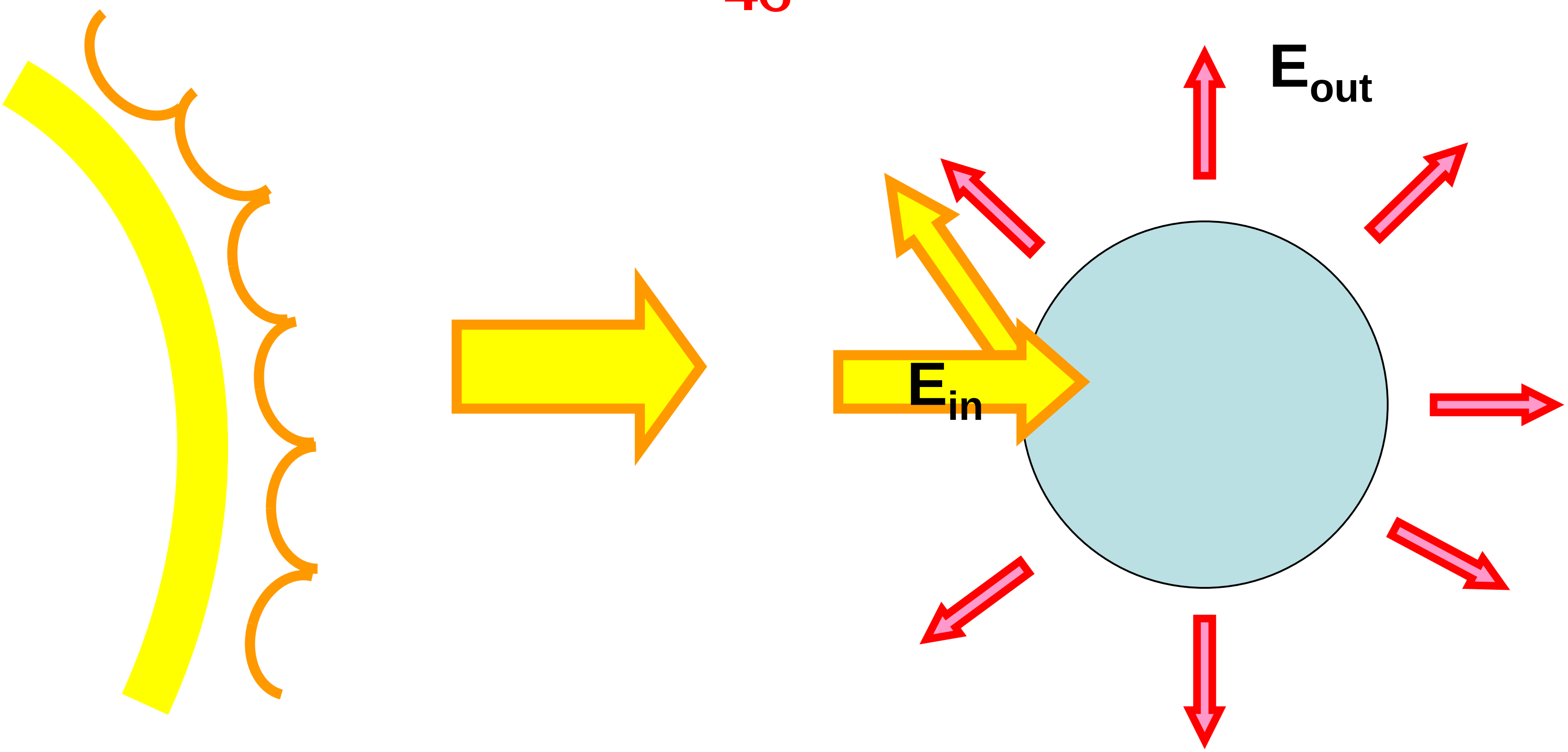


Energy Balance:

$$E_{in} = E_{out}$$

$$S_o\,(1\text{-}A) = \sigma\, T^4\,(4)$$

$$T^4 = \frac{S_o(1\text{-}A)}{4\sigma}$$



Objeto/Superfície	**Albedo**
Terra	0.306
Lua	0.22
Mercúrio	0.088
Vênus	0.76
Marte	0.25
Júpiter	0.503
Saturno	0.342
Urano	0.300
Netuno	0.290
Europa (lua de Júpiter)	0.67
Encélado (lua de Saturno)	0.81
19P/Borrely (cometa)	0.03
Terra cultivada (média)	0.16
Prado	0.21
Floresta tropical	0.12
Tundra	0.17
Neve	0.66
Gelo marítimo	0.62
Oceano	0.07

Earth's average temperature

$$T^4 = \frac{S_o(1-A)}{4\sigma}$$

For Earth:

S_o = 1370 W/m^2
A = 0.3
σ = 5.67 x 10^{-8} W/m^{2}K^4

$$T^4 = \frac{S_o(1-A)}{4\sigma}$$

For Earth:

$S_o = 1370\ W/m^2$

$A = 0.3$

$\sigma = 5.67 \times 10^{-8}$

$$T^4 = \frac{(1370\ W/m^2)(1-0.3)}{4\ (5.67 \times 10^{-8}\ W/m^2K^4)}$$

$T^4 = 4.23 \times 10^9\ (K^4)$

T = 255 K

Expected Temperature:

T_{exp} = 255 K

(^oC) = (K) - 273

So….

$\mathbf{T_{exp}}$ = (255 - 273) = **-18 ^oC**

O Efeito Estufa é tão mau assim?

No caso da Terra não

Temperatura do equilíbrio radiativo: $T_{rad} = - 18\ ^oC$

Temperatura observada: $T_{obs} = 15\ ^oC$.

A diferença T_{obs} - T_{rad}= ΔT é o **efeito estufa** ΔT :

$$\Delta T = T_{obs} - T_{rad}$$

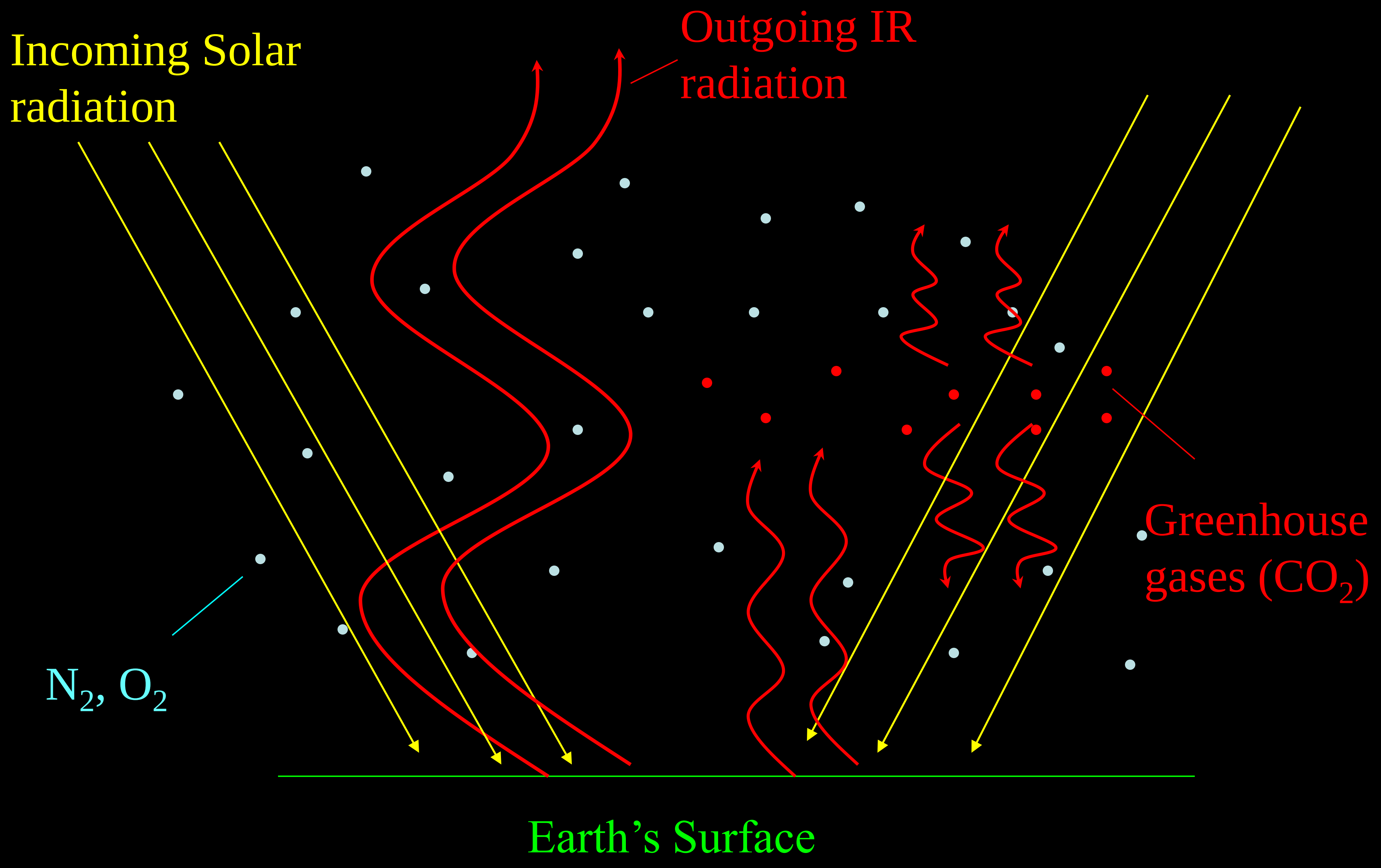
$$\Delta T = 15 - (-18)$$

$$\Delta T = + 33\ ^oC = 33\ K$$

O efeito estufa tem um efeito de aquecimento

Sem o efeito estufa, a Terra estaria congelada!

Atmospheric Greenhouse Effect



Original Greenhouse

- Precludes heat loss by inhibiting the upward air motion
- Solar energy is used more effectively.
  Same solar input – higher temperatures.

Warming results from interactions of gases in the atmosphere with incoming and outgoing radiation.

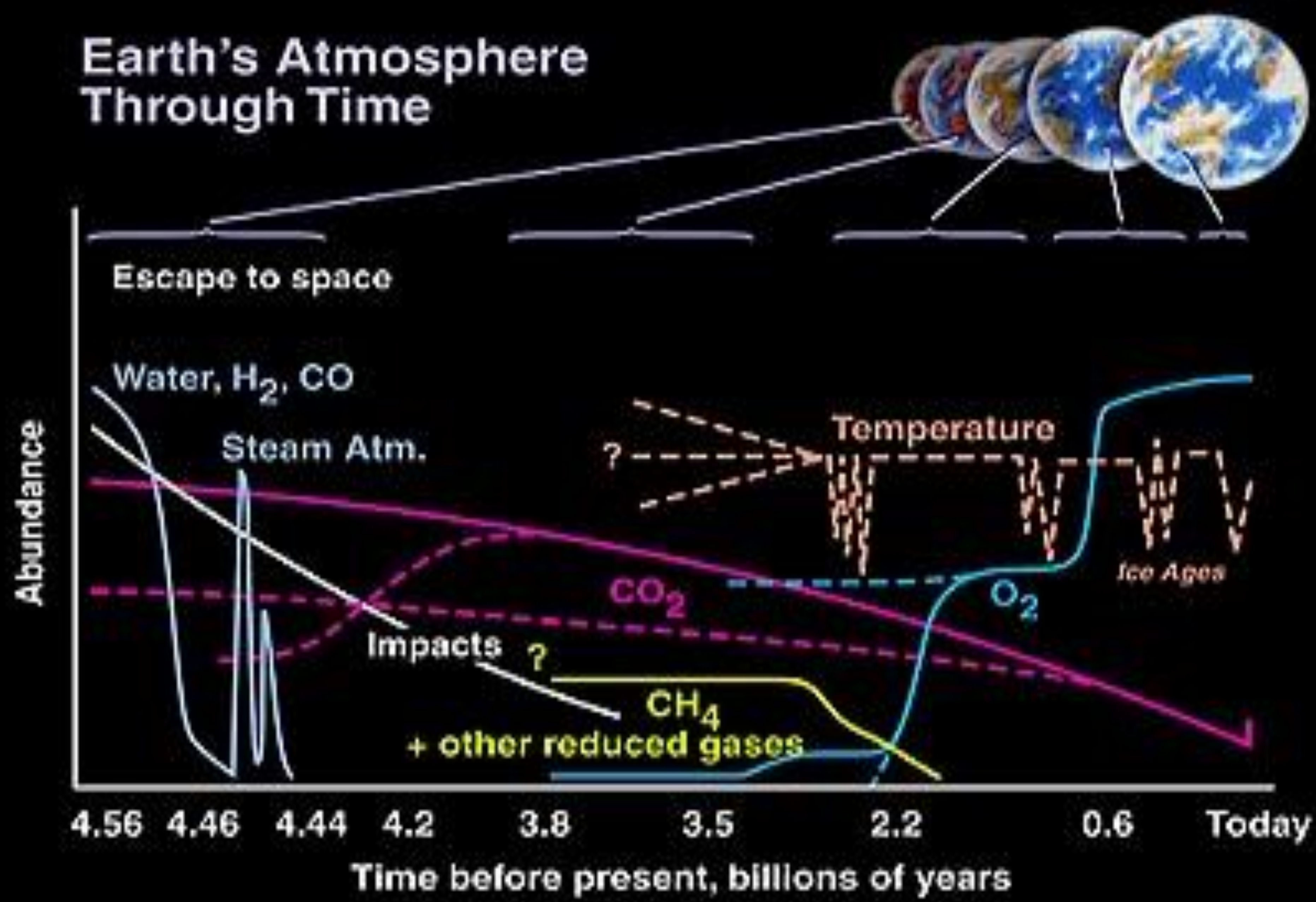
To evaluate how this happens, we will focus on the **composition** of the Earth’s atmosphere.

