ON THE POSSIBILITIES OF EXISTENCE OF PHOTOSYNTHETIC LIFE AROUND ALPHA CENTAURI B

SOBRE LAS POSIBILIDADES DE EXISTENCIA DE VIDA FOTOSINTÉTICA ALREDEDOR DE ALFA DEL CENTAURO B

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We start with a brief description of the Alpha Centauri system and its main characteristics. Afterwards, we carry out calculations of several habitability metrics, such as the Π biological productivity and photosynthesis rates, in the oceans of the hypothetical exoplanets orbiting around Alpha Centauri B. By including a function of the temperature in a photosynthetic model, we describe the behavior of the metrics mentioned above for organisms with prokaryotic and eukaryotic cells that could potentially live in these exoplanets.

Comenzamos con una breve descripción del sistema Alpha del Centauri y sus características fundamentales. Luego, realizamos cálculos sobre varias métricas de habitabilidad, como la productividad biológica Π y las tasas fotosintéticas, en los océanos de los exoplanetas hipotéticos que orbitan alrededor de Alpha del Centauri B. Mediante la inclusión de una función de la temperatura en un modelo fotosintético, describimos el comportamiento de las métricas arriba mencionadas para organismos con células procariotas y eucariotas que pudieran potencialmente vivir en esos exoplanetas.

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I. INTRODUCTION

The system Alpha Centauri comprises three stars. Alpha Centauri A is a yellow star, very similar to the Sun (spectral type G), and Alpha Centauri B is an orange type K star. Both spin around themselves in an orbit of approximately 80 years. Since they have similar masses, they move around one space point approximately equidistant between them, the center of mass. The third star is Proxima Centauri, which rotates around the two previous at a much bigger distance. There is a debate about the eccentricity of Proxima Centauri and if this star is actually related to the system. However, the three stars have similar parallax and proper movement. In the event that Proxima is related to the other two, its orbit would last for several hundreds of thousands of years. It is a small and red star that only can be seen through powerful telescopes.

Both Alpha Centauri A and Alpha Centauri B have high metallicity, so both should have circumstellar disks with a relatively high fraction of solid material, which would favor the formation of terrestrial planets. As Alpha Centauri B has less luminosity than Alpha Centauri A, the former has the zone of habitability closer to the star. For this reason, a planet located there would be less exposed to the gravitational negative disturbances that could come from the nearby binary star. In table 1 general properties of the Alpha Centauri system as compared with the Sun are shown.

Tabla 1. General properties of the stars that conform the triple system Alpha Centauri compared with the Sun

Parameter	Alpha Centauri A	Alpha Centauri B	Proxima Centauri	Sun	Unit of measurement
Age	4850	4850	4850	4650	Million years
Mass	1100	0.907	0.123	1	Solar masses
Radius	1227	0.865	0.145	1	Solar radiuses
Temperature	5790	5316	3040	5780	K
Luminosity	1519	0.44	0.000138	1	Solar luminosity
Hydrogen	71.5	69.4	69.5	73.7	%
Helium	25.8	27.7	27.8	24.5	%
Heavier elements	2.74	2.89	2.90	1.81	%

II. MATERIALS AND METHODS

We refer the reader to reference [1], where the process of formation of planetary systems around a star is simulated using the package of integration MERCURY. This package is designed to study the growth of planets around binary stars. Among the planets obtained, eleven were formed inside the habitability zone. In this section we present three habitability metrics used to quantify habitability in them: Earth Similarity Index (ESI), E model of photosynthesis, and Π model of biological productivity.

II.1. Earth Similarity Index

The Earth Similarity Index (ESI), introduced in [2], is given by:

$$ESI = \prod_{i=1}^{n}\left(1 - \left|\frac{x_i - x_{i0}}{x_i + x_{i0}}\right|\right)^{\frac{w_i}{n}}, \tag{1}$$

where:

- x_i is one property of the planet, for example the temperature at planet surface,
- x_{i0} is the value of that same property in current Earth,
- w_i is a weight exponent and
- n is the total number of properties that are used in calculation.

The properties of above mentioned eleven planets are shown in table 2.

II.2. E Model of Photosynthesis

The main characteristics of this model are presented in [3]. The rate P of the photosynthetic process in this model can be calculated as:

$$P = P_{Pot}\left(\frac{1}{E^*_{UV}}\right). \tag{2}$$

Here E^*_{UV} is the inhibitory dimensionless irradiance, while P_{pot} is the speed of the process in the absence of photo-inhibition, which is given in the following way:

$$P_{Pot} = P_s\left(1 - e^{-\left(\frac{E_{PAR}}{E_s}\right)}\right). \tag{3}$$

In the previous expression P_s is the maximum rate of photosynthesis in the absence of inhibition, E_{PAR} (W/m^2) is the irradiance of the photosynthetically active radiation (PAR), while E_s (W/m^2) is a parameter measuring the efficiency of photosynthesis, the smaller its value, the more efficiently the species uses PAR.

