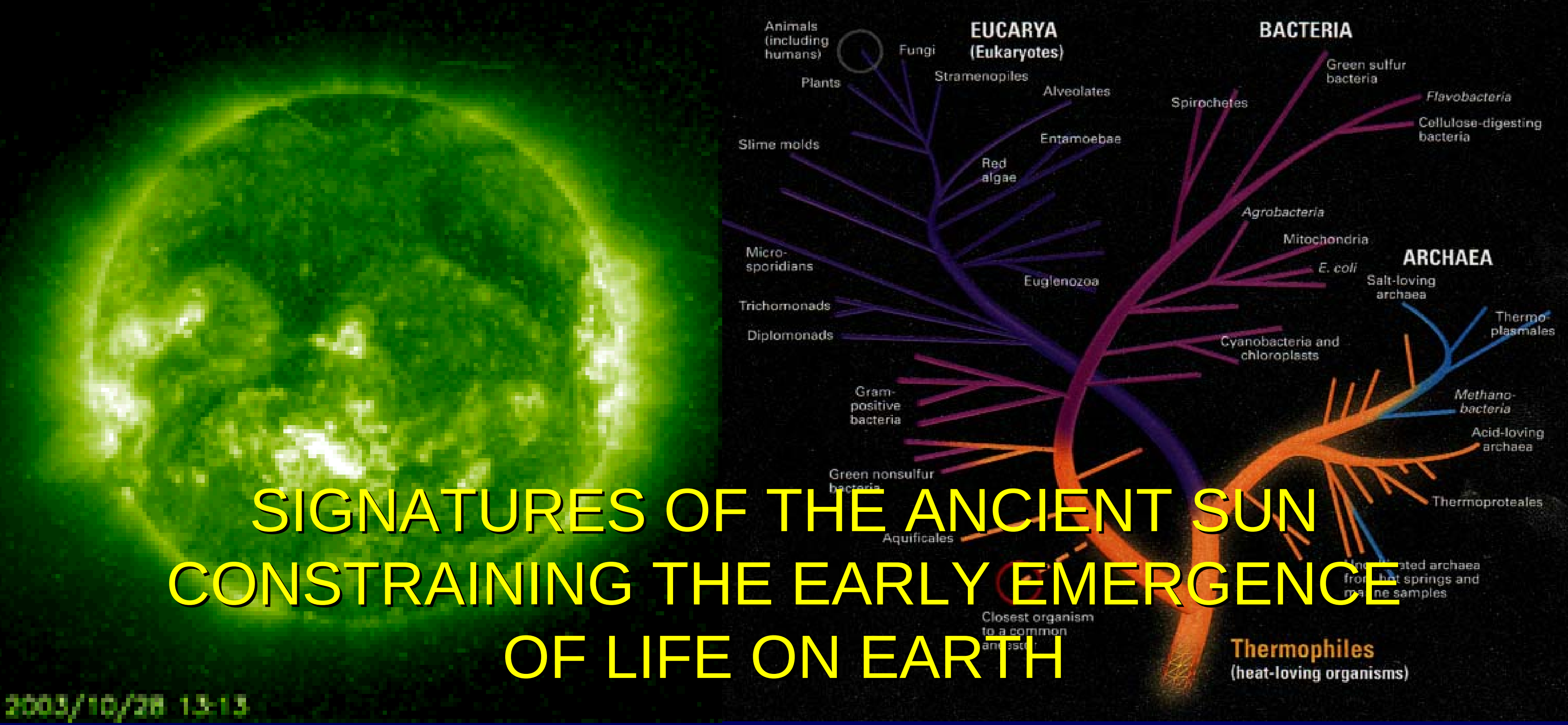

SIGNATURES OF THE ANCIENT SUN CONSTRAINING THE EARLY EMERGENCE OF LIFE ON EARTH

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Scheme of the Talk

- Introduction

- Isotopic fractionation of the noble gases on Earth
- Depletion of volatile elements on the Moon
- Preparing the Solar System for life emergence
- Solar radiation as a factor in life emergence
- Extra-solar radiation as a factor in life evolution
- Solar radiation as a factor in life distribution