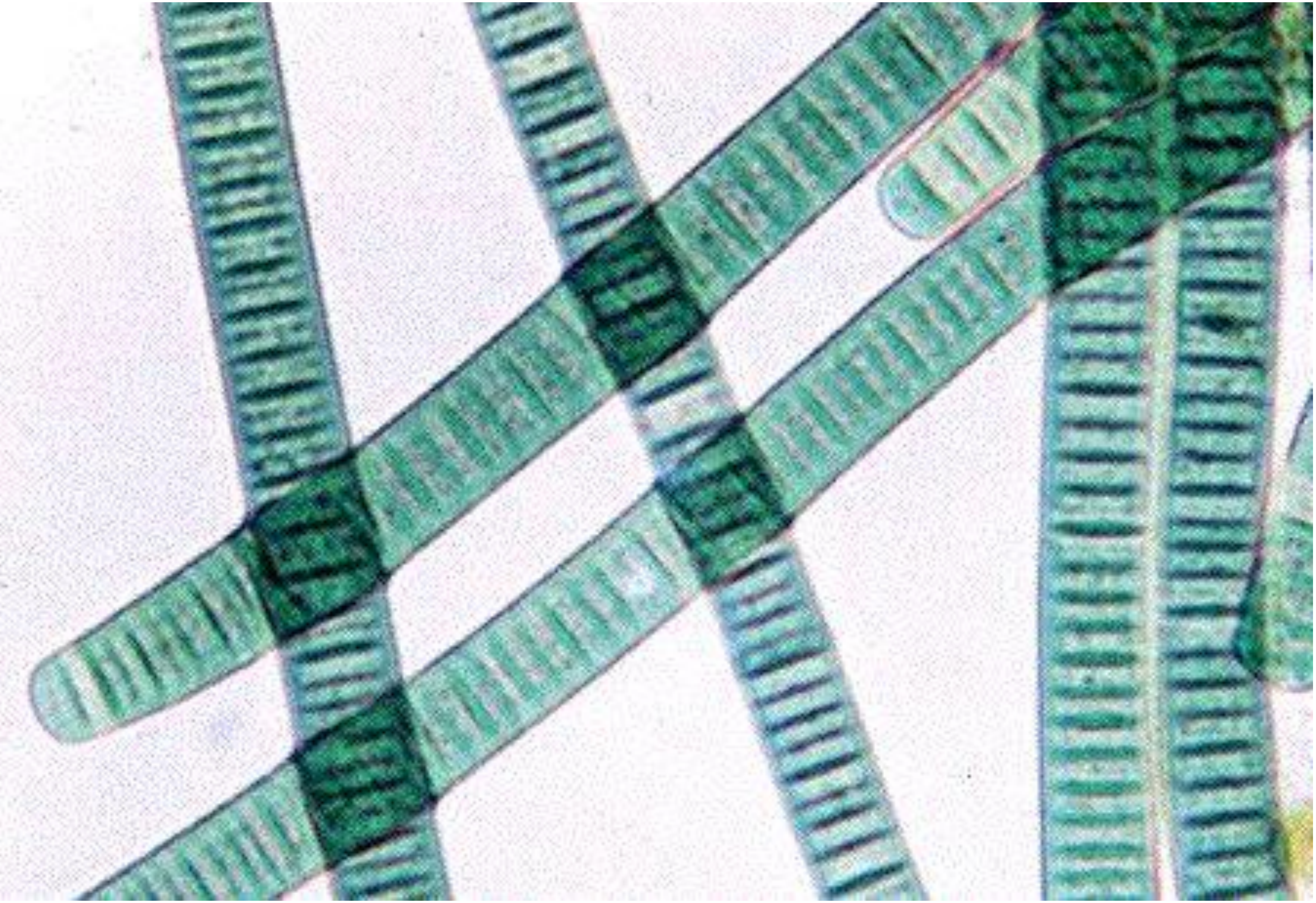
Composition of the Atmosphere

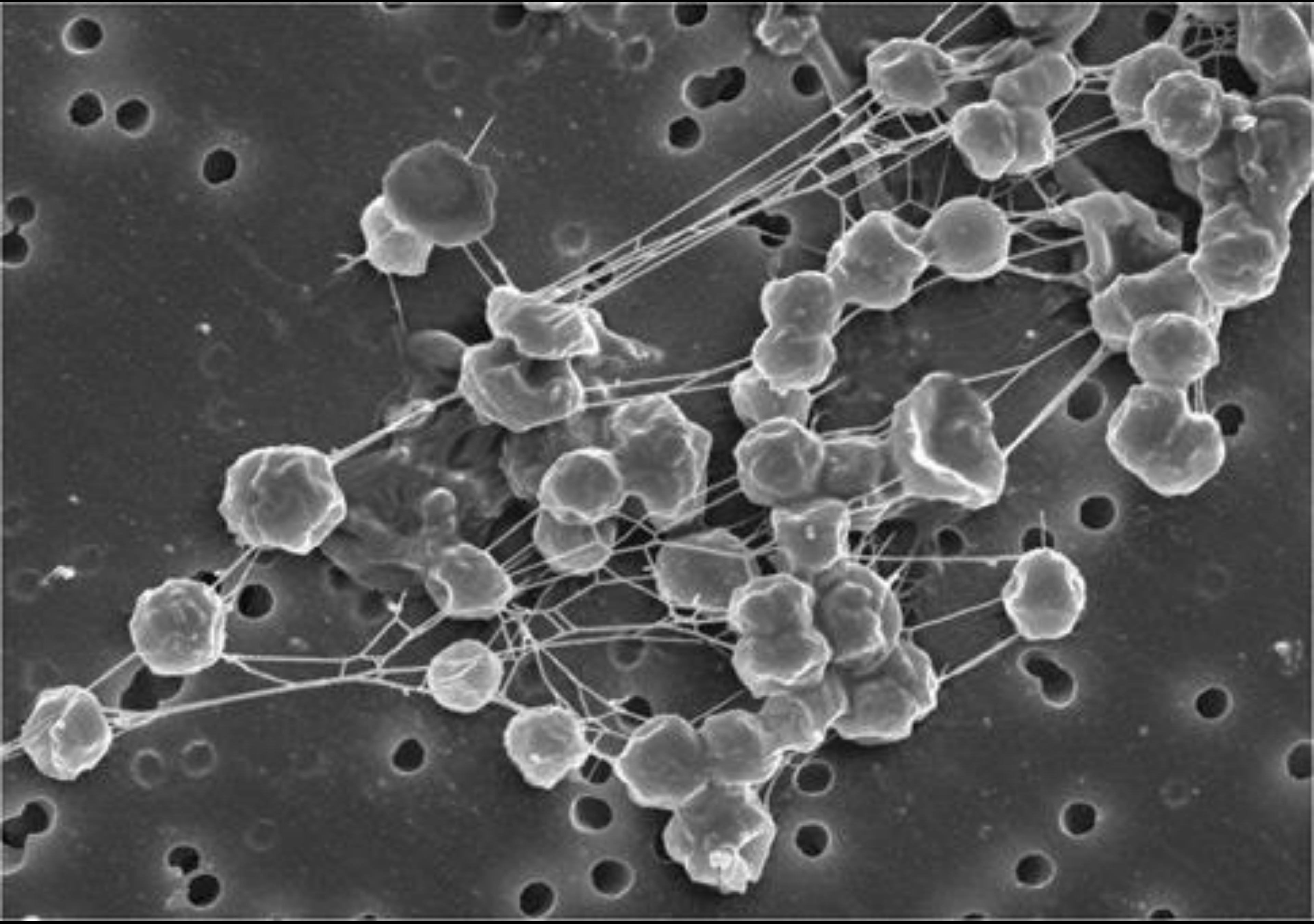
Air is composed of a mixture of gases:

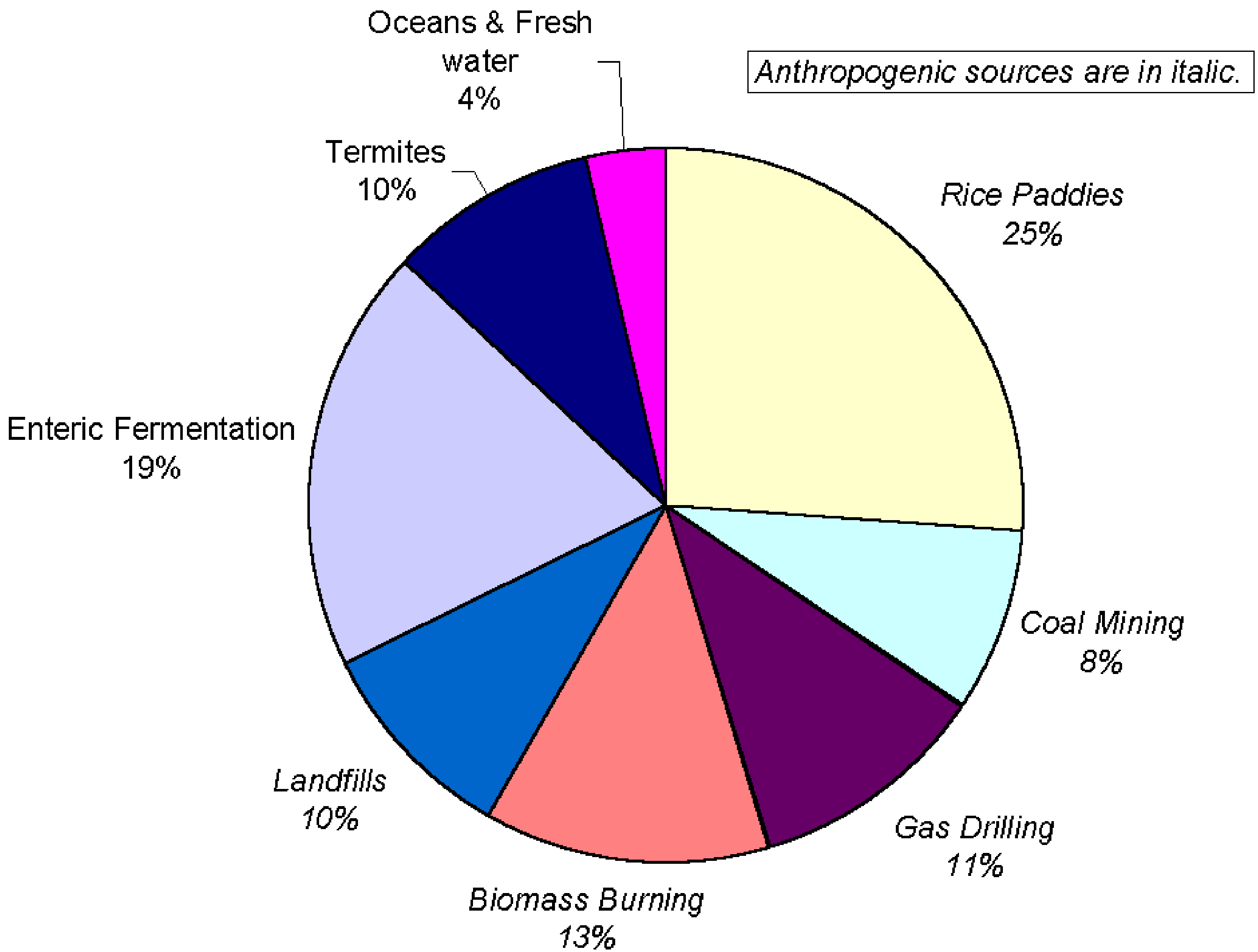
Gas	concentration (%)	
N_2	78	
O_2	21	
Ar	0.9	
H_2O	variable	
CO_2	0.037	370 ppm
CH_4		1.7
N_2O		0.3
O_3		1.0 to 0.01
		(stratosphere-surface)

greenhouse gases: H_2O, CO_2, CH_4, N_2O, O_3


Earth's Atmosphere
Through Time
Escape to space
Water, H_2, CO
Steam Atm.
Temperature
?
Ice Ages
CO_2
O_2
Impacts
?
CH_4
+ other reduced gases
Abundance
4.56
4.46
4.44
4.2
3.8
3.5
2.2
0.6
Today
Time before present, billions of years