The inhibitory dimensionless irradiance of the ultraviolet light is be given by:

$$E^*_{UV} = \sum_{\lambda_i = 176\text{ nm}}^{\lambda_i = 340\text{ nm}} \varepsilon(\lambda_i)E(\lambda_i)\Delta\lambda, \tag{4}$$

where $\varepsilon(\lambda_i)$ (m^2/W) are the biological action spectra that quantify the effectiveness of the spectral exposition $E(\lambda_i)$ (W/(m^2·nm)). This means that $\varepsilon(\lambda_i)$ represents the inhibition of the photosynthesis caused by the ultraviolet light of wavelength λ_i.

Substituting 3 in 2 and normalizing by P_s we obtain:

$$\frac{P}{P_s} = \frac{1 - e^{-\left(\frac{E_{PAR}}{E_s}\right)}}{1 + E^*_{UV}} \tag{5}$$

This is a common form of expressing this model.

II.3. Π Model of Biological Productivity

The Π model of biological productivity reads as follows [4]:

$$\frac{\Pi}{\Pi_{max}} = \left(1 - \left(\frac{T_{opt} - T}{T_{opt} - 273}\right)^2\right)\left(\frac{P_{atm} - P_{min}}{P_{1/2} + (P_{atm} - P_{min})}\right). \tag{6}$$

In this equation T is temperature at planetary surface, P_{atm} is the atmospheric partial pressure of CO_2, P_{min} is the minimum partial pressure of CO_2 needed to sustain photosynthesis, and $P_{1/2}$ is the partial pressure giving $\Pi/\Pi_{max} = 1/2$. The function of temperature is an inverted parabola symmetric to the optimum temperature for life (taken equal to 25°C in this study).

As this study is based on an atmosphere with a similar composition to the one of the Earth, it was assumed that the dependence with the partial pressure of CO_2 in the atmosphere of the exoplanets would be similar to the one of the Earth. Then this model would depend only on temperature.

In table 3 we show results of previous application of the three habitability metrics presented in this section [5].

III. RESULTS AND DISCUSSION

When analyzing the results of the previous table it is observed that the tendency of the values of the rates of photosynthesis does not match the tendencies of the remaining metrics. This is because the E model of photosynthesis does not take into account the temperature, which is a very important magnitude for determining if an environment is capable to hold life.

Therefore, we propose a modification to the photosynthesis model by introducing a function of temperature:

$$\frac{P}{P_s} = \left(\frac{1 - e^{-\left(\frac{E_{PAR}}{E_s}\right)}}{1 + E^{*}_{UV}} \right) \left(1 - \left(\frac{T_{opt} - T}{T_{opt} - 273} \right)^2 \right) \tag{7}$$

The new results are shown in table 4, and are more coherent since the exoplanets that have an Earth Similarity Index between 0.9 and 1.0 are also the ones with higher biological productivity (Π model) and higher rates of photosynthesis.

By including this temperature function we see a major improvement in the behavior of the indexes for different kinds of organisms that, at the same time, have different optimum temperatures for their development. For example, the most beneficial mean temperature to attain a higher rate of biological productivity for thermophilic prokaryotic organisms can be taken as 51°, for eukaryotic organisms would be equal to 25°, and in multicellular organisms would be equal to 15°.

Tabla 2. Properties of the planets selected in the paper

Planet	Superficial Temperature (K)	Density (kg/m^3)	Radius (m)	Velocity of Escape	ESI
a1	291.75	6326.14	7737661.45	14546.43	0.924
a5	290.85	6182.42	7489052.58	13918.21	0.936
a6	271.46	6689.11	8376072.70	16192.04	0.875
a8	267.88	5995.90	7170038.50	13122.79	0.911
b2	336.46	5813.04	6861304.53	12364.76	0.864
b3	349.08	5150	3005075.99	5098.55	0.750
b4	285.27	6389.72	7848401.97	14828.57	0.926
b7	310.85	5150	5429452.60	9211.85	0.918
b8	364.98	5150	2385130.39	4046.72	0.688
c1	373.79	5150	4636756.26	7866.93	0.776
c3	282.77	6534.01	8101441.98	15478.52	0.911

Tabla 3. Habitability Metrics for Exoplanets around Alpha Centauri B

Planet	ESI	Superficial Temperature (K)	Π/Π_{max}	$\langle P/P_s \rangle$ Ocean water I	$\langle P/P_s \rangle$ Ocean water II	$\langle P/P_s \rangle$ Ocean water III
a1	0.924	291.75	0.56	0.72	0.52	0.37
a5	0.936	290.85	0.55	0.72	0.52	0.36
a6	0.875	271.46	0	0.69	0.48	0.35
a8	0.911	267.88	0	0.68	0.48	0.34
b2	0.864	336.46	0	0.78	0.57	0.40
b3	0.750	349.08	0	0.79	0.59	0.41
b4	0.926	285.27	0.44	0.71	0.51	0.36
b7	0.918	310.85	0.44	0.75	0.54	0.38
b8	0.688	364.98	0	0.79	0.60	0.42
c1	0.776	373.79	0	0.80	0.61	0.43
c3	0.911	282.77	0.37	0.71	0.50	0.36

Tables 5-7 collect results considering above mentioned temperatures.