- Conclusions

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Introduction

- An important factor for understanding the origin and evolution of life on Earth is the evolution of Solar Weather and Solar Climate

- It is important to reconsider the constraints that the present knowledge of our star implies for the emergence of life on Earth

- This will provide further insights into what may happen in any of the multiple solar systems that are known to date

Isotopic fractionation of noble gases on Earth

- The isotopic fractionation of the 5 stable noble gases (He, Ne, Ar, Kr, Xe) is a signature of the early Sun.
- The early atmosphere arose from collisions during the accretion period (HV, Heavy Bombardment).
- Planetesimal impacts increase the surface temperature, affecting the formation of either a proto-atmosphere or a proto-hydrosphere by degassing of volatiles (Matsui & Abe, 1986).
- This generated a “steam atmosphere” and a rapid outflow of hydrogen & some compounds (e.g. methane), carrying along heavier gases in its trail (Hunten, 1993) by aerodynamic drag.
- The upward drag of noble gases atoms of similar dimension competes with gravity → isotopes with different masses → mass dependent fractionation.

Settlement of appropriate conditions for life

- Solar analogs indicate a larger EUV emission by the early Sun, which can drive mass fractionation in the noble gases: the $^{22}Ne/^{20}Ne$ ratio is larger than in the Earth mantle or in the Solar Wind,
- The observed fractionation is an indicator of:
  a) The presence of the postulated escape flux.
  b) The evidence for the solar energy source that drives the outward flux of gases.
- The emergence of appropriate conditions for life is associated with the decrease of solar radiation that characterizes the accretion period.