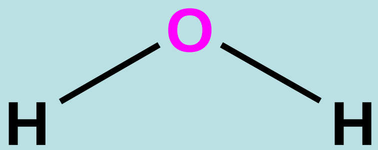


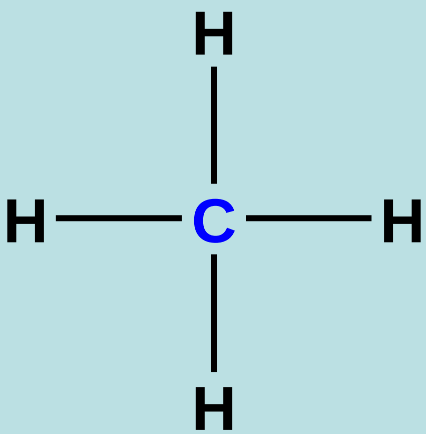
Fontes de Metano na Terra

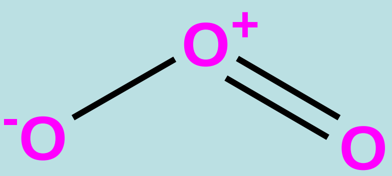
(University of Toronto, Dept. Atmospheric Physics)

Greenhouse Gases


carbon dioxide


water


methane


ozone

Non-greenhouse Gases

N_2 O_2

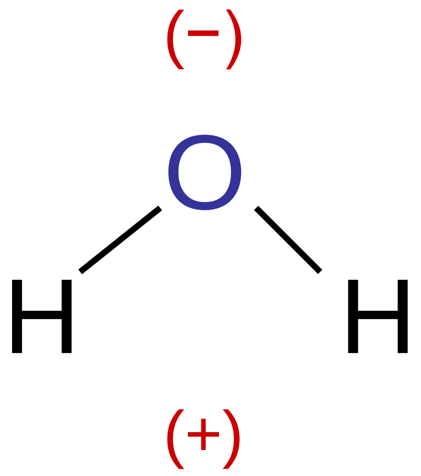
$N \equiv N$ $O = O$

Non-greenhouse Gases

$N \equiv N$ $O = O$

Non-greenhouse gases have symmetry!

(Technically speaking, greenhouse gases have a *dipole moment* whereas N_2 and O_2 don't)

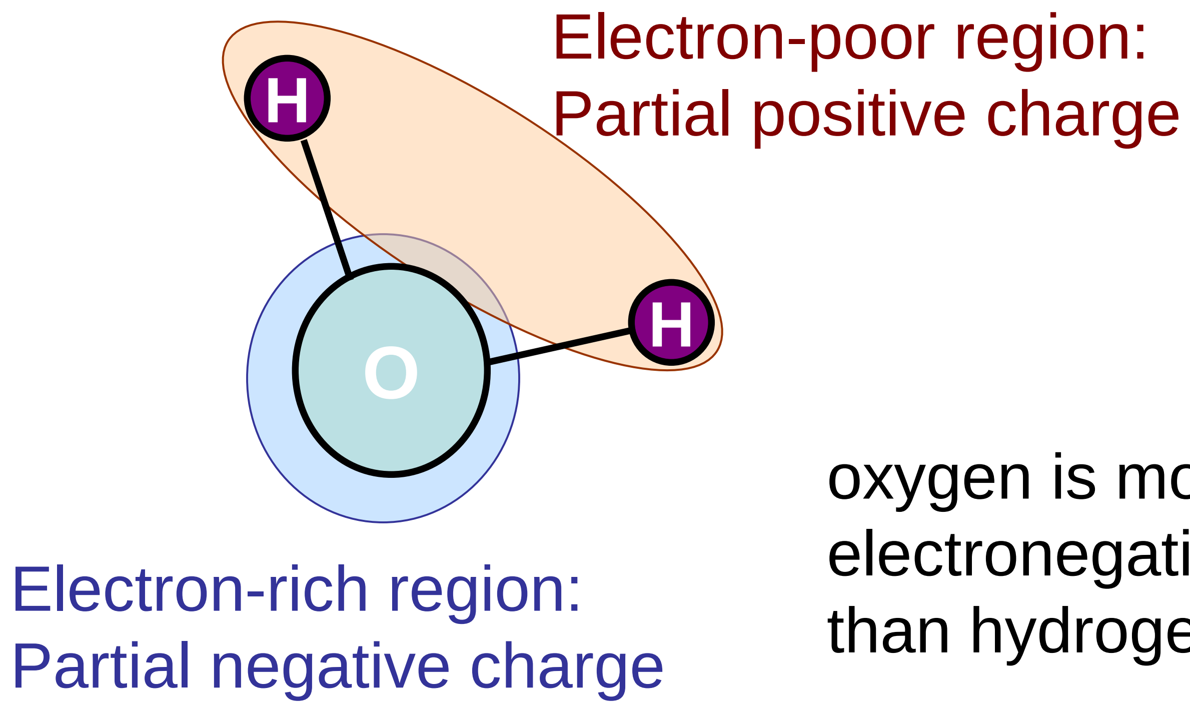


- Oxygen has an unfilled outer shell of electrons (6 out of 8), so it wants to attract additional electrons. It gets them from the hydrogen atoms.

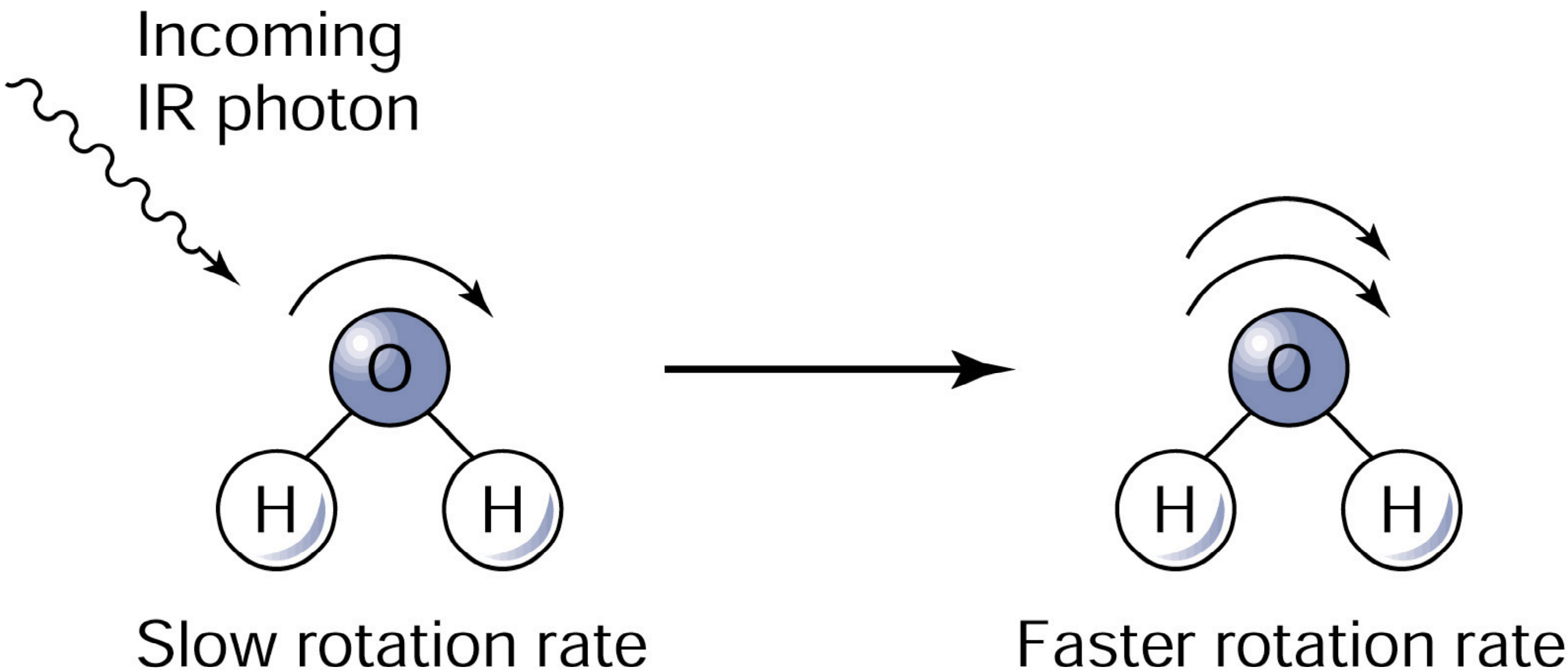
Molecules with an <u>uneven distribution of electrons</u> are especially good absorbers and emitters.

These molecules are called **dipoles**.

Water



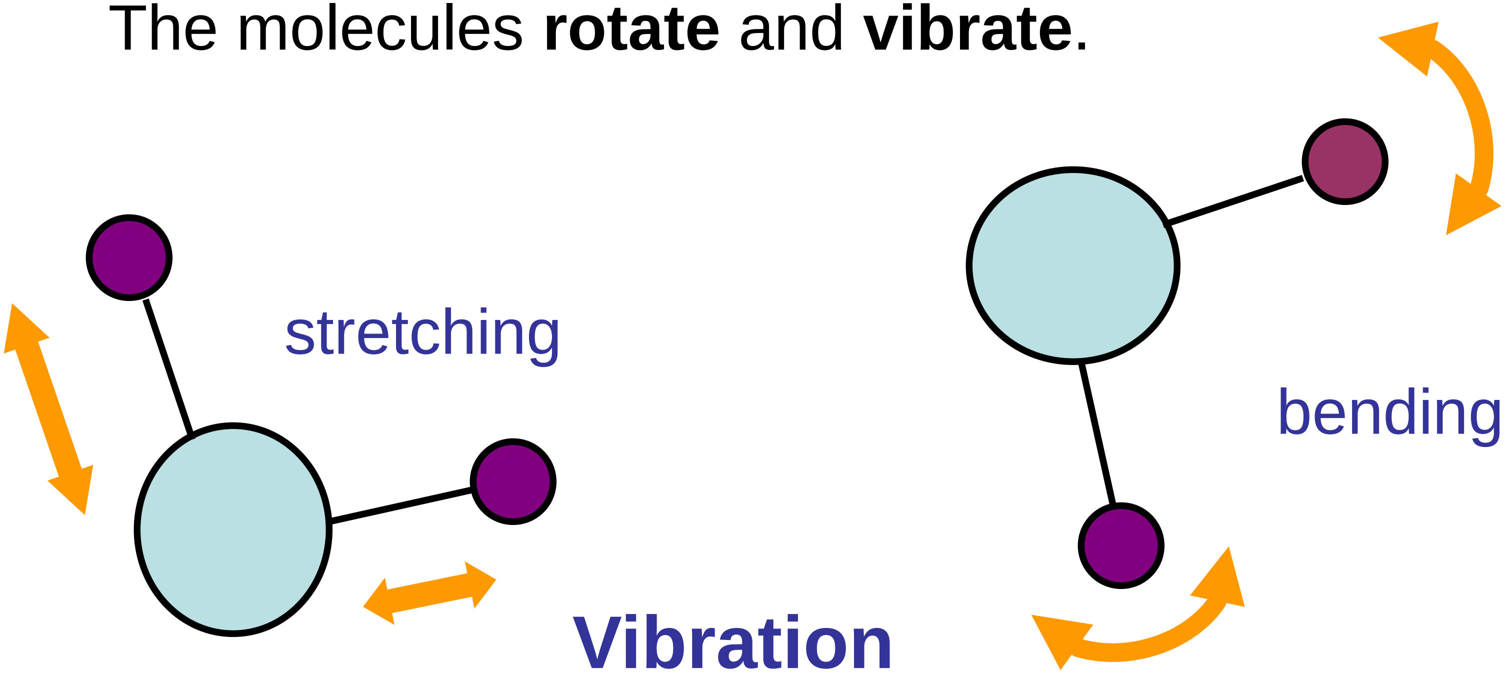
oxygen is more electronegative than hydrogen

