Investigating the parameters needed to determine the habitable zones of exoplanets

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0 Abstract:

In the last two decades the assumption that exoplanets exists comes to certainty. At the writing of that lines about 1200 system with known exoplanets exists, about 500 of that star systems have more than one exoplanet. Further 2000 exoplanet candidates exist. The above numbers of exoplanets comes only from a small sample of a milkyway survey, that an estimate says that in average, every star of the milkyway have one to two planets. Every answered question generates two other unsolved questions. One of that question is, is it possible that a far planet around a star of the milkyway is in the habitable zone of this star? But what means habitable zone? This literature based project will analyse these questions. In case of the relatively broad issue, the project will make an overview about the earth similarity index (ESI), the planetary habitable index (PHI), it will further discuss the habitable zone widths around sun like stars with the spectral class F, G, K and M. Further the literature based project looks at the lifetime of exoplanets around main sequence stars. The whole indices which exist, have a very anthropocentric/earth centric view, so that the project will give finally some suggestions to improve the habitable zones around stars and make a more accurate description of the habitable zones. The above indices do not respect extremophile organism, the lifecycle of a star and exotic life-forms, so that also ideas for this will be suspected, this will be handled in the last chapter.

(251 words)

0.1 Contents

1.0 Introduction

This project report examines a relatively new research chapter, the habitable zones of exoplanets.

Exoplanets are planets which orbits around a star outside of our solar system. The theory behind exoplanets was designed in the early 1980 and the theory was confirmed with the found of an exoplanet around the pulsar PSR 1257+2. The first exoplanet around a main sequence star was found around the sun like star 51 Pegasi (spectral class G5V) in 1995. First exoplanets can be found only with indirect methods, like spectral analyses, nowadays it is possible to see an exoplanet direct with an space based telescope. The biggest question of mankind is, are we alone in the universe? This is why the question of habitable exoplanets arises.

Habitability is the measure of a planet to develop and sustain life. To be in a habitable zone several parameters must be fulfilled. A requirement for life on a far planet is an energy source this is in nearly all cases a star, in that project report we look only at main sequence stars with spectral class F, G, K, M. Further geophysical, geochemical and astrophysical criteria must be fulfilled. To overcome this few requirements two important indices were developed, the Earth similarity index (ESI) and the planetary habitable index (PHI). The ESI makes a weighted comparison of an exoplanet with the earth and is divided into two parts, the interior ESI and the surface ESI. For example the Earth has an ESI value of 1 and the Venus of 0.444. The PHI index includes the substrate, the energy, the chemistry and the availability of liquid solvent. A combination of the two indices gives a two tiered approach of the habitability of exoplanets. The two indices and the two tiered approach has one weak point, it makes a comparison with the Earth. This occurs in a very anthropocentric/earth-centric approach and it reflects only the possibility of Earth like life. A star evolves over its lifetime, so that the habitable zone from an exoplanet alters also over the time, so that this is also an important factor for the determination of the habitable zone.

1.1 Objectives:

With the above determinations the following objectives for that work can be defined

1. Brief Overview exoplanets and Earth similarity index (ESI) and the planetary habitable index (PHI)
2. Discuss the habitable zone widths around F, G, K and M stars with respect to the ESI and PHI index
3. Analyse the change in the parameters in the ESI and PHI as the habitable zone lifetime of exoplanets around main sequences stars evolves.
4. Suggest ways the parameters in the ESI and PSI can be better defined to give a more accurate description of habitable zones to use in future exoplanet discoveries.

