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Article

On the Habitability of Aquaplanets

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Abstract: An Aquatic Habitability Index is proposed, based on Quantitative Habitability Theory, and considering a very general model for life. It is a primary habitability index, measuring habitability for phytoplankton in the first place. The index is applied to some case studies, such as the habitability changes in Earth due to environmental perturbations caused by asteroid impacts.

Keywords: life emergence; habitability; primary production; photosynthesis; phytoplankton

1. Introduction

The existence of rocky planetary bodies in the Solar System, and the frequent discovery of exoplanets in the last two decades, has motivated the development of generic quantitative habitability criteria. This has led to some interaction, yet insufficient, between the communities of astrobiologists, planetary scientists and environmentalists. Of special interest is the emergent and interdisciplinary area of Quantitative Habitability Theory (QHT), which traces a bridge between Ecology and Astrobiology [1].

The goal of QHT is to explain the distribution, abundance, and productivity of life. It integrates Habitat Suitability Models, the Metabolic Theory of Ecology, Population Dynamics, Macroecology, Biogeography, and Ecophysiology; and can be applied to any life, from prokaryotes to eukaryotes [1]. A very important feature of QHT is that it is scalable in space and time; therefore, it can be applied

both on Earth's ecosystems and exoplanets. Its main postulate states that, in principle, a habitability index can be written as a product of functions of environmental variables which influence life:

$$HI = \prod_{i=1}^{n} f_i(x_i) \quad (1)$$

A crucial fact about habitability indexes is that through them an estimation of net primary productivity *NPP* can be done:

$$NPP \approx HI.NPP_{\max} \quad (2)$$

where NPP_{max} is the maximum net primary productivity that the environment can sustain indefinitely (some sort of carrying capacity). It means the maximum speed at which living matter is formed (per unit area). This parameter could in principle be theoretically estimated considering how much light is captured by the environment and then examining how efficient the process of photosynthesis is. However, the ecological interactions between individuals complicate this. An alternative is to consider time series of *NPP* measurements for a given environment (ecosystem), and from them determining NPP_{max} [2]. On current Earth; estuaries, swamps, marshes and tropical rain forests have the highest NPP_{max}, while extreme deserts have the smallest. Almost all life on Earth is directly or indirectly reliant on primary productivity. The organisms responsible for it are known as primary producers or autotrophs, and form the base of the food assemblage. Therefore, the estimation of *NPP* is of utmost importance to estimate the habitability of an environment. Usually habitability indexes take values between 0 (dead environment) and 1 (optimum for life).

An example of a terrestrial habitability index is the standard primary habitability SPH (or Arecibo model) [1,2]:

$$SPH = f(T)f(RH) \quad (3)$$

where *T* is the temperature and *RH* is the relative air humidity. Despite its apparent simplicity (as it considers only two environmental variables, *T* and *RH*), this model was validated with ground NPP measurements [2]. Based on the values of *SPH*, a Planetary Habitability Classification has been developed [2]. It is shown in Table 1 below:

Table 1. Planetary Habitability Classification based on Standard Primary Habitability Index.

SPH	Vegetation Type	Kind of Planet
>0.8–1.0	Dense vegetation	Amazonian
>0.6–0.8	Mixed vegetation	Serengetian
>0.4–0.6	Shrublands	Mediterranean
>0.2–0.4	Grasslands	Pampian
>0.0–0.2	Sparsely vegetated	Saharan
= 0.0	None	Dead

Standard Primary Habitability is a climatological habitability index, applicable to terrestrial ecosystems or to whole planets with a surface predominantly covered by a lithosphere. In this paper we present a habitability index applicable to aquaplanets, that is, planets whose surface is predominantly covered by oceans.

2. Materials and Methods

It is challenging to formulate a habitability index without being influenced by life "as we know it".

We consider necessary three generic aspects for life emergence and evolution, whenever the region of the Universe we are looking at:

(a) *Mineral/Rock aspect*: Chemical elements are needed to form stable structures (biogenic elements; for instance, on Earth all studied species contain C, H, O, N, P and S). Other elements (or its compounds) can be harmful for life; representing mineral toxicity (for instance, increased salinity near coastal areas). This is to be represented as f_M in a habitability index.

(b) *Mixing (or solvent) aspect*: Biogenic chemical elements need the (intermediate) mobility of a liquid medium to combine and form complex biomolecules. This liquid is called the solvent (on Earth it is water, but it could be hydrocarbons in colder worlds). This is to be represented as f_S in a habitability index.