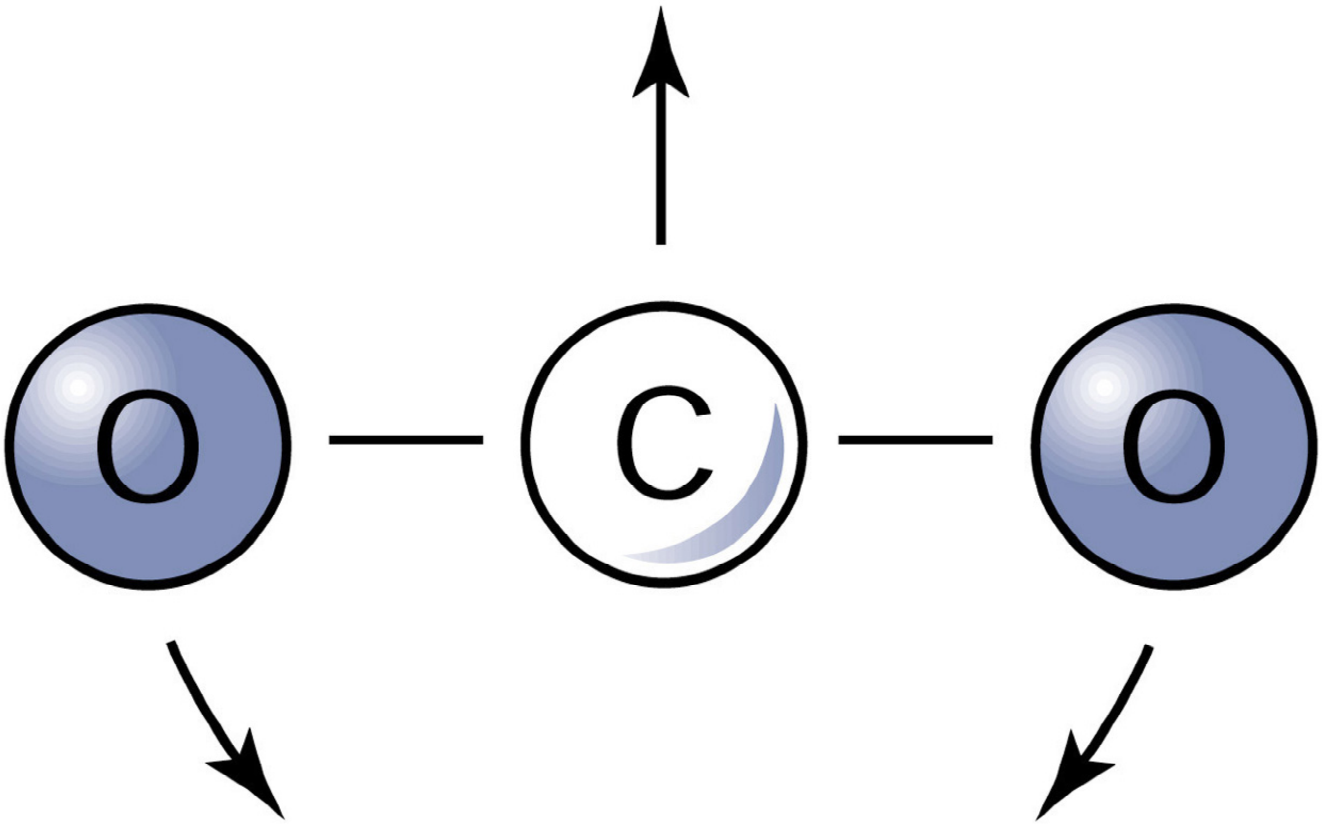

Incoming
IR photon
O
H
H
O
H
H
Slow rotation rate
Faster rotation rate

Molecules absorb energy from radiation.

The energy increases the movement of the molecules.

The molecules **rotate** and **vibrate**.

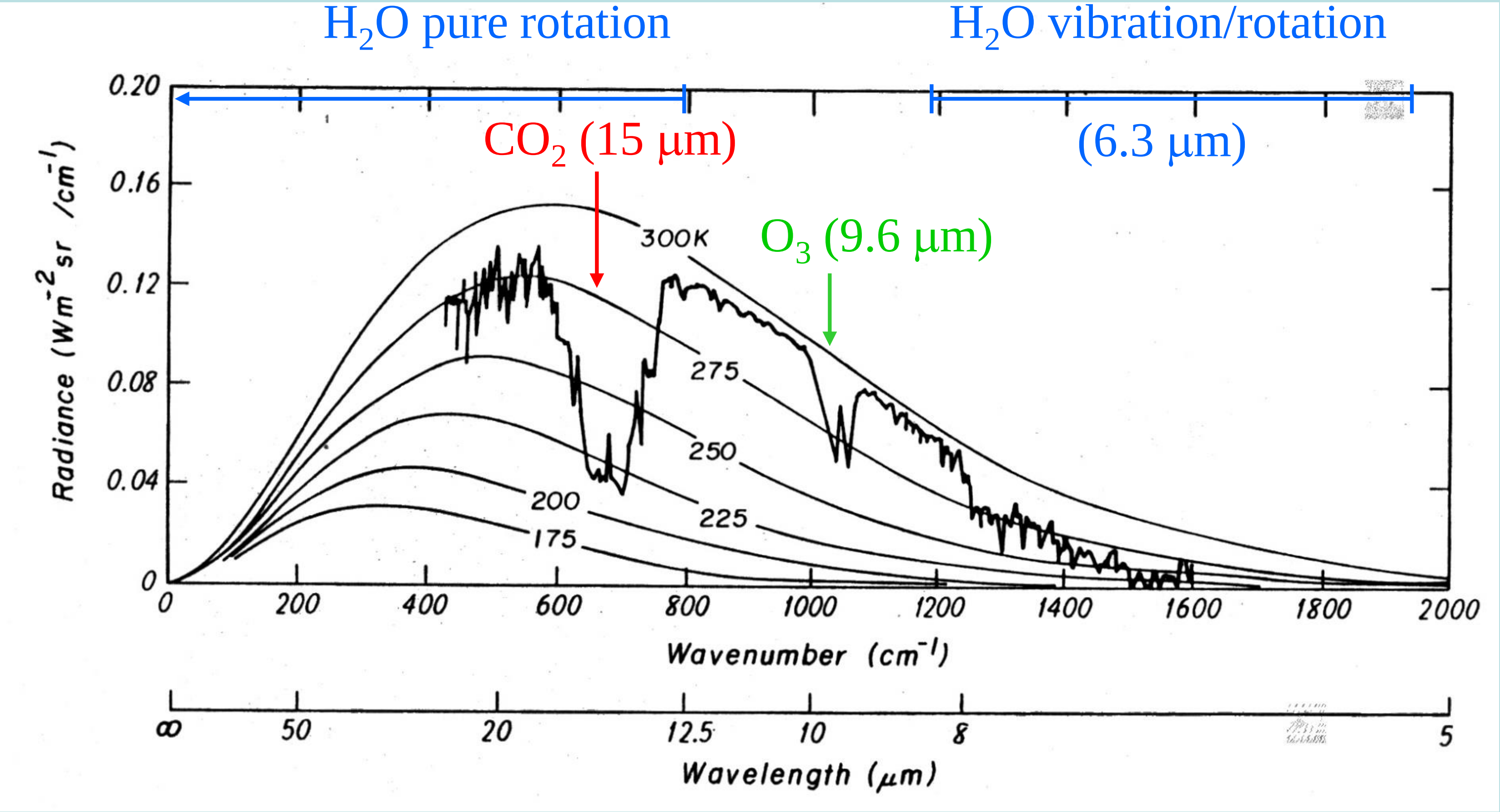




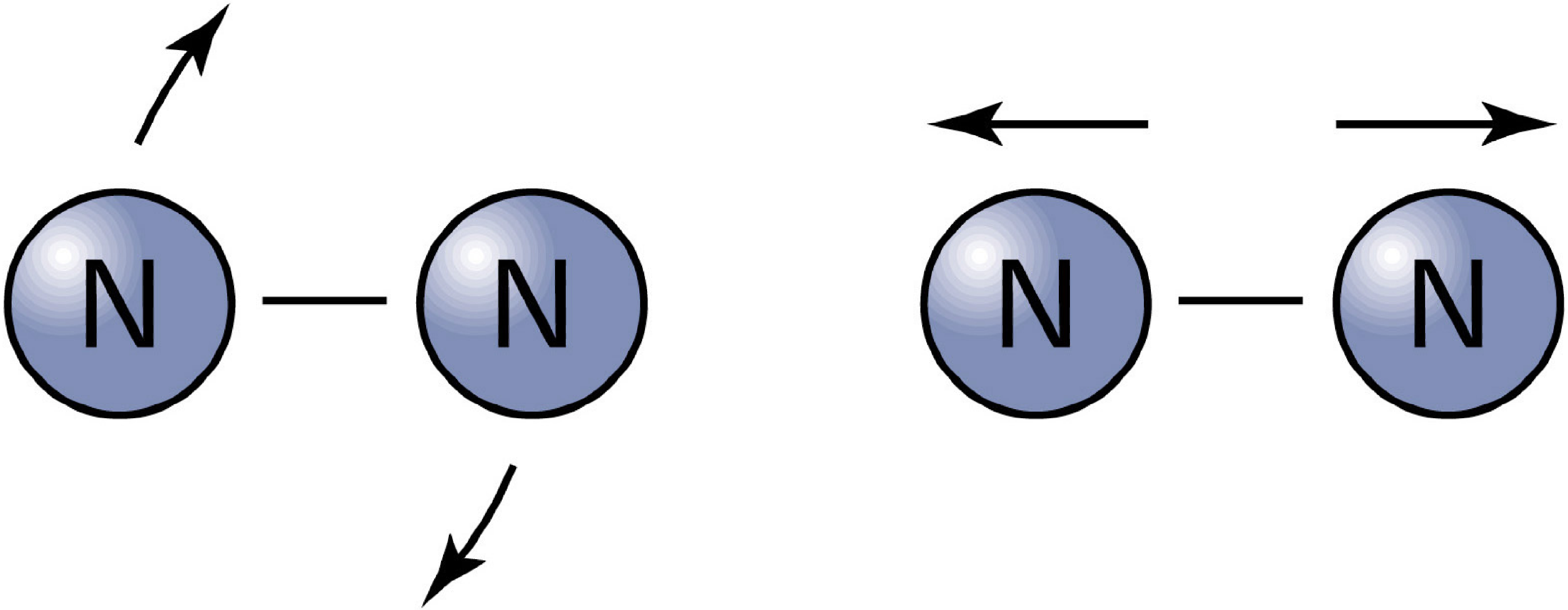
Bending mode
(15-μm band)

Thermal IR Spectrum for Earth

Greenhouse gases absorb IR radiation at specific wavelengths



<u>Ref.</u>: K.-N. Liou, *Radiation and Cloud Physics Processes in the Atmosphere* (1992)



Rotation Vibration

Non-Greenhouse Gases

- The molecules/atoms that constitute the bulk of the atmosphere: O^2, N^2 and Ar; do not interact with infrared radiation significantly.
- While the oxygen and nitrogen molecules can vibrate, because of their symmetry these vibrations do not create any transient charge separation.
- Without such a transient dipole moment, they can neither absorb nor emit infrared radiation.

Atmospheric Greenhouse Effect (AGE)

- AGE increases surface temperature by returning a part of the outgoing radiation back to the surface
- The magnitude of the greenhouse effect is dependent on the abundance of greenhouse gases (CO_2, H_2O etc.)