1.2 Research method:

The method of that project is a literature based project and it builds only on published papers or internet sources. The literature based project is a review of existing literature, the sources are found in the internet and at the online library of the Open University. Most of the used papers are peer reviewed or prepared for a peer review (like arXiv). The internet sources were used, mostly for pictures or for a fast overview of an issue (like Wikipedia, Wikimedia etc.), no Wikipedia article were directly cited. The internet and library research was done with keywords, like exoplanets, habitable zone, planet lifetime, star evolution and combination of these keywords. The results were papers in *.pdf Format or “Internetlinks”, this papers or information were printed out and read and the essential information was extracted for that work. Mostly of the papers are with costs, but the Open University library has an access online to these sources. (620 words)

2.0 The earth similarity index and the planetary habitable zone index

2.1 Definitions:

Before we go deeper in the chapter issue, we should answer two questions, this questions are:

1) What is life?
2) What is planetary habitability?

Life is a status which differences any creature (including plant, bacteria etc.) from dead material. The question is essential for the definition of the habitability zone.

The principle characteristics of creatures are (Rensing, 1975):

- Creatures are differentiated from the environment.
- Creatures have a metabolism and an energy exchange with the environment.
- Creatures are self-regulating and self-organising.
- Creatures can reproduce themself.
- Creatures are growing and they can differentiate themself.
- Creatures can react on chemical or physical changes of their environment.

But Hazen (2007) means also that extraterrestrial life can also be not subsumable for us. This means also that habitability is depended of the kind of life. This short excurse to the biology was necessary to explain the habitability of a planet but that work concentrates on the issues radiation and matter

Planetary habitability is a measurement of the possibility of a planet or a natural moon to develop life and to sustain life over a recognisable lifetime. Planetary habitability is determined by many parameters and it is a question which goes hand in hand with the definition of life. In case of lacking of other examples we can only determine at the moment the habitability of a planet or a natural moon from a very anthropocentric position. But this position is the only meaningful position at this time.

One of the main articles, which determine the different parameters of habitability very well is the article from Schulze-Makuch (2011) which has a two parameter approach to the question “if a planet is habitable or not”. The two parameters are the earth similarity index or short ESI and the planet habitability index or short PHI. The two parameters would be arranged in an x-y diagram, which shows the position of the analysed exoplanets. An example diagram is shown in figure 1 (Figure 1 shows only a small part of the known exoplanets).

2.2 The ESI value

The ESI (Schulze-Makuch, 2011; University of Puerto Rico, 2015) is an index of earth-likeness for exoplanets, the index shows a number between zero and one. A number of 0 determines no similarity with the earth, a number of 1 is identical to the earth. An exoplanet with an ESI value of above 0.8 can be determined as earth like, which means that it has a similar diameter and composition of the planet. The ESI Index has 4 main subparameters, with reference values and a weighted exponent. The ESI value includes the following parameters:

- Mean Radius of the Planet, as reference value the earth radius is taken
- The Bulk density of the planet, with a reference value of the earth bulk density
- The escape velocity of the planet, with a reference value of earths escapes value.
- The surface temperature of the planet, with a reference value of 288K (15°C).

These four parameters are provided with a weighted exponent.

The weight exponent for the mean radius is 0.57, for the bulk density weight exponent is 1.07, the escape velocity weight exponent is 0.7 and the surface temperature weight exponent is 5.58.

The above parameters results in a table, which is shown in table 1. The reference values for the mean radius, bulk density and escape velocity is 1 Earth unit, for the surface temperature it is Kelvin. The surface temperature is a very important parameter, because under the assumption that carbon based life needs liquid water, like on Earth the weighting exponent is high. (604 words)

Planetary Property		**Reference Value**		**Weight Exponent**	
Mean Radius		1		0,57	
Bulk Density		1		1,07	
Escape velocity		1		0,7	
Surface Temperature		288		5,58	

Table 1: Reference values and weight exponents for four main parameters for the ESI value (Schulze-Makuch, 2011)

The ESI value will be calculated with the following expression:

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

Table 2: ESI value formula (Schulze-Makuch, 2011)

The parameter x_i is a planetary property (e.g. the mean radius) of the researched exoplanet, and x_{i0} is the reference value of the earth, wi is the the weight exponent and n is the number of the used planetary properties. The result is the ESI index of the exoplanet in comparision with the earth. The most important index is the surface temperature, because the weight exponent has a relatively high value.