(c) *Energetic aspect*: In the above mentioned (liquid) medium, an energy source is needed to overcome potential barriers between reactants (biogenic elements) and products (biomolecules). On Earth, for primary producers, the most common energy source is photosynthetically active radiation (PAR) coming mostly from the Sun. In hydrothermal vents some bacteria use geothermal PAR from hot water, or chemical energy from simple redox reactions. Both energetic aspects would reflect, in broad terms, the external and internal geodynamic activity of the planet or moon. This is to be represented as f_E in a habitability index.

Thus, we can rewrite (1) as:

$$HI = f_M f_S f_E \quad (4)$$

2.1. An Aquatic Primary Habitability Index

As stated in [3], radiation (light) is the most important natural factor limiting primary production on current Earth. For all ecosystems, this is especially true at night. In aquatic ecosystems other factors can also be limiting: nutrients, carbon dioxide, temperature [4]. The one that shows the most extreme variation within the aquatic medium is light: the irradiance decreases with depth from intensities that are so high as to be damaging down to levels that cannot support photosynthesis. Furthermore, to a much greater extent than the other limiting factors, light availability varies with time: both within the day (from night darkness to the full noon Sun), and with the seasons during the course of the year [4]. This implies that in temperate and higher latitudes primary production shows a strong seasonal cycle with a peak, the spring bloom, lower levels during summer, a slight increase in fall and a minimum during winter [5]. This cycle is closely related to the light availability and the existence of a thermocline, which implies a relatively shallow upper mixed layer. During winter the thermocline is missing and the upper mixed layer can be rather deep due to wind mixing and convective cooling. Due to deep mixing, high nutrient concentrations are found in the surface water but the abundance of algae during winter time is very low. This implies that phytoplankton growth is limited by light [5]. Two factors are responsible for light limitation in winter: (a) a short day length and (b) deep mixing due to strong winds, convection and low or no heating of surface water. Owing to the deep mixing the

plankton cells are moved vertically up and down and experience only a very small amount of daylight (when they are near the sea surface for a short time) [5].

Another example in which light can limit primary production are exoplanets orbiting red dwarfs. A typical red dwarf star emits a low intensity of light, and thus the habitable zone is very close to it. This should imply tidal lock in most cases: the rotation of an orbiting planet is synchronous with its orbital motion, in such a way that one hemisphere of the planet is always illuminated, while the other one is always dark. It is believed that life in these planets is more suitable in the frontiers of the illuminated and dark hemispheres (the terminator or twilight zone). In this area, the star is always close to the horizon, providing very low intensities of light. Due to the temperature gradient, fierce winds blowing from the illuminated hemisphere to the dark one should imply a very active surface circulation, originating very deep mixed layers. This is an environmental situation similar (but more extreme) to the above mentioned, and therefore we consider a well educated guess to assume that light will limit primary production. Being red dwarfs the most common type of star in the Universe (around three quarters of the stars in our galaxy); our aquatic habitability index could be useful to estimate primary aquatic habitability in many planets.

Therefore, in this first version of our index, we will consider contexts in which production is limited by light availability, that is, by the energetic aspect of life. Thus, our Aquatic Primary Habitability Index (APH) can be written:

$$APH = f_E = f(L)f(T) \tag{5}$$

where *f(L)* and *f(T)* are functions of light *L* and temperature *T*, respectively. The reason to include *f(L)* is obvious (photosynthesis), while the inclusion of *f(T)* comes from the fact that the speed of biochemical reactions strongly depends on temperature. We point out that writing the habitability index as in Equation (5) does not imply that mineral nutrients are infinitely available. It just means that light will limit primary production, preventing phytoplankton to reach abundance levels capable of exhausting mineral nutrients. A function of carbon dioxide concentration *f(CO_2)*, could also be considered, but on current Earth CO_2 is typically sufficient for photosynthesis in the aquatic ecosystems. This certainly might not be the case after the depletion of CO_2 in the planet due to the silicate-carbonate cycle: CO_2 substitutes silicates in the rocks to form carbonates, which dissolve with rain and end up in the ocean floor. Then, in the subduction sites the ocean floor submerges into the crust. A part of this CO_2 comes back to the atmosphere with the volcanic eruptions, but usually less than the previously captured, slowly depleting current atmosphere from CO_2 and making it inhabitable for photosynthetic organisms in around 800 million years.