Clouds

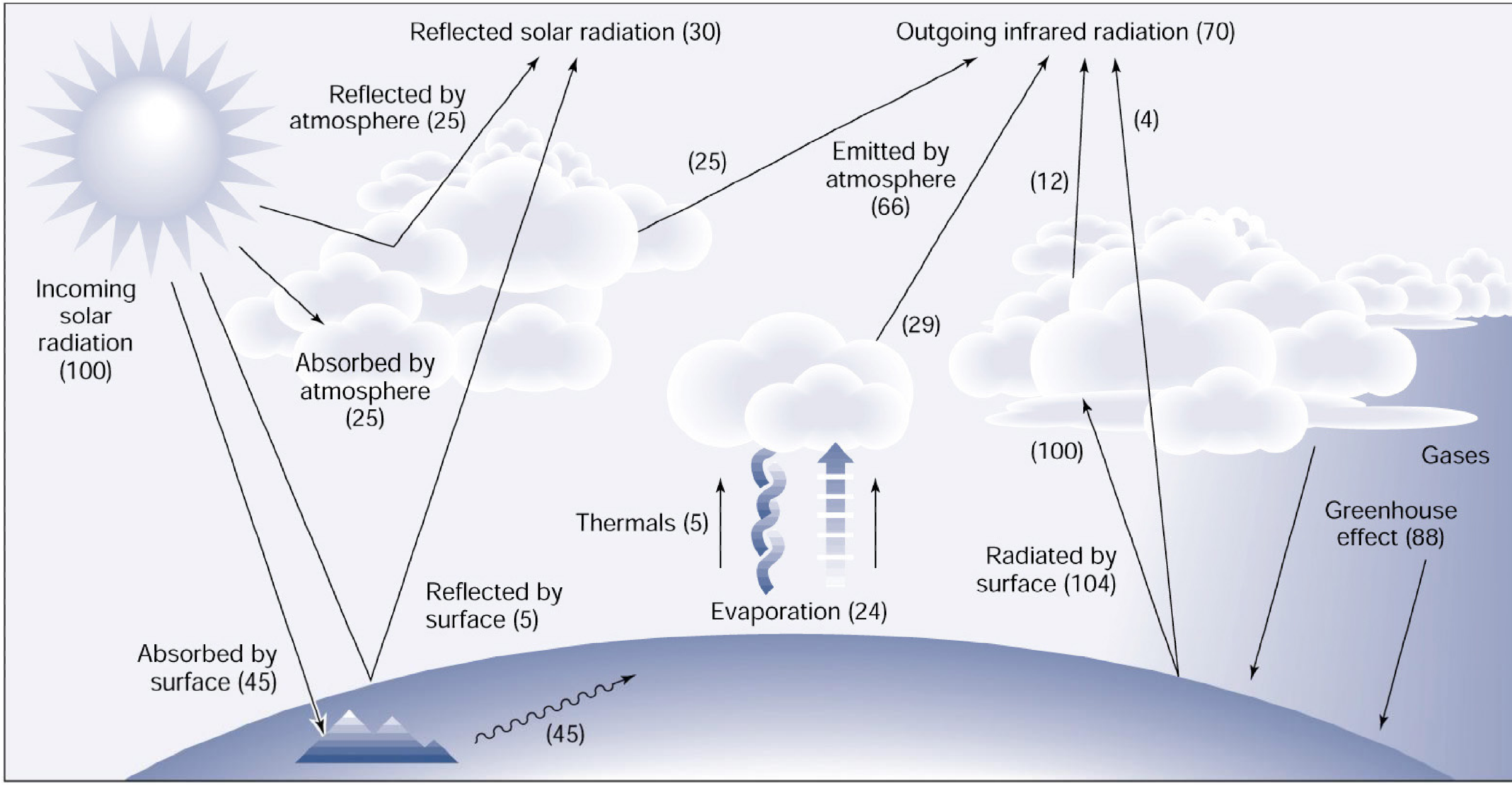
- Just as greenhouse gases, clouds also affect the planetary surface temperature (albedo)
- Clouds are droplets of liquid water or ice crystals
- Cumulus clouds – puffy, white clouds
- Stratus clouds – grey, low-level clouds
- Cirrus clouds – high, wispy clouds

Cumulus cloud

Cirrus cloud

Climatic Effects of Clouds

- Clouds reflect sunlight (cooling)
- Clouds absorb and re-emit outgoing IR radiation (warming)
- Low thick clouds (stratus clouds) tend to cool the surface
- High, thin clouds (cirrus clouds) tend to warm the surface


Reflected solar radiation (30)
Outgoing infrared radiation (70)
Reflected by atmosphere (25)
(25)
Emitted by atmosphere (66)
(12)
(4)
Incoming solar radiation (100)
Absorbed by atmosphere (25)
(29)
(100)
Gases
Thermals (5)
Greenhouse effect (88)
Radiated by surface (104)
Reflected by surface (5)
Evaporation (24)
Absorbed by surface (45)
(45)

Back to the HZ

- Let's assume that a planet has Earth's atmospheric greenhouse warming (33 K) and Earth's cloud coverage (planetary albedo ~ 0.3)
- Where would be the boundaries of the HZ for such planet?

- Recall that the Solar flux: $S = L/(4\pi R^2)$
- We can substitute formula for the Solar flux to planetary energy balance equation:
  $S \times (1-A) = \sigma \times T^4 \times 4$

$$L/(4\pi R^2) \times (1-A) = \sigma \times T^4 \times 4$$

$$\sqrt{\frac{L \times (1-A)}{16 \times \pi \times \sigma \times T^4}} = R$$

Global surface temperature (T_s)

- Global surface temperature (T_s) depends on three main factors:

a) Solar flux
b) Albedo (on Earth mostly clouds)
c) Greenhouse Effect (CO_2, H_2O , CH_4, O_3 etc.)

- We can calculate T_e from the “Energy balance equation” and add the greenhouse warming:

$$T_s = T_e + \Delta T_g$$

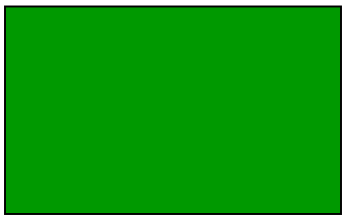
- But! The amount of the atmospheric greenhouse warming (ΔT_g) and the planetary albedo can change as a function of surface temperature (T_s) through different feedbacks in the climate system.

Climate System and Feedbacks

- We can think about climate system as a number of components (atmosphere, ocean, land, ice cover, vegetation etc.) which constantly interact with each other.

- There are two ways components can interact – positive and negative couplings

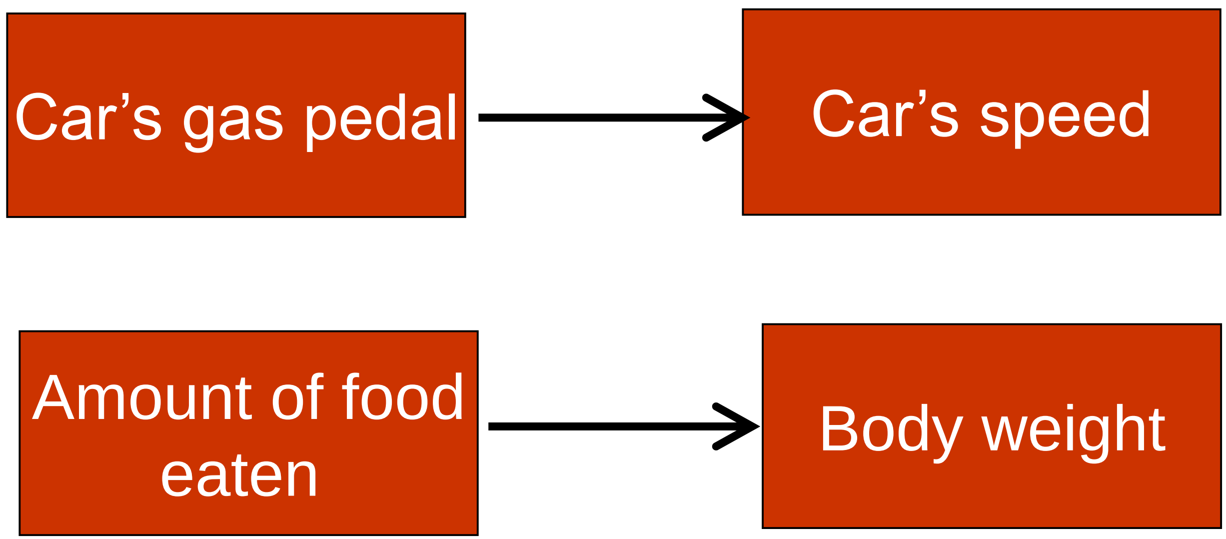
Systems Notation

 = system component

 = positive coupling

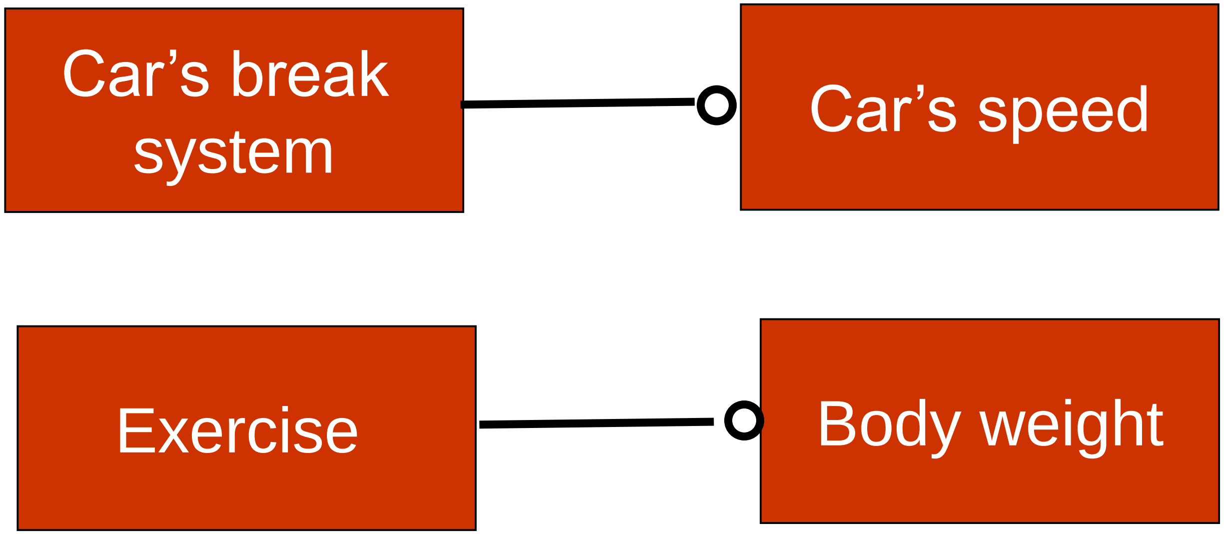
 = negative coupling

Positive Coupling



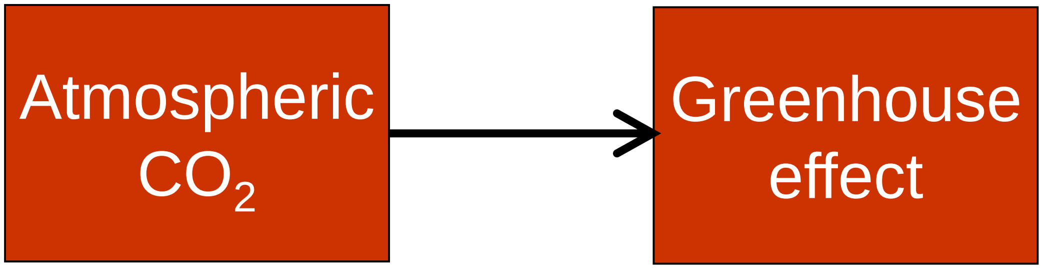
- A change in one component leads to a change of the same direction in the linked component

Negative Coupling



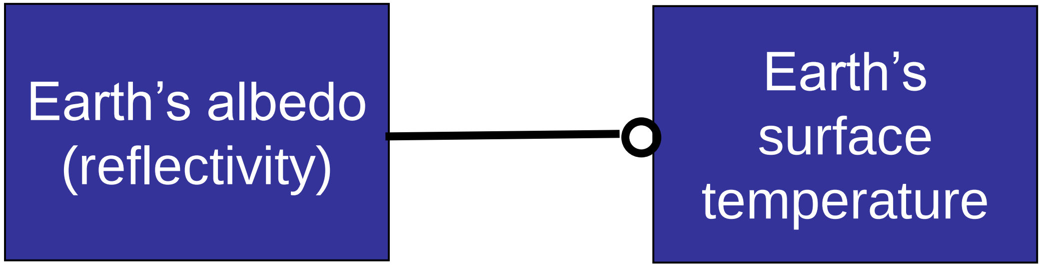
- A change in one component leads to a change of the opposite direction in the linked component

Positive Coupling



- An *increase* in atmospheric CO_2 causes a corresponding *increase* in the greenhouse effect, and thus in Earth's surface temperature
- Conversely, a *decrease* in atmospheric CO_2 causes a *decrease* in the greenhouse effect

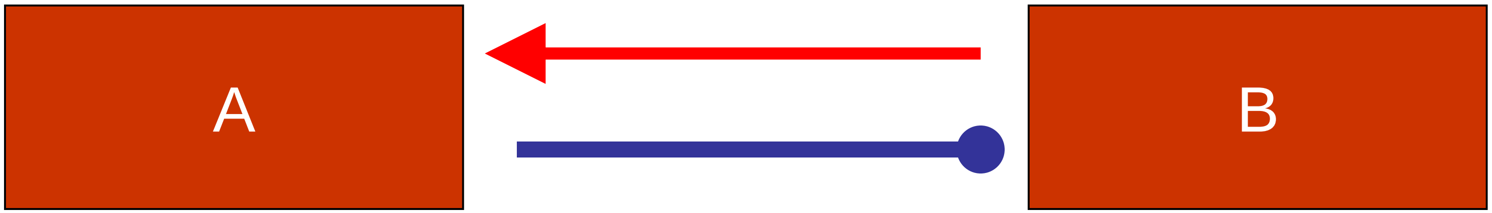
Negative Coupling



- An *increase* in Earth's albedo causes a corresponding *decrease* in the Earth's surface temperature by reflecting more sunlight back to space
- Or, a *decrease* in albedo causes an *increase* in surface temperature

Feedbacks

- In nature component A affects component B but component B also affects component A. Such a “two-way” interaction is called a feedback loop.