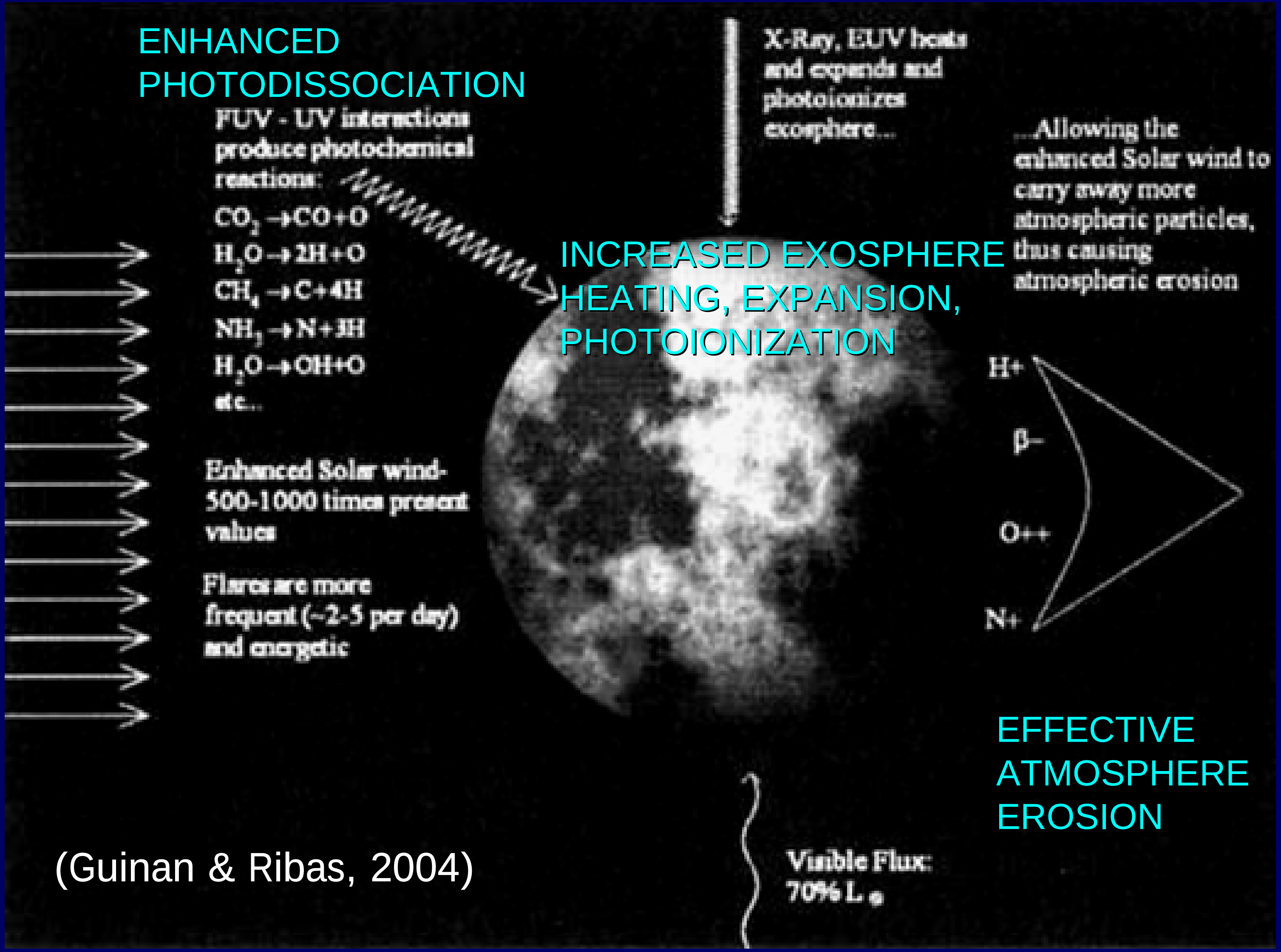
The generation of the hydrosphere

- At the end of the accretion period, the surface heat flux diminishes.
- The "steam atmosphere" rains into a global ocean (Kasting, 1993).

primitive atmosphere $\rightarrow$ hydrosphere + atmosphere

- This splitting leaves behind Carbon and Nitrogen compounds $\rightarrow$ ingredients for subsequent chemical evolution and, eventually, the dawn of life.

Effects of the young Sun on the Earth's paleoathmosphere



Depletion of volatile elements on the Moon

- It is widely accepted that the Moon formed by the impact of a Mars-size body with the Earth.
- This process depleted volatile elements such as H, C, N and noble gases.
- Despite that, the lunar soil is rich in volatiles.
- The isotopic composition of noble gases is subsequent to Moon formation.
- Various hypotheses for volatiles such as N:
  - Solar origin: Direct implantation from solar wind ions.
  - Non-solar origin (but: N abundance & $^{15}N/^{14}N$ 30% var.?)
  - Terrestrial origin: from Earth's atmosphere when no m.f.

Preparing the Solar System for the emergence of life

- Solar activity is the most relevant process
- The more intense solar wind is a key factor via its interaction with the spreading accretion disk → the shock blows the residual gas and fine dust. (Evidence from meteorites, Bertout et al. 1991)
- No terrestrial geologic records give information about the processes taking place from that moment onwards.
- During the first 100 million years → flux of impactors → separation of iron and silicate → metallic core

The early Earth environment

- During the core formation, a planetary impact ejected a significant fraction of mass from the Earth
- The Moon formed, it cooled quickly, no atmosphere
- The original atmosphere of the Earth is blown away by the intense solar wind from the early Sun
- The geological activity on Earth causes the partial outgassing of the secondary atmosphere, whose original composition can be inferred from the isotopic composition of noble gases
- Comets can have plaid a role in feeding the noble gases in the correct proportions (Owen & Bar-Nun, 1995).
- After the end of accretion (4.4 Gy BP) the temperatures had descended to about 100° C.