2.1.1. The Function *f(L)*

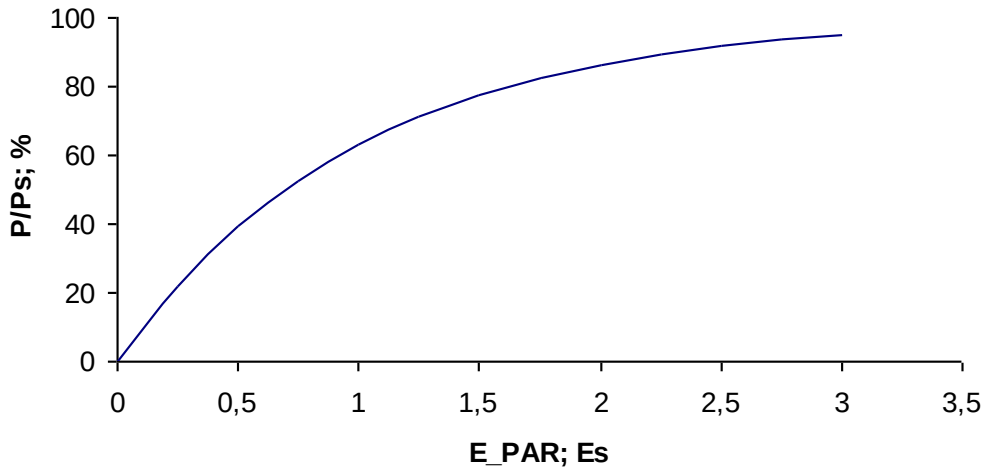
We consider the so called *E* model for photosynthesis [6], initially developed for Antarctic phytoplankton:

$$\frac{P(z)}{P_S} = \frac{1 - \exp\left(-E_{PAR}(z)/E_S\right)}{1 + E^*_{UV}(z)} \tag{6}$$

P(z) and P_S are the photosynthesis rates at depth *z* and the maximum possible, respectively. $E_{PAR}(z)$ is the photosynthetically active radiation at depth *z*; while $E^*_{UV}(z)$ is the ultraviolet radiation

(UV) at *z*, convolved with a biological action spectrum $\varepsilon(\lambda)$ which weighs UV wavelengths according to its potential to inhibit photosynthesis. This model reproduces correctly the photosynthesis-irradiance curves of plenty of known aquatic species. The parameter E_S is the irradiance which yields 63% of the maximum possible photosynthesis rate (provided UV radiation is negligible). It is a measure of the efficiency of the species in the use of the photosynthetically active radiation: the smaller E_S, the more efficient the species. A plot of Equation (6), considering negligible UV, can be seen in Figure 1 (the inclusion of UV only slows down the increase of the photosynthesis rate with E_{PAR}, but the form of the curve keeps being the same).

Figure 1. Photosynthesis—irradiance curve predicted by Equation (6).



The normalized photosynthesis rate $P(z)/P_S$ depends on depth *z*. Its maximum value (unity, 1) will only be achieved at a given depth, having smaller values above and below it. Therefore, when working with all the photic zone, the average $< P(z)/P_S >$ will take values from 0 up to some value smaller than 1. Thus, in order to set the range of $f(L)$ between 0 and 1, we normalize $< P(z)/P_S >$ dividing it by the maximum (optimum) possible average $< P(z)/P_S >_{opt}$. As shown by some of us [7], these optimum conditions for photosynthesis are achieved in optical ocean water types I (in the context of Jerlov's optical classification of ocean waters [8]). Thus, our function for light stands as:

$$f(L) = \left\langle \frac{P(z)}{P_S} \right\rangle \Big/ \left\langle \frac{P(z)}{P_S} \right\rangle_{opt} \tag{7}$$

2.1.2. The Function *f(T)*

We take:

$$f(T) = 1 - \left[\frac{T_{opt} - T}{T_{opt} - 273} \right]^2 \tag{8}$$

Above Equation is symmetrical around T_{opt} (which is the optimum temperature for the life of most aquatic primary producers on current Earth).