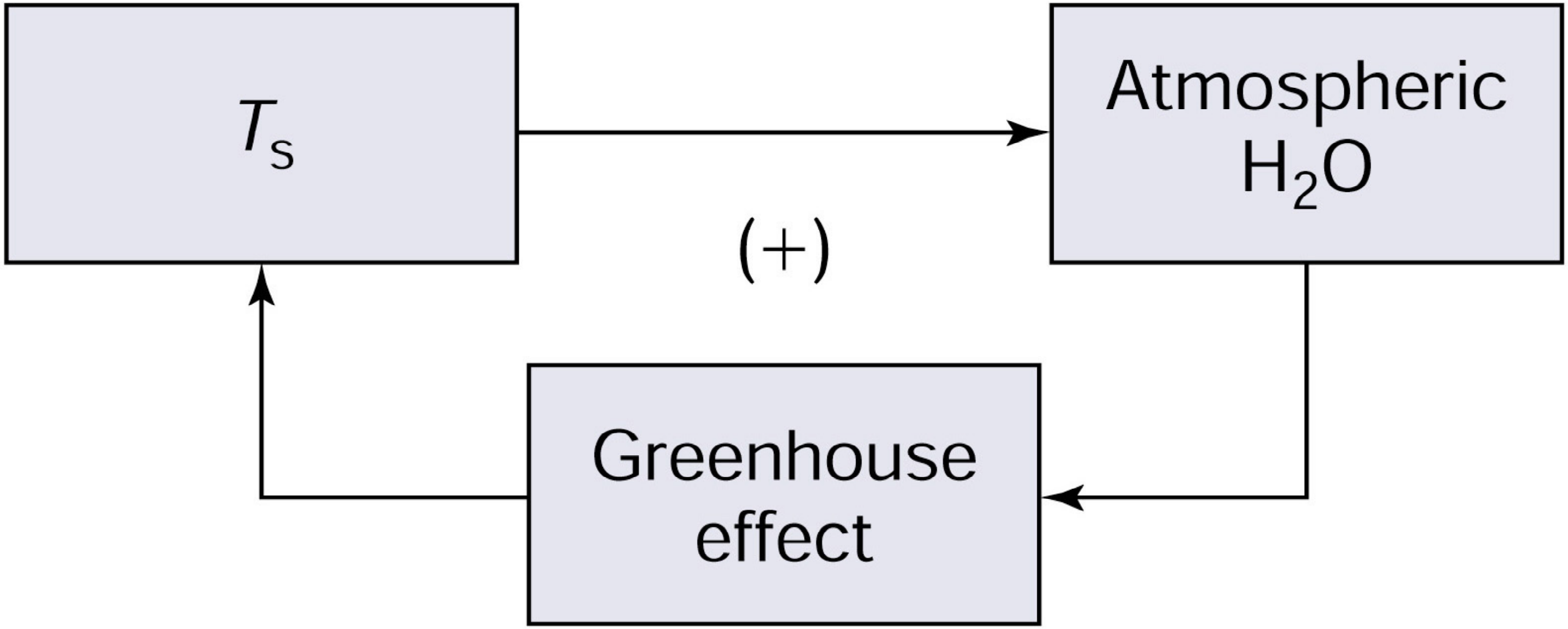


- Loops can be stable or unstable.

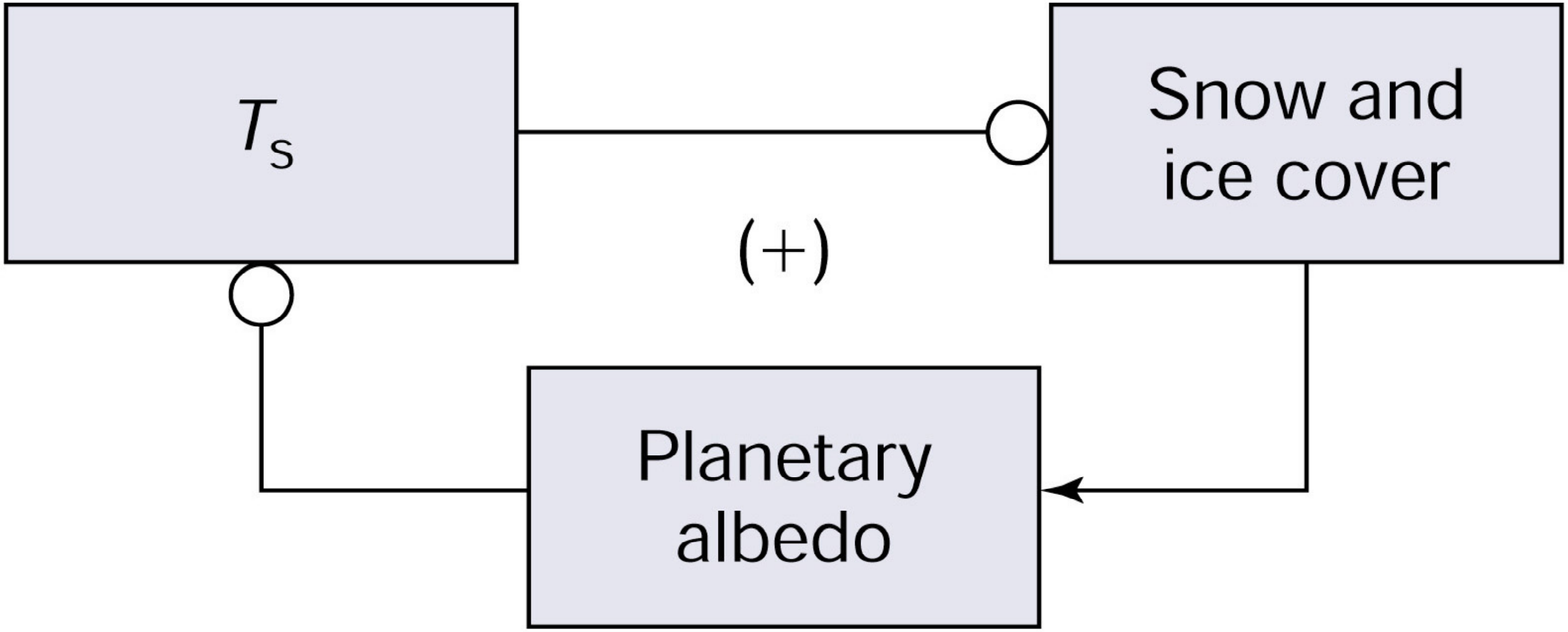
- Negative feedback loops have an odd number of negative couplings within the loop.