The ESI value formula can be used to calculate the index for every known planet. The following table shows ESI values for 2 solar planets and 3 exoplanets: (133 words)

Planet		**ESI value**	**planet type**
Earth		1	Solar Planet
Mars		0,815	Solar Planet
Jupiter		0,36	Solar Planet
GJ581g		0,901	Exoplanet
HD69830d		0,636	Exoplanet
55 Cnc f		0,536	Exoplanet

Table 2: ESI Values for some planets (Schulze-Makuch, 2011)

Appendix 1 shows solar planets and moons and Appendix 2 shows exoplanets.

Like above described the ESI value is a measure of Earth likeness for planets and it is a number between 0 and 1. Zero means the exoplanet has no similarity with the Earth, 1 means that the planet is identical with Earth.

The ESI value is a very anthropocentric, better “Earth centric” index, it makes comparison only with earth parameters. It is a good estimate for the human habitability of a planet or exoplanet, but it shows not the possibility of extraterrestrial habitability or the possibility of actually life on that researched planet.

2.3 The PHI value

The PHI index (Schulze-Makuch, 2011) is a similar index shows more on chemical and physical parameters that are conducive to life in general. The PHI value includes the substrate, the energy, the chemistry and the availability of liquid solvent. The PHI value is the possibility or better a compilation about the requirements for life.

The PHI value is calculated by the following formula:

PHI = $(S*E*C*L)^{1/4}$

S…the substrate

E…enough energy

C…the chemistry of the planet

L…the possibility of a liquid solvent

It makes also a comparison with the Earth.

The parameter substrate includes:

- Massive surface, consisting of ice or rock
- Radioactive decay in the core of the planet
- CO2 cycle
- Overall atmosphere with greenhouse effect
- Magnetosphere

The parameter Energy includes:

- Light for photosynthesis
- Surface-temperature
- Chemical reactions
- Gravitational tide

The parameter Chemistry includes:

- Required elements for life building (C,H,O,N,S,P)
- Possibility to form polymers

The parameter liquid solvent includes:

- Liquids solvents in the atmosphere and on the surface.

Each of the parameters will be inscribed in a matrix. Than the PHI value will be calculated out of these matrix parameters. Table 4 shows the PHI value of some planets, moons and exoplanets. (308 words)

Planet	PHI
Mercury	0
Venus	0,37
Earth	0,96
Moon	0
Mars	0,59
Jupiter	0,37
Europa	0,49
Titan	0,64
GJ581b	0,27
GJ581g	0,45
HD69830d	0,29
55Cnc c	0,26

Table 3: PHI values of some planets, moons and exoplanets (Schulze-Makuch, 2011)

2.4 The two tier approach.

The combination of the PHI and the ESI values results in a two tier approach. This two tier approach results in a diagram which is shown in figure 1, it shows the earth in right above edge with an index of 1.0;1.0 and the moon with 0;0.6 (the high ESI value is determined from the assumption that the moon is from the same origin like the earth). (84 words)