Tabla 4. Habitability Metrics for Exoplanets around Alpha Centauri B considering the influence of temperature in photosynthesis

Planet	ESI	Superficial Temperature (K)	Π/Π_{max}	$\langle P/P_s \rangle$ Ocean water I	$\langle P/P_s \rangle$ Ocean water II	$\langle P/P_s \rangle$ Ocean water III
a1	0.924	291.75	0.56	0.69	0.49	0.35
a5	0.936	290.85	0.55	0.66	0.47	0.33
a6	0.875	271.46	0	0	0	0
a8	0.911	267.88	0	0	0	0
b2	0.864	336.46	0	0	0	0
b3	0.750	349.08	0	0	0	0
b4	0.926	285.27	0.44	0.52	0.37	0.26
b7	0.918	310.85	0.44	0.56	0.40	0.28
b8	0.688	364.98	0	0	0	0
c1	0.776	373.79	0	0	0	0
c3	0.911	282.77	0.37	0.44	0.31	0.22

Tabla 5. Habitability Metrics for Thermophilic Prokaryotic Organisms ($T_{opt} = 51°$C)

Planet	ESI	Superficial Temperature (K)	Π/Π_{max}	$\langle P/P_s \rangle$ Ocean water I	$\langle P/P_s \rangle$ Ocean water II	$\langle P/P_s \rangle$ Ocean water III
a1	0.924	291.75	0.36	0.44	0.31	0.22
a5	0.936	290.85	0.34	0.41	0.30	0.21
a6	0.875	271.46	0	0	0	0
a8	0.911	267.88	0	0	0	0
b2	0.864	336.46	0.57	0.73	0.54	0.38
b3	0.750	349.08	0.46	0.60	0.45	0.31
b4	0.926	285.27	0.25	0.30	0.21	0.15
b7	0.918	310.85	0.56	0.70	0.51	0.36
b8	0.688	364.98	0.22	0.29	0.22	0.15
c1	0.776	373.79	0.03	0.04	0.03	0.22
c3	0.911	282.77	0.20	0.24	0.17	0.12

Tabla 6. Habitability Metrics for Eukaryotic Organisms ($T_{opt} = 25°$C)

Planet	ESI	Superficial Temperature (K)	Π/Π_{max}	$\langle P/P_s \rangle$ Ocean water I	$\langle P/P_s \rangle$ Ocean water II	$\langle P/P_s \rangle$ Ocean water III
a1	0.924	291.75	0.56	0.69	0.49	0.35
a5	0.936	290.85	0.55	0.66	0.47	0.33
a6	0.875	271.46	0	0	0	0
a8	0.911	267.89	0	0	0	0
b2	0.864	336.46	0.57	0.73	0.54	0.38
b3	0.750	349.08	0	0	0	0
b4	0.926	285.27	0.44	0.52	0.37	0.26
b7	0.918	310.85	0.44	0.56	0.40	0.28
b8	0.688	364.98	0	0	0	0
c1	0.776	373.79	0	0	0	0
c3	0.911	282.77	0.37	0.44	0.31	0.22

From the tables above it is clear that the potential for the existence of the prokaryotic life is much bigger than for the eukaryotic or the multicellular one, that is, the number of suitable planets to develop this type of life is much bigger compared to the other two. Also, one observes that in table 5 and in table 7 the biological productivity (Π model) and the rates of photosynthesis do not coincide with the ESI. This happens because the optimal mean temperature for the realization of the photosynthesis in these cases was assumed to be 51° and 15° respectively, which differ with the one of the Earth, which is around 25°.

IV. CONCLUSIONS

In order to describe the habitability in exoplanets of terrestrial type successfully, they should satisfy several parameters at the same time. For the results to have more precision and the model to recreate a habitable planet of terrestrial type, the model should take into account the temperature.

The results demonstrate that the less complex is the form of life, the greater are the possibilities that any of these exoplanets have it.

Tabla 7. Habitability Metrics for Multicellular Organisms ($T_{opt} = 15°$C)

Planet	ESI	Superficial Temperature (K)	Π/Π_{max}	$\langle P/P_s \rangle$ Ocean water I	$\langle P/P_s \rangle$ Ocean water II	$\langle P/P_s \rangle$ Ocean water III
a1	0.924	291.75	0.57	0.69	0.49	0.35
a5	0.936	290.85	0.58	0.70	0.50	0.35
a6	0.875	271.46	0	0	0	0
a8	0.911	267.89	0	0	0	0
b2	0.864	336.46	0	0	0	0
b3	0.750	349.08	0	0	0	0
b4	0.926	285.27	0.58	0.69	0.49	0.35
b7	0.918	310.85	0	0	0	0
b8	0.688	364.98	0	0	0	0
c1	0.776	373.79	0	0	0	0
c3	0.911	282.77	0.52	0.62	0.44	0.31

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