Climate Feedbacks

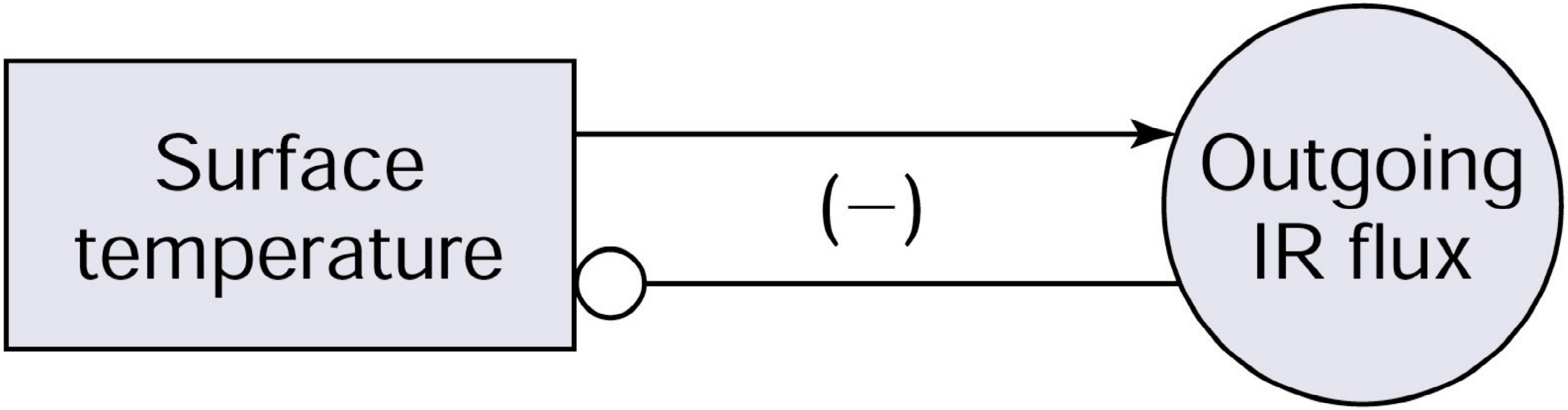
Water Vapor Feedback



Snow and Ice Albedo Feedback

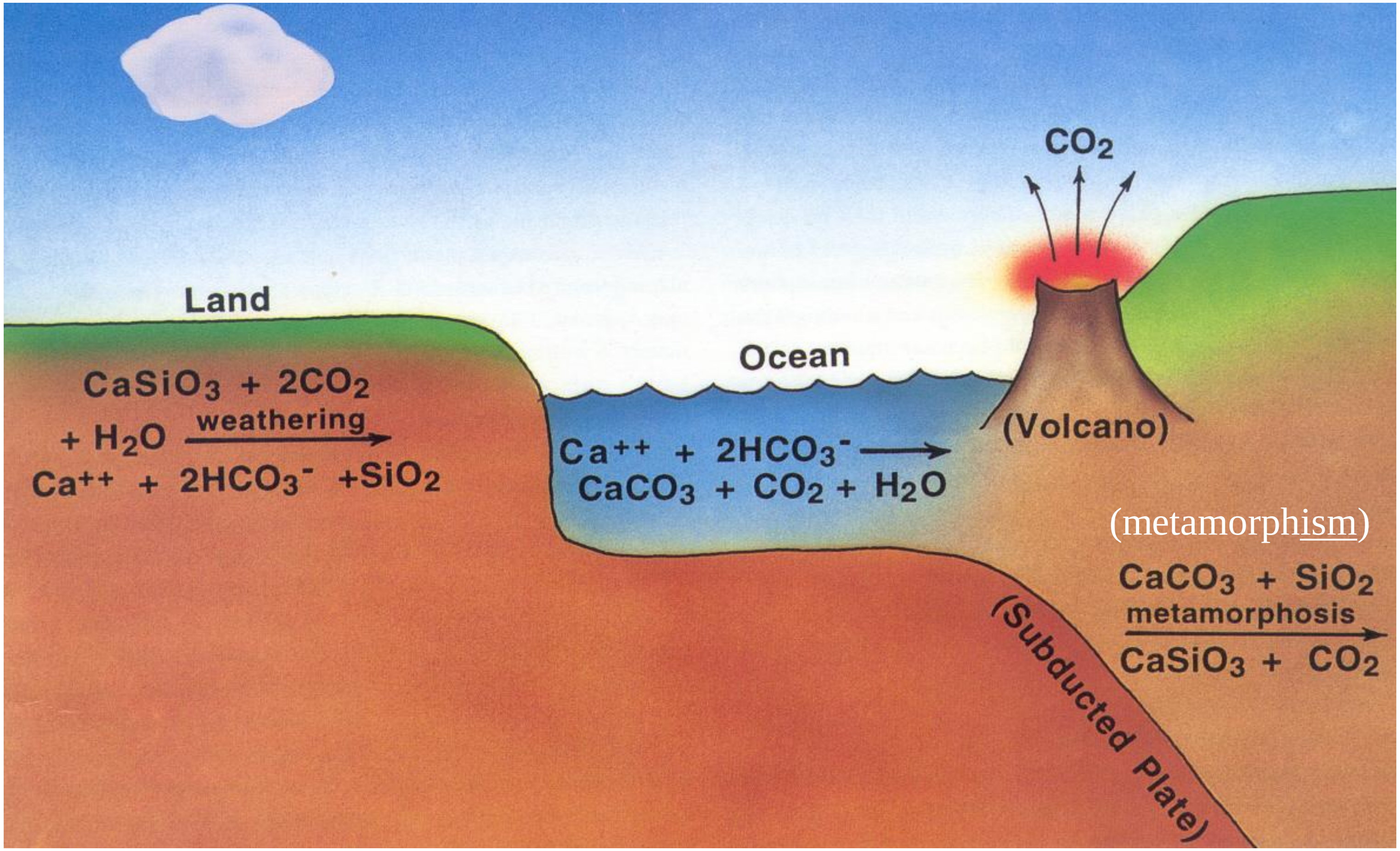


The IR Flux/Temperature Feedback



Short-term climate stabilization

The Carbonate-Silicate Cycle

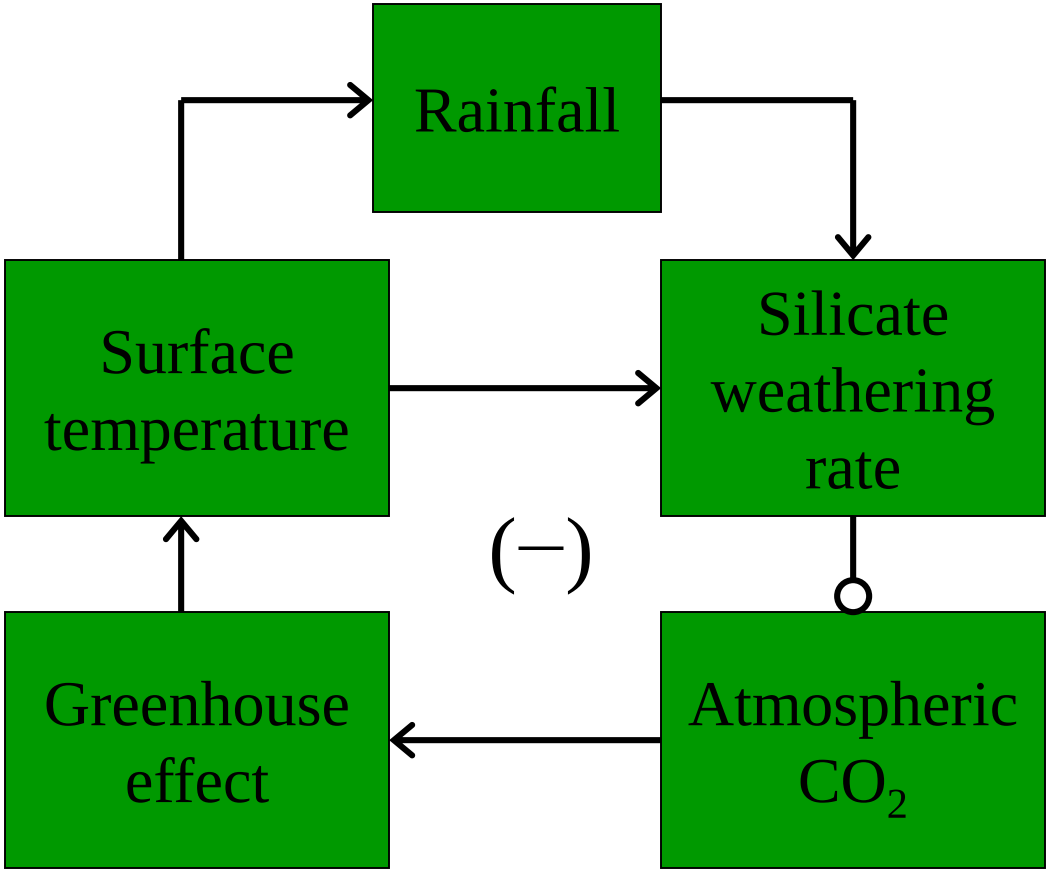


Long-term climate stabilization

- $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$ (weathering)
- $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$ (metamorphosis)

Negative Feedback Loops

The carbonate-silicate cycle feedback

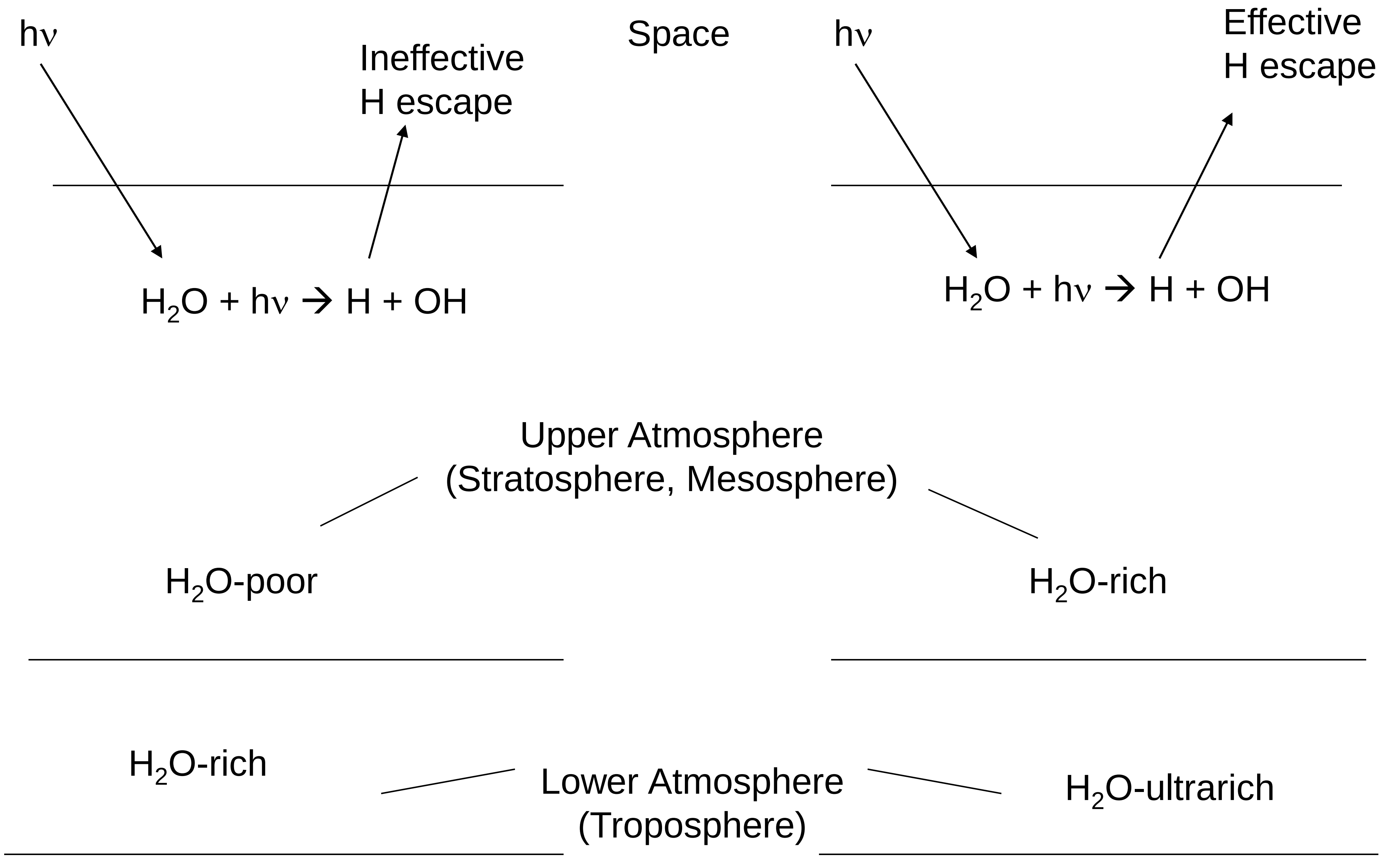


The inner edge of the HZ

- The limiting factor for the inner boundary of the HZ must be the ability of the planet to avoid a runaway greenhouse effect.
- Theoretical models predict that an Earth-like planet would convert all its ocean into the water vapor ~0.84 AU
- However it is likely that a planet will lose water before that.

Moist Greenhouse

- If a planet is at 0.95 AU it gets about 10% higher solar flux than the Earth.
- Increase in Solar flux leads to increase in surface temperature → more water vapor in the atmosphere → even higher temperatures
- Eventually all atmosphere becomes rich in water vapor → effective hydrogen escape to space → permanent loss of water

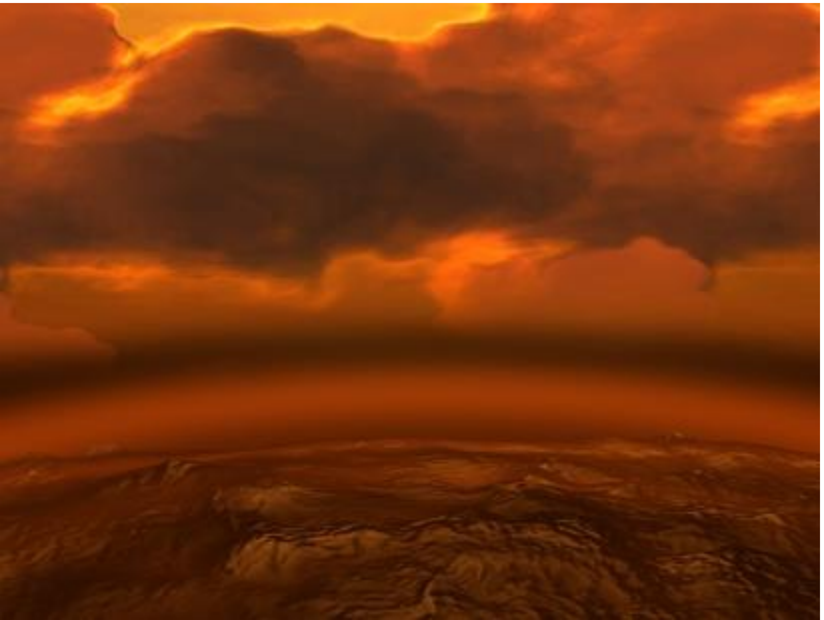


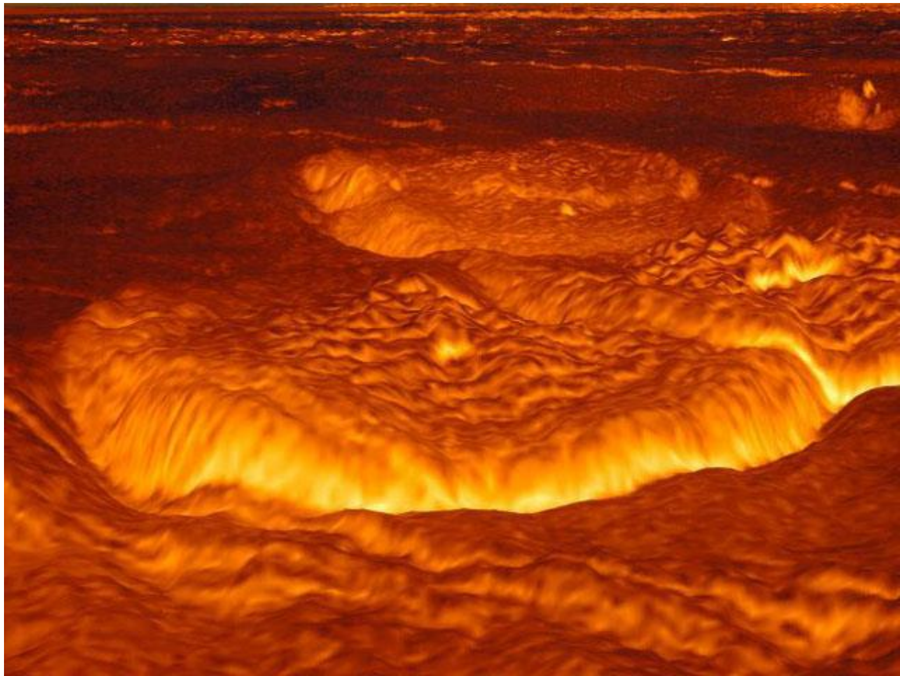
hν
Ineffective
H escape
Space
hν
Effective
H escape
H_2O + hν → H + OH
H_2O + hν → H + OH
Upper Atmosphere
(Stratosphere, Mesosphere)
H_2O-poor
H_2O-rich
H_2O-rich
Lower Atmosphere
(Troposphere)
H_2O-ultrarich