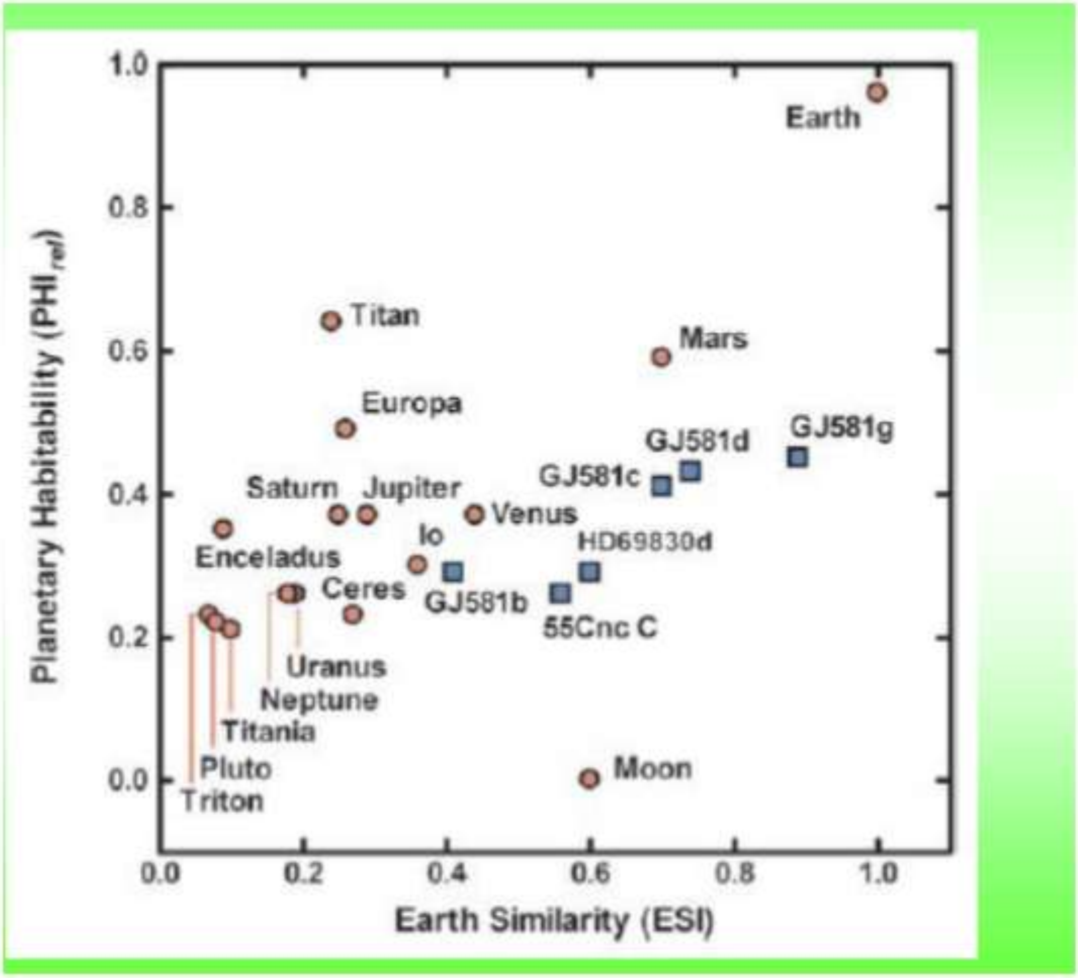

Figure 1: Two Tier approach (Schulze.Makuch et. al, 2011))

In summary the ESI value gives a hint for earth similarity. The parameters in the ESI value give the possibility for a fast summary of the earth similarity. The PHI value shows the possibility of earth similar life. Other life-forms are not ascertainable. The two tier approach is a possibility to categorize the exoplanets and all objects in the solar system.

With the critique of the two tier approach further research and more inputs for suggestions of the habitable zone should be done for the habitability of exoplanets. There are some other parameters to determine a habitability of an exoplanet, one is the host sun, which the planet orbits this sun.

In that work we look only of main sequence stars of spectral classes F, G, K and M. The papers from Pintr (2014), Rushby (2013) , Kopparapu (2013) are a rich source for that question. The spectral class (we look only at main sequence stars) determines the position of a star in the Hertz-Sprung-Russel diagramm, it determines the luminosity of the star and with the spectral class the surface temperature of the star. Figure 2 shows the Hertz-Sprung-Russel diagram. The luminosity and the surface temperature determine theoretically the surface temperature dependent of the distance to the host star of the exoplanet. This further determines the possibility of habitability, especially if liquid water can be found on the planet. Liquid water is for earth similar habitability an essential chemical substance.