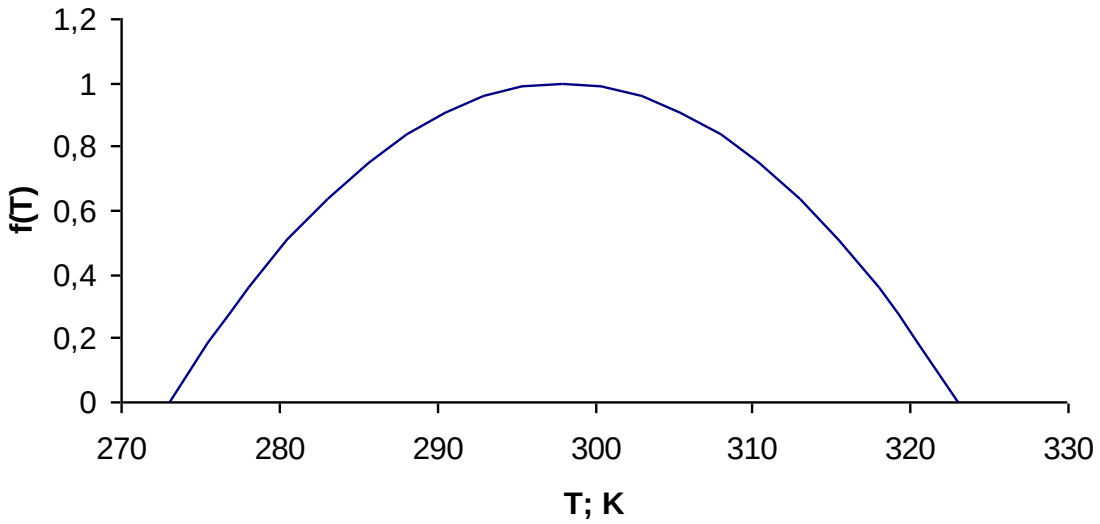
3. Results and Discussion

3.1. Calibration of the Aquatic Primary Habitability Index

Equations (5)–(8) tell us that our index has two parameters: T_{opt} and E_S.

We consider $T_{opt} = 298\ K$, which implies that *f(T)* is valid in the temperature range (273–323) K, as values of temperature out of this range would give values for *f(T)* out of the desired range 0–1 (a plot of *f(T)* can be seen in Figure 2). One might wonder whether above selection implies being too centered on current Earth conditions. However, if temperature is low, biochemical reactions are slow; and if it is high, biomolecules break apart. Indeed, above range of temperatures and the optimum taken are quite close to those selected in [2].

Figure 2. The function of temperature *f(T)*, when optimum temperature for aquatic life is 298 K.



It remains to determine the current value for E_S. For this we make the assumption that current terrestrial productivity on Earth approximately equals the aquatic one. Terrestrial productivity can be characterized by the Standard Primary Habitability Index, SPH [2]. The above mentioned hypothesis can then be written:

$$APH_0 \approx SPH_0 \approx 0{,}39 \tag{9}$$

Taking $T_{opt} = 298\ K$, and current average surface planetary temperature $T = 288\ K$, we have:

$$f_0(T) = 0{,}84 \tag{10}$$

Considering Equation (5):

$$f_0(L) = APH_0 / f_0(T) = 0{,}46 \tag{11}$$

For current Earth Equation (7) reads:

$$f_0(L) = \left\langle \frac{P(z)}{P_S} \right\rangle_0 \Big/ \left\langle \frac{P(z)}{P_S} \right\rangle_{opt,0} \tag{12}$$

Average optimum normalized photosynthesis rates are calculated splitting the photic zone of ocean optical water type I (from 0 to 200 meters depth) into 20 layers with thickness of 10 m each:

$$\left\langle \frac{P(z)}{P_S} \right\rangle_{opt,0} = \frac{\sum_{i=1}^{20} \left(\frac{P(z)}{P_S} \right)_i}{20} \tag{13}$$

In the *i-th* layer $P(z)/P_S$ was calculated in the mid depth *z* and using Equation (6). To do this, the irradiances of photosynthetically active radiation at depth *z* were calculated through:

$$E_{PAR}(z) = \sum_{\lambda=400nm}^{700nm} E(\lambda, z)\Delta\lambda \tag{14}$$

where $\Delta\lambda$ = 1 nm is the wavelength interval splitting the PAR band. Spectral irradiances $E(\lambda,z)$ at depth z were calculated using the well known Lambert Beer's law of Optics:

$$E(\lambda, z) = E(\lambda, 0^-)\exp[-K_d(\lambda).z] \tag{15}$$

where $K_d(\lambda)$ are the attenuation coefficients for downwelling spectral irradiance in ocean optical water type I. $E(\lambda,0^-)$ are spectral irradiances just below the ocean surface, calculated subtracting reflected incident light from incident spectral irradiance $E(\lambda,0^+)$ at ocean surface:

$$E(\lambda,0^-) = E(\lambda,0^+)[1-R] \tag{16}$$

R is the reflection coefficient of light, averaged for solar zenithal angles in the range 0°–90°, and calculated from Fresnel formulae applied to the interface air-water.