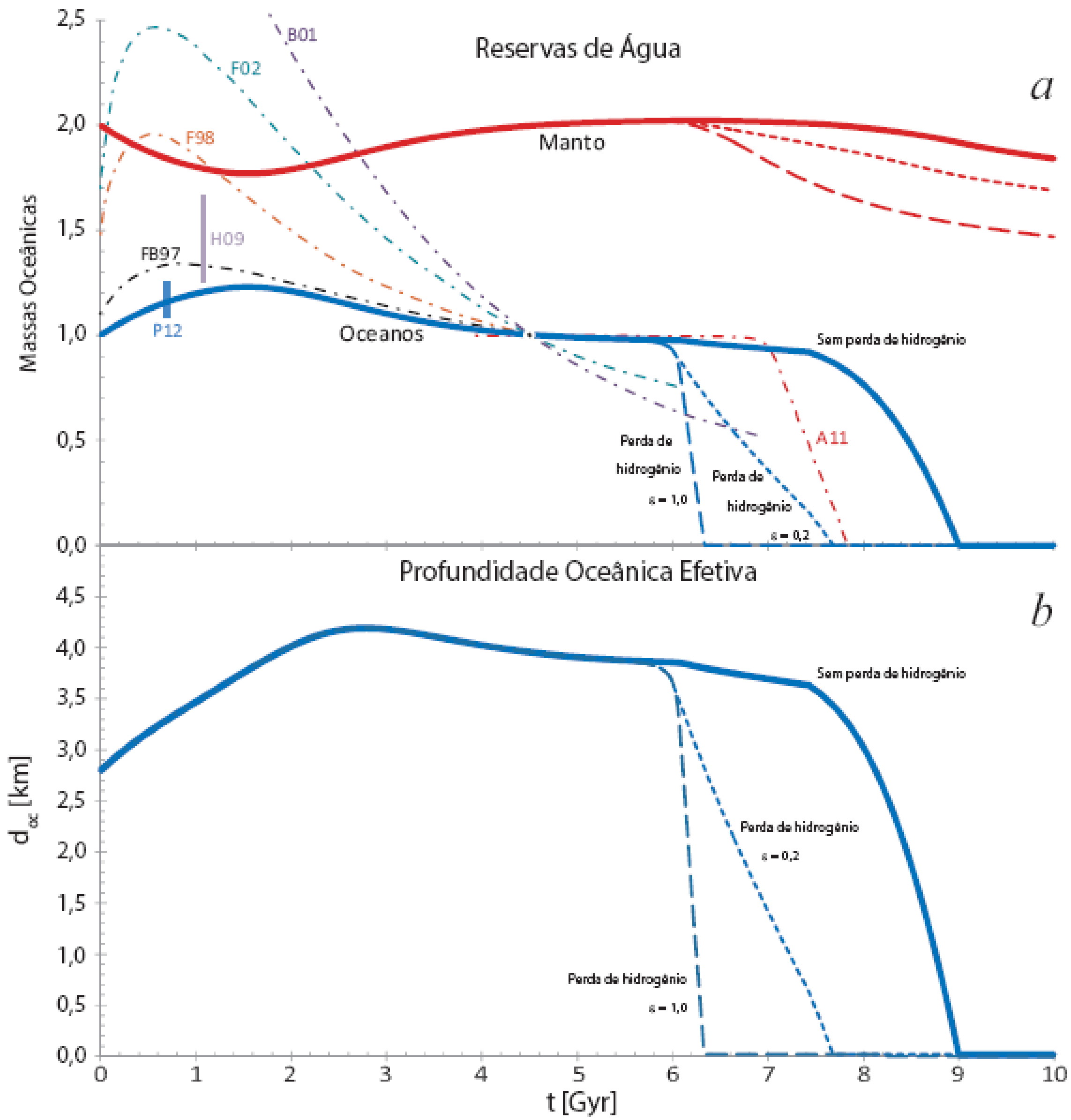
Venus fate

- Runaway (or moist) greenhouse and the permanent loss of water could have happened on Venus
- Venus has very high D/H (~120 times higher than Earth's) ratio suggesting huge hydrogen loss

- Without water CO_2 would accumulate in the atmosphere and the climate would become extremely hot – present Venus is ~ 90 times more massive than Earth’s and almost entirely CO_2.
- Eventually Earth will follow the fate of Venus







Reservas de Água
a
Massas Oceânicas
2,5
2,0
1,5
1,0
0,5
0,0
B01
F02
F98
Manto
H09
FB97
P12
Oceanos
Sem perda de hidrogênio
Perda de hidrogênio ε = 1,0
Perda de hidrogênio ε = 0,2
A11
Profundidade Oceânica Efetiva
b
d_{oc} [km]
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
Sem perda de hidrogênio
Perda de hidrogênio ε = 0,2
Perda de hidrogênio ε = 1,0
0 1 2 3 4 5 6 7 8 9 10
t [Gyr]

The outer edge of the HZ

- The outer edge of the HZ is the distance from the Sun at which even a strong greenhouse effect would not allow liquid water on the planetary surface.
- Carbonate-silicate cycle can help to extend the outer edge of the HZ by accumulating more CO2 and partially offsetting low solar luminosity.

Limit from CO_2 greenhouse

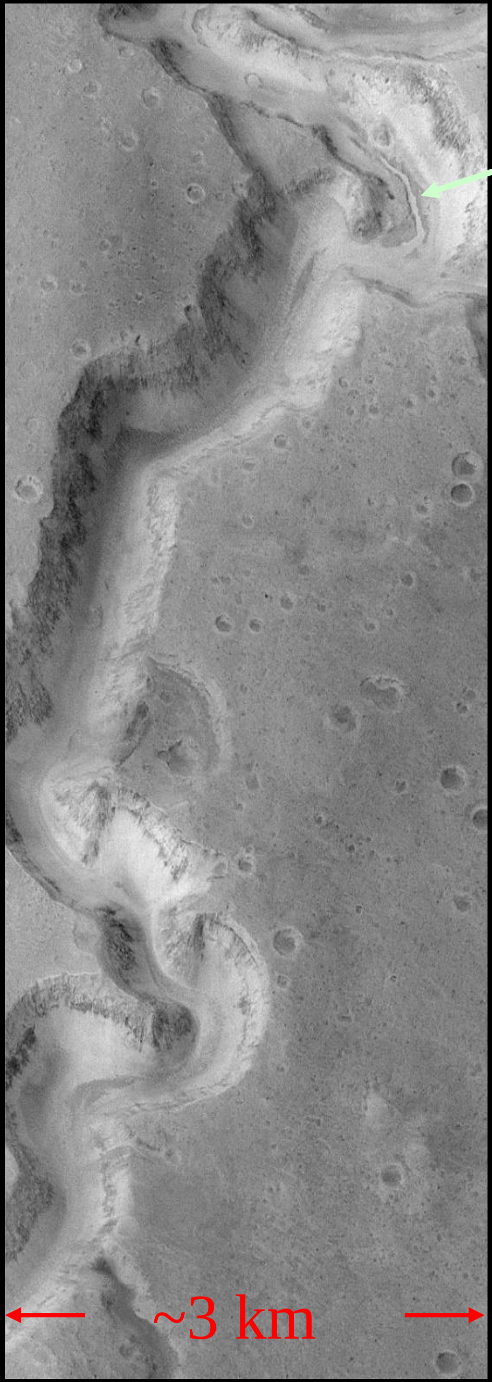
- At low Solar luminosities high CO_2 abundance would be required to keep the planet warm.
- But a very high CO_2 abundance does not produce as much net warming because it also scatter solar radiation.
- Theoretical models predict that no matter how high CO_2 abundance would be in the atmosphere, the temperature would not exceed the freezing point of water if a planet is further than 1.7 A.U.

Limit from CO_2 condensation

- At high CO_2 abundance and low temperatures carbon dioxide can start to condense out (like water condense into rain and snow)
- Atmosphere would not be able to build CO_2 if a planet is further than 1.4 A.U.

Fate of Mars

- Mars is on the margin of the HZ at the present
- But! Mars is a small planet and cooled relatively fast
- Mars cannot outgas CO_2 and sustain Carbonate-Silicate feedback.
- Also hydrogen can escape effectively due to the low martian gravity and lack of magnetic field.



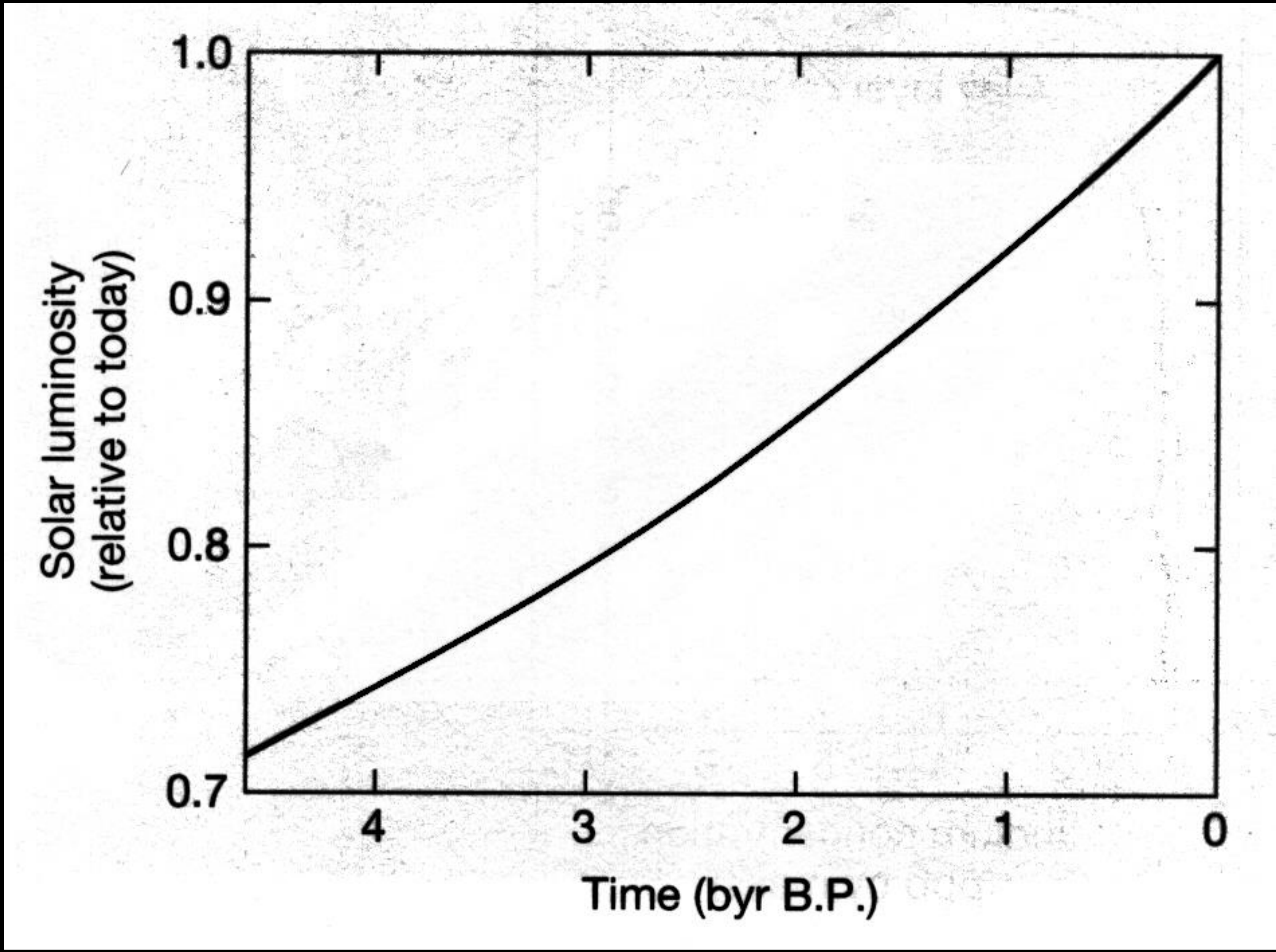
Nanedi Vallis

(from Mars Global Surveyor)

Why the Sun gets brighter with time

- H fuses to form He in the core
- Core becomes denser
- Core contracts and heats up
- Fusion reactions proceed faster
- More energy is produced $\Rightarrow$ more energy needs to be emitted

Solar Luminosity versus Time



See *The Earth System, ed. 2*, Fig. 1-12

Continuous Habitable Zone (CHZ)

- A region, in which a planet may reside and maintain liquid water throughout most of a star's life.