Origins: From the Protosun to the First Steps of Life
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Towards astrobiological experimental approaches to study planetary UV surface environments

Ximena C. Abrevaya[1,2], Martin Leitzinger[3], Oscar J. Oppezzo[4], Petra Odert[3], G. Juan M. Luna[1,2], Manish Patel[5], Ana F. Forte-Giacobone[4,6] and Arnold Hanslmeier[3]

[1]Instituto de Astronomía y Física del Espacio (UBA-CONICET)
Ciudad Autónoma de Buenos Aires, Argentina.
email: abrevaya@iafe.uba.ar

[2]Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires
Ciudad Autónoma de Buenos Aires, Argentina.

[3]Institute of Physics, IGAM, University of Graz, Austria.

[4]Departamento de Radiobiología, Comisión Nacional de Energía Atómica. Buenos Aires, Argentina.

[5]School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, U.K.

[6]Departamento de Ingeniería, Universidad Nacional de Tres de Febrero. Buenos Aires, Argentina.

Abstract. The stellar ultraviolet radiation (UVR) has been studied in the last decade and has been found to be an important factor to determine the habitability of planetary surfaces. It is known that UVR can be a constraint for life. However, most of the studies of UVR and habitability have missed some fundamental aspects: i) Accurate estimation of the planetary atmospheric attenuation, ii) The biological inferences used to represent the impact of the stellar UVR on life are theoretical and based on the action spectrum (for DNA or microorganisms) or considering parameters as the "lethal dose" obtained from non-astrobiological experiments. Therefore, the conclusions reached by previous studies about the UVR habitability of planetary bodies may be inaccurate. In this work, we propose how to address these studies in a more accurate way through an interdisciplinary approach that combines astrophysics, microbiology, and photobiology and by the use of specially designed laboratory experiments.

Keywords. stars: activity, ultraviolet: stars, methods: laboratory, astrobiology

1. Introduction

Astrobiology is a relatively new and multidisciplinary field of science that focused on the research about the origin, evolution and distribution of life in the universe. The main international roadmaps for research in astrobiology, as NASA astrobiology Roadmap and The European AstRoMap project (supported by the European Commission Seventh Framework Programme), have among their objectives the characterization of habitable environments in the universe considering the evolution of life and its physical environment that includes radiation (DesMarais *et al.* 2008, Horneck *et al.* 2016). Even though classically the habitability zone (HZ) is defined by the presence of liquid water on the surface of the planet, there are several factors that can constrain the existence of life on planetary bodies. Among these factors, radiation appears to be crucial because habitability is strongly dependent on stellar activity (Hanslmeier 2018). In general: (i) The radiation received by the planetary body and the plasma environment provided by the parent star, play a role on the evolution of the planet and its atmosphere (e.g: Khodachenko *et al.* 2007), (ii) Radiation may have a role in the origin of life, as could be part of photochemical reactions necessary for the polymerization of prebiotic organic molecules (e.g: Ranjan *et al.* 2017), (iii) Radiation can damage cells and therefore can be detrimental for life (e.g: Kielbassa *et al.* 1997). These effects on life can be beneficial or detrimental depending mainly on the radiation flux and wavelength. In particular, radiation at UV wavelengths (200 - 400 nm) have multiple targets at cellular level and can reach the surface of a planet. Therefore, UVR can be a constraint for life (Abrevaya & Thomas 2017) and the effects of radiation on life will depend on activity, evolution and spectral type of the parent star. The variability in stellar activity is also another important factor for habitability and can be particularly observed as sudden and energetic explosive events known as "flares", originated in magnetic processes affecting all the layers of the stellar atmosphere (photosphere, chromosphere and corona), which heat the stellar plasma and accelerate its protons, electrons and heavy ions to velocities near the speed of light. Studies related to stellar activity comprise energetic events as stellar cosmic rays, flares, coronal mass ejections (CMEs), enhanced coronal X-rays, and enhanced chromospheric UV emission, among others (e.g, Ayres *et al.* 1997; Gershberg 2005; Scalo *et al.* 2007). These analyses also included young solar analogs, in the context of the early Earth (Ribas *et al.* 2010).