Ultraviolet spectral irradiances at depth *z* were convolved with a biological weighting function $\varepsilon(\lambda)$, giving more weight to wavelengths with a greater inhibition action on photosynthesis:

$$E^*_{UV}(z) = \sum_{\lambda=280nm}^{399nm} \varepsilon(\lambda)E(\lambda, z)\Delta\lambda \tag{17}$$

The other steps were analogous to the case of PAR irradiances. The result was:

$$\left\langle \frac{P(z)}{P_S} \right\rangle_{opt,0} = 0.71 \tag{18}$$

Using Equations (11), (12) and (18) we get:

$$f_0(L)\left\langle \frac{P(z)}{P_S} \right\rangle_{opt,0} = \left\langle \frac{P(z)}{P_S} \right\rangle_0 = 0{,}33 \tag{19}$$

which implies $E_S = 20\ W/m^2$. Now we are ready to calculate values of the Aquatic Habitability Index in several cases.

3.2. Case Studies

3.2.1. Earth after a Galactic Gamma Ray Burst (from Core-Collapse Supernova)

Several of us have studied the potential effects of a galactic gamma ray burst on planetary atmospheres and biospheres [9–13]. The main effects we consider here are 20% ozone depletion (leading to increased UV at planetary surface) and global cooling. Both effects are due to the formation of nitric oxides in the atmosphere (they catalyze ozone destruction and block sunlight, cooling planetary surface [10,14]). To calculate *f(L)*, average planetary spectral irradiances were calculated using the (free) radiative transport code NCAR/ACD TUV: Tropospheric Ultraviolet & Visible Radiation Model [15]. Radiative transfer in the ocean was treated as explained in above sections. On another note, it is easy to calculate *f(T)* just substituting in Equation (8).

For a "moderate" scenario of diminution of temperature in 5 K, APH diminishes from 0.39 to 0.19. For an extreme scenario in 10 K, APH goes down to 0.10. In both cases there is a considerable reduction of aquatic habitability.

3.2.2. Earth Ocean after Chicxulub Asteroid Impact

Chicxulub asteroid impact claimed the life of around half of existing genera some 66 million years ago, including dinosaurs and pterosaurs. The initial scenario was a "cold and darkness one", due to the blocking of sunlight for a least half a year. So, in the immediate aftermath, photosynthesis totally collapsed due to absence of PAR, giving $f(L) = 0$ and therefore $APH = 0$, that is, no aquatic primary habitability.

In the following years, evolution of the atmosphere led to slow increase in aquatic primary habitability. Phytoplankton cells in dormant state started again to produce as the atmosphere cleared and PAR slowly returned [16]. It is beyond the scope of this paper a detailed modeling of the evolution of the atmosphere and the aquatic habitability after this impact. Currently, this is work in progress in our group [17].

3.2.3. Current Climate Change

Current changes in Earth's climate system affect both *f(L)* and *f(T)*. The first one changes due to increased UV (effective) penetration in marine water (due to shallower mixed layers), polar ice melting and variations in global biogeochemical cycles [18]. This was included in the light function as decreased UV attenuation coefficients in ocean waters. The function for temperature obviously changes due to the current warming of the planet.

A moderate scenario with an increase of temperature in 2.5 K in this century and a 5% decrease of effective UV attenuation coefficients in water gives $APH = 0.39$; which means no change in aquatic primary habitability. An extreme scenario with an increase of temperature in 5 K and a 10% decrease of effective UV attenuation coefficients in water gives $APH = 0.38$; which means a slight reduction in aquatic primary habitability.

Therefore, climate change seems to affect little the aquatic primary producers, basically because the reduction of *f(L)* due to increased UV is compensated by the increase in *f(T)* due to global warming. For the sake of comparison we refer the interested reader to check results in [2], in which an increase of terrestrial planetary habitability is reported since the beginning of past century. This does not mean that for humans current climate change is good. Both indexes (the terrestrial SPH outlined in [2] and our aquatic APH) measure primary production, which is related to human well being in an extremely complicated way.

4. Conclusions

We have presented an aquatic primary habitability index being developed in our Planetary Science Laboratory, with the collaboration of other researchers. It can be applied to aquatic ecosystems in which primary production is limited by light, and not by nutrients or other factors. Thus, it is not a closed index, and refinements could be done in the near future, to include the effect of nutrient scarcity. Therefore, the discussion made in the case studies should not be seen as absolute, they are correct provided light (PAR and UV) is indeed the "dominant" environmental variable. We consider this will especially be applicable in aquaplanets orbiting red dwarfs, but also in a plethora of aquatic settings in other planets.