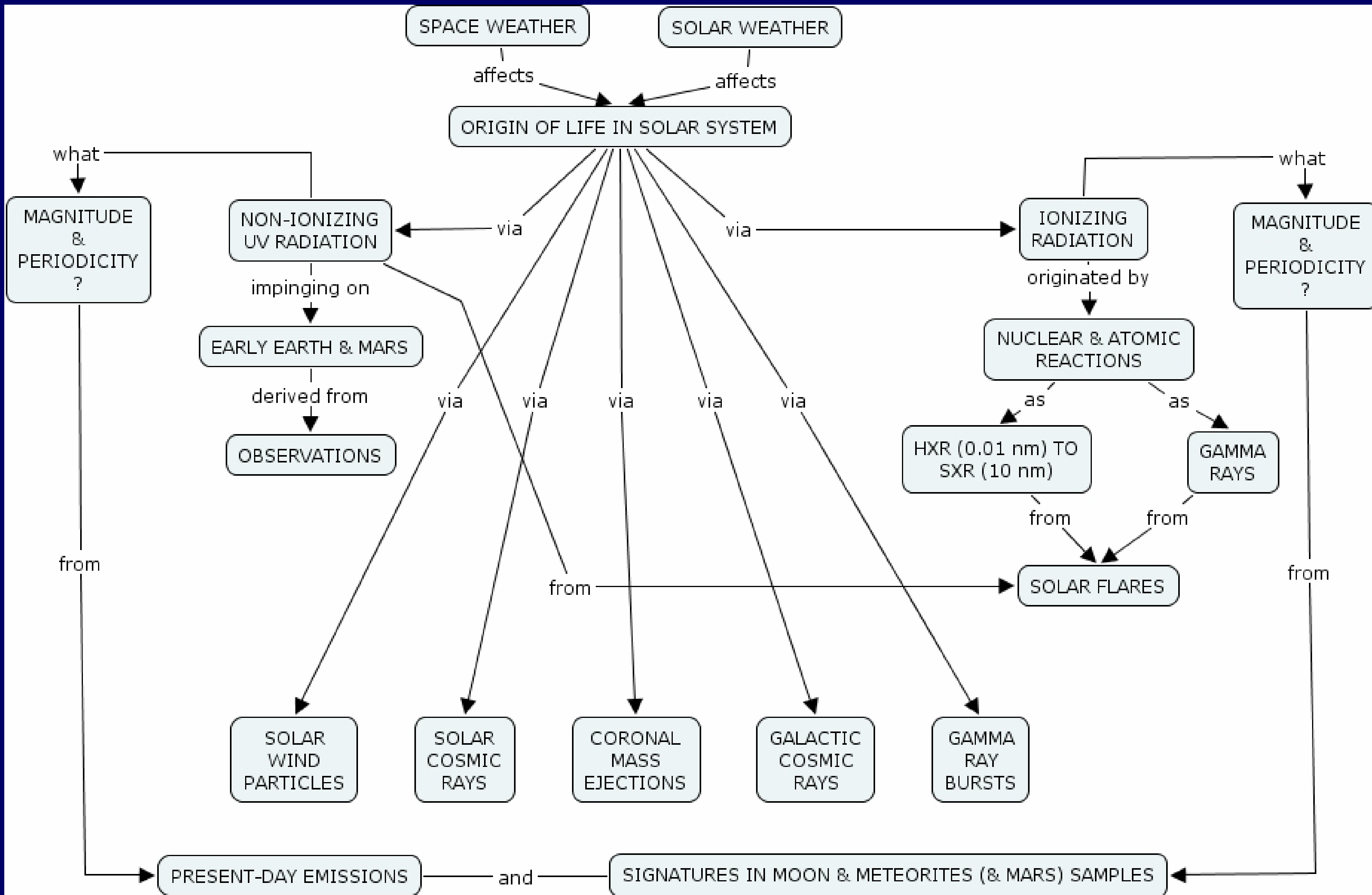
Early origin and evolution of life on Earth

- Solar climate and solar weather should have been sufficiently mild BUT
- The Imbrium Basin on the Moon was formed by a major impact 3.8-3.9 Gy BP (Hartmann et al., 2000) → Late Heavy Bombardment (LHB)
- Persistence of catastrophic impacts (Sleep et al., 1989), possibily triggered by the rapid migration of the giant planets (Gomeset al., 2005)
- If life emerged before LHB, it has been annihilated and it started again after LHB fading out.
- The HB of terrestrial-like planets in exoplanetary systems was considered in Levison et al. (2003)

Solar radiation as a factor in the origin of life

- Components of solar weather relevant to life
  - Non-ionizing UVR (incidence on the surface of the early Earth and Mars $\rightarrow$ inferred from observations)
  - Ionizing radiation (HXR, SXR, γ)
  - Low-energy solar wind particles
  - Solar Cosmic Rays (SCR)
- Any scenario for the early onset of life must take into account the paleo-solar-weather and –climate
- Inferences can be derived from:
  - The study of solar analogs (e.g. the Sun-In-Time project)
  - The signatures of solar energetic particles in extraterrestrial materials (lunar rocks and meteorites)