This is also an anthropocentric/earth-centric approach, but at the moment the only meaningful approach, like described at the start of that chapter. (274 words)

3.0 Habitable zones around main sequence stars with spectral class F,G,K and M with respect of the ESI and the PHI

3.1 Star classification

Stars are classified by their spectral characteristics. The spectral class of a star is a short code to summarize the characteristics of a star. The classification of most stars will be done with the Morgan-Keenan (MK) system using the letters O,B,A,F,G,K,M. The system has been expanded over the time with the star class W for Wolf Rayet stars, L and T for brown dwarfs, D for white stars and C for carbon stars. Each letter class is subdivided in 10 subclasses with digits from 0 to 9, 0 is being the hottest and 9 being the coolest star. Finally a roman numeral shows the luminosity class of a star:

VII are white dwarfs
VI are subdwarfs
V are dwarfs – main sequence stars.
IV are subgiants
III are giants
II are bright giants
Ia and Ib are bright giants
0 are Hypergiants

All above information can be summarized in a diagram. The Hertzsprung-Russel diagram in figure 3 shows the position of stars dependent of their spectral type and their luminosity. (193 words)

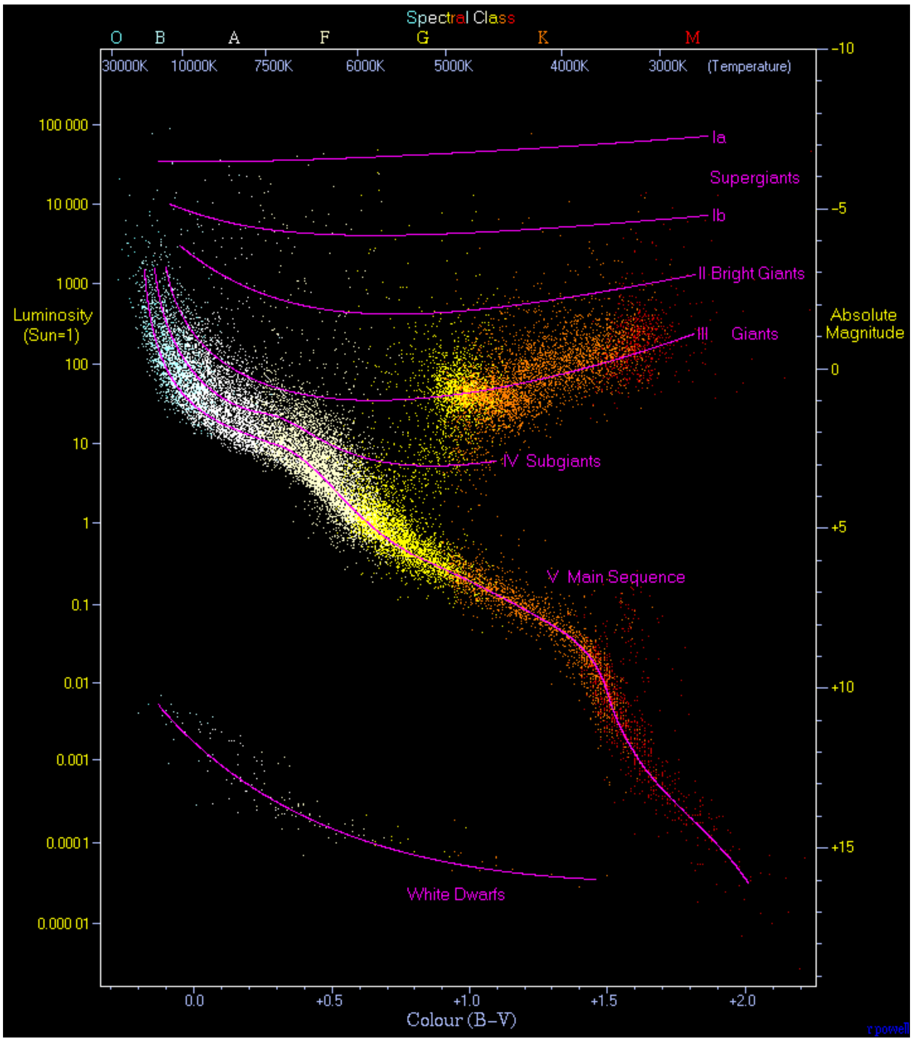

Figure 2: Hertzsprung-Russeldiagram (Powell R., 2015)