Author Contributions

Noel Perez and Osmel Martin did the calculations for radiative transfer in the atmosphere. Rolando Cardenas devised the habitability index, did all remaining calculations, and the general conception of the paper. Jesus Martinez-Frias contributed with useful comments and suggestions.

Conflict of Interest

The authors declare no conflict of interest.

References

1. Quantitative Habitability Theory. Available online: http://phl.upr.edu/projects/planetary-habitability (accessed on 8 May 2014).
2. Méndez, A. Evolution of the Global Terrestrial Habitability during the Last Century. In Proceeedings of Sixth Astrobiology Science Conference, Houston, TX, USA, 26–29 April 2010.
3. Hadjibiros, K. *Ecology and Applied Environmental Science*; CRC Press, Taylor and Francis Group: Boca Raton, Florida, USA, 2013; pp. 49–51.
4. Kirk, J. *Light and Photosynthesis in Aquatic Ecosystems*, 3rd ed.; Cambridge University Press: New York, NY, USA, 2011; p. 453.
5. Fennel, W.; Neumann, T. *Introduction to the Modelling Marine Ecosystems*; Elsevier B.V.: Amsterdam, The Netherlands, 2004; p. 133.
6. Fritz, J.; Neale, P.; Davis, R.; Pelloquin, J. Response of Antarctic phytoplankton to solar UVR exposure: Inhibition and recovery of photosynthesis in coastal and pelagic assemblages. *Mar. Ecol. Prog. Ser.* **2008**, *365*, 1–16.

7. Rodriguez, L.; Cardenas, R.; Avila-Alonso, D. On the photosynthetic potential in open oceans. *Rev. Cub. Fis.* **2014**, *31*, 15–17.
8. Jerlov, N. *Marine Optics*, 2nd ed.; Elsevier Scientific Publishing Company: Amsterdam, The Netherlands, 1976; pp. 127–137.
9. Martin, O.; Galante, D.; Cardenas, R.; Horvath, J. Short-term effects of gamma ray bursts on Earth. *Astrophys. Space. Sci.* **2009**, *321*, 161–167.
10. Martin, O.; Cardenas, R.; Guimarais, M.; Peñate, L.; Horvath, J.; Galante, D. Effects of gamma ray bursts in Earth's biosphere. *Astrophys. Space Sci.* **2010**, *326*, 61–67.
11. Martin, O.; Cardenas, R.; Horvath, J.; Peñate, L. Effects of galactic gamma rays bursts on planetary atmospheres. *Int. J. Mod. Phys. E-Nucl. Phys.* **2011**, *20*, 67–70.
12. Peñate, L.; Martin, O.; Cardenas, R.; Agusti, S. Short-term effects of gamma ray bursts on oceanic photosynthesis. *Astrophys. Space Sci.* **2010**, *330*, 211–217.
13. Cardenas, R.; Martin, O.; Peñate, L.; Horvath, J. Effects of galactic gamma rays bursts on planetary biospheres. *Int. J. Mod. Phys. E-Nucl. Phys.* **2011**, *20*, 132–135.
14. Thomas, B.; Melott, A.; Jackman, C.; Laird, C.; Medvedev, M.; Stolarski, R.; Gehrels, N.; Cannizzo, J.; Hogan, D.; Ejzak, L. Gamma-ray bursts and the Earth: Exploration of atmospheric, biological, climatic and biogeochemical effects. *Astrophys. J.* **2005**, *634*, 509–533.
15. Tropospheric Ultraviolet and Visible Radiation Model. Available online: http://cprm.acd.ucar.edu/Models/TUV/ (accessed on 21 August 2014).
16. Ribeiro, S.; Berge, T.; Lundholm, N.; Andersen, T.; Abrantes, F.; Ellegaard, M. Phytoplankton growth after a century of dormancy illuminates past resilience to catastrophic darkness. *Nat. Commun.* **2011**, *2*, 1–7.
17. Perez, N.; Martin, O.; Cardenas, R. Photobiological damage associated to the Chicxulub asteroid impact. *Rev. Cub. Fis.* **2014**, submitted.
18. Hader, D.; Kumar, H.; Smith, R.; Worrest, R. Effects of solar UV radiation on aquatic ecosystems and interactions with climate change. *Photochem. Photobiol. Sci.* **2007**, *6*, 267–285.