The determination of UV habitable environments has been an active field of research in the last 10 years (see e.g.: Cnossen *et al.* 2007; Rugheimer *et al.* 2015; O'Malley-James & Kaltenegger 2017; Howard *et al.* 2018). However, although several authors have analyzed UV radiation fluxes in order to determine the UV habitability of planetary bodies, most of these studies have missed some fundamental aspects. In general: (i) They did not assume the presence of a planetary atmosphere or assumed atmospheric compositions that may not be accurate enough considering the spectral type and stellar activity which may lead to an inaccurate estimation of UV fluxes (fluence rates) reaching the planetary surface. (ii) The estimation of the UV habitable zone through biologically relevant UV fluxes has been done using theoretical calculations based on extrapolations of the action spectrum (DNA or microorganisms) or considering parameters as the "lethal dose". The use of the DNA action spectrum is not accurate from the biological point of view because the irradiation effects on isolated DNA molecules does not represent the complex and multiple effects of radiation on cells. Additionally, when considering extrapolations from microorganisms action spectrum or lethal doses from the literature, some important information is missing as the stage of the growth and physiological conditions of the microbial population. Moreover this information is taken in general from experimental works that were done at low fluence rates and this may not represent some astrophysical scenarios. Therefore, the conclusions reached by previous studies about the UVR habitability of planetary bodies may be inaccurate. In this work we propose how to address these problems by using an interdisciplinary astrobiological approach, that includes astrophysics in combination with microbiology and photobiology and by using specially designed laboratory experiments.

2. Effects of UVR on life

It is possible to distinguish two main effects of UVR on life : (i) Direct effects, when radiation is affecting prebiotic chemistry or cells (e.g.: microorganisms). (ii) Indirect effects, when radiation is affecting the planetary atmosphere, and therefore life on the planet (Abrevaya 2013; Abrevaya & Thomas 2017). If we consider direct effects, UVR can be very harmful and even lethal to living beings, as it is capable to damage DNA but also damaging other cellular components through direct or indirect mechanisms

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(Kielbassa *et al.* 1997). However, if the doses are not lethal, they could induce mutations and increase the genetic variability, thus providing new raw material for all sorts of selective pressure. At the same time, higher doses of UVR can also act as a selective pressure itself, leading to the appearance of organisms adapted to live under UVR stress, such as those with pigments for instance (Scalo *et al.* 2007; Wynn-Williams *et al.* 2002). Additionally, UVR could have played an important role during the polymerization of the first organic molecules in the chemical evolution of the prebiotic era on the Earth (Sagan & Khare 1971; Chyba & Sagan 1992; Pestunova *et al.* 2005). Additionally, among the indirect effects we find that UVR can affect the photochemistry at atmospheric level. For example, very recently, new photochemical models have determined that Earth-like atmospheres (ozone) are less feasible for exoplanets in the HZ of some main sequence stars as M dwarfs (García-Sage *et al.* 2017). To determine the influence of UVR on life on planetary bodies, previous studies have been using extrapolations from the DNA action spectrum (Cockell 1998, 1999, 2000; Buccino *et al.* 2006, 2007; Cuntz *et al.* 2010; Rugheimer *et al.* 2015), and microorganisms action spectra (O'Malley-James & Kaltenegger 2017; Estrela & Valio 2018). Nevertheless, the action spectrum represents the relative effectiveness of radiation of different wavelengths to produce a given biological effect and does not represent the chances of survival of a microbial population, but at which wavelengths the radiation is more effective producing an effect. Additionally, DNA is not the only target that can be affected during radiation damage, as proteins and other cellular structures can also be affected. Other studies used extrapolations from parameters as the lethal dose (LD) (Howard *et al.* 2018), that represent the amount of radiation that is necessary to kill a percentage of microorganisms of the population (e.g.: LD90, the percentage necessary to kill the 90 percent of the population). This value is obtained as a parameter from the exponential region of the survival curve for a particular microorganism. However the shape of the curve will depend on the fluence rate of radiation, stage of the growth and physiological conditions of the microbial population under consideration. In general, the probability to suffer damage or to survive to radiation is dependent on several physiological mechanisms as DNA repair and shielding strategies or photoprotection mechanisms to cope with radiation (e.g.: pigments). These mechanisms are particularly important in radioresistant microorganisms. The overall biological effect will depend, therefore, on the balance between photoprotection, damage and DNA repair. Therefore, experimental approaches are needed to determine more accurately the chances of life to arise or develop in a planetary context.