Ionizing and non-ionizing radiation during the origin of life



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Solar radiation when life emerged

- Possible periods for life emergence:
  - Hadean (4.6-3.8 Gy BP) (?)
  - Archean (3.8-2.5 Gy BP)
- In the Archean the atmosphere was anoxic (from isotopic and geologic evidences, Walker et al. 1983)
- No UV defense mechanism by ozonosphere
- UVB (280-315 nm) & UVC (190-280 nm) radiation could have penetrated to the Earth's surface
- Biological consequences expected (Margulis et al., 1976; Cockell, 1998)

Extra-solar radiation as a factor in the origin of life

- GRBs are originated in distant galaxies by evolution/merging of compact objects
- The SWIFT mission contributes to the determination of recent burst rates
- These were used to infer life robustness in the Ordovician (510-438 My BP), when the second major mass extinction occurred (440-450 My BP)
- This extinction was ascribed to a GRB (Thomas et al., 2005) due to the depletion of the ozone layer (half of the mass is depleted by a 10 s GRB with a recovery time of 5 years).
- In such a case, solar UVR can kill most life forms on land and near the surface of oceans and lakes, and disrupt the food chain.

Solar radiation as a factor in the distribution of life

- At the present time, most UV and X radiation is absorbed at the top of the atmosphere
- The early Sun was producing a higher level of UVR and X radiation (4x – 11x wavelength dependent)
- No UV protection mechanism was originally present
- To explore the consequences at biological level the following topics were investigated:
  - The paleo-Sun radiation environment (Lammer et al., 2002)
  - The Earth's magnetic field reversal (Biernat et al., 2002)
  - The biological effects of solar flares (Belisheva et al., 2002)
  - The uracil dosimetry for life molecules preservation (Berces et al., 2002)
  - Various experiments aboard ISS.

Distribution of life by transfer of microorganisms

- The possibility that life was distributed in the Solar System by transfer of microorganisms between planets and satellites was estensively investigated (Cockell & Horneck, 2001)
- The constraints on the possible transfer are set by the solar weather during the early stages of the evolution of life
- Bacillus Subtilis (Gram+ bacterium) produce endospores resistant to heat and dessication
- Its inactivation was studied in Earth's orbit under different simulated ozone-column abundances to define the photobiological effects of an early ozone-free atmosphere
- It resulted that the spectral sensitivity of DNA increases sharply towards shorter wavelengths from UVB to UVC:
  - This is the primary reason for the observed high lethality of extratrerrestrial UV radiation
  - It could provide a barrier to the distribution of life in the Solar System

Biological resistance to ionizing radiation

- Many radiation-resistant organisms are known
- *Deinococcus radiodurans* (“terrible berry that withstands radiation”) is a Gram+, red-pigmented, non-motile, non-spore-forming, extremophile bacterium, which is resistant to ionizing and UVR:
  - It grows under chronic radiation (50 Gy/h)
  - It recovers from gamma doses of 10,000 Gy
  - Survivors are found from doses of 20,000 Gy
  - (E. Coli is 200 times less resistant to gamma)
  - (Humans cannot tolerate radiation of up to 5 Gy)
  - Possibly due to its genome and to the adaptation to dessication: lack of water and excessive radiation doses stimulated the activation of massive DNA repair mechanisms
- *Cyanobacteria* effectively withstand dessication

Conclusions

- We attempted a preliminary comprehensive discussion of how research in the conditions of the early Sun combine with observations in several relevant disciplines to give us insights into the factors that lead to the emergence of life in a given solar system.
- The considered fields are, respectively, biogeochemistry, lunar science, micropaleontology and chemical evolution.
- These considerations are necessary in order to gradually approach an understanding of the general conditions that will allow life to emerge in a given solar system anywhere in the universe,
- Such a multi-disciplinary approach demonstrates the fundamental role for scientific research of monitoring solar weather and modelling solar climate: **an important scientific spin-off of an applied discipline**