3. New approaches and future work

Very recently Ranjan *et al.* (2017), clearly postulate the lack of experimental approaches to study UV habitability in exoplanets, emphasizing also the need to further develop experimental studies under laboratory conditions. In our studies we propose a two step interdisciplinary approach (Abrevaya 2013): a first step with astrophysical analysis to provide the data of UVR fluence rates on the planetary surfaces that will be used in a second step to reproduce UVR planetary scenarios on laboratory conditions to perform biological experiments.

Step 1: estimation of planetary atmospheric attenuation and planetary UVR surface fluxes.

The amount of UVR reaching the surface of planetary bodies (200 -400 nm) will depend on the stellar emission and the atmospheric features of the planetary bodies being considered. Therefore, we will use the stellar radiation fluxes from the observations already available in the IUE and FUSE databases to compute the 1D-radiative transfer modeling of atmospheres (adapted from a previous model in Patel *et al.* 2002), which will be applied considering different atmospheric compositions. These compositions will be

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chosen according to the current knowledge about photochemical modelling obtained from the literature.

Step 2: determination of radiation constraints for life by using experimental approaches The UVR fluence rates obtained in step 1 will be used to simulate radiation environments in laboratory experiments. In these experiments several kinds of microorganisms will be exposed to different UVR fluences (in wavelenghts between 200-400 nm) to evaluate biological effects and potential lethality of the microbial population under different fluence rates, that will depend on the planetary scenario to be considered. For these experiments we will take into consideration: (i)Physiological condition and stage of the growth of the microbial population: we will irradiate liquid cultures of microorganisms in stationary phase, as an approximation to the physiological condition of microorganisms in the environment, (ii)Potential attenuation of radiation by environmental factors or UV absorbing compounds: we will irradiate the microorganisms in a "worst case scenario", avoiding any external factor that can attenuate radiation and with continuous stirring to prevent shielding, (iii)Evaluation of DNA repair capabilities and survival: we will recover the irradiated cultures under "dark" and under "light" conditions, to evaluate the photorreactivation of the DNA repair system in the microorganisms under evaluation. The survival will be evaluated by the plate counting technique.

This will allow us to determine a potential range of UVR fluence rates and fluences according to stellar spectral type, stellar age and planetary atmospheric conditions where it would be possible to find life as we know it.

The proposed approaches are also currently being developed as part of two different interdisciplinary projects: the BioSun and the EXO-UV projects (Abrevaya *et al.* 2014a,b), aiming to expand and improve previous studies, by the incorporation of experimental laboratory approaches.

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Discussion

Artur de la Villarmois: Do you think that the presence of an atmosphere will change your results?

Abrevaya: Yes, in the sense of the fluency rate and wavelengths of UVR that are reaching the surface, and therefore, the amount of UVR that the microorganisms will receive. This depends on the atmospheric opacity, that's why we consider the atmospheric features in the radiative transfer modelling, in the first step of our approach.

Johnstone: Can you extend the experiment to see if the survivors repopulate and are then more resistant to the radiation?

Abrevaya: Yes, this will be part of our future experiments.

Benz: Superflares are very rare. Ten times smaller flares are about 100 times more frequent and a hundred times smaller flares are 10^4 times more frequent. How will this change your results?

Abrevaya: We will consider that in our experiments, this is another very important factor to be analyzed. We need to do more experiments to answer this question.

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