For example our sun and Alpha Centauri A is a star with the full spectral class G2V, this indicates a main-sequence star with a surface temperature around 5800K.

3.2 F,G,K and M stars and their habitable zones.

In that work we look only at stars which are similar to our sun, with the spectral characteristics F,G,K and M. This is indicates stars from 2400K to 7500K surface temperature, with a main sequence mass from 0.08 to 1.4 Sun-masses.

The most important parameter of the habitable zone is the distance from a planet to its host sun.

The average habitable zone itself can be calculated by the following formula (Kasting et.al, 1993; Pintr, 2014):

$D=(1AU)^{*}\ (L_{star}/L_{Sun})^{0.5}$

D… is the average radius of the habitable zone.

L_{star}… is the bolometric luminosity of a star.

L_{Sun}… is the bolometric luminosity of the sun.

For the inner and the outer radius of the habitable zone (in AU) the following formula will be used (Kane and Gelino, 2012):

$r_{inner} = (L_{star}/S_{inner})^{0.5}$

$r_{outer} = (L_{star}/S_{outer})^{0.5}$

$S_{inner} = 4.190*10\text{-}^{8}T_{effs}{}^{2}\text{-}2.139*10^{-4}T_{effs}+1.268$

$S_{outer}=6.190*10\text{-}^{9}T_{effs}{}^{2}\text{-}1.319*10\text{-}5\ T_{effs}+0.234$

Where T_{effs} ist the effective stellar surface temperature.

The two habitable boundaries can also be computed with simplified empirical formulas:

$r_{inner}=(L_{star}/1.1)^{0.5}$

$r_{outer}=(L_{star}/0.53)^{0.5}$

The above formulas do only respects the stellar flux of the star and no other parameters.

Kopparapu et.al (2013) describes in their paper that the inner habitable zone of a host sun is not only a function of the loss of water and that outer limit of the habitable zone of the sun is determined by the maximum greenhouse effect by a CO_2 atmosphere. Kopparapu et.al (2013) had developed a 1-D radiative-convective, cloud-free climate model to determine the habitable zone widths around F, G, K and M stars. This new model is based on on CO_2 absorption coefficients, which are derived from the HITRAN 2008 and HITEMP 2010 line-by-line databases. For our solar system the inner habitable zone lies by 0.99 AU and the outer habitable zone lies by 1.70 AU. Calculation for stars between 2600K and 7200K surface temperature results in a not clear distinct greenhouse and water loss limit for stars with surface temperature <5000K. Stars with that surface temperature are stars of spectral class F,G,K and M.

As a result of that calculation Kopparapu et al (2013) uses the stellar flux instead the equilibrium temperature.

$D = (1AU)^* [(L_{star}/L_{sun})/S_{eff}]^{0.5}$

The value for S_{eff} varies in dependence from the spectral class and can be calculated by this formula:
$S_{eff}=S_{effs}+a(T_{effs}-5780)+b(T_{effs}-5780)^2+c^*(T_{effs}-5780)^3+d(T_{effs}-5780)^4$

The coefficients Seffs, a,b,c,d are constants which are published by Kopparapu et.al (2013) with the following values: (428 words)

Constant	Moist Greenhouse	Maximum Greenhouse	RecentVenus	EarlyMars
Seff;s	1.0140	0.3438	1.7753	0.3179
a	8.1774x10-5	5.8942x10-5	1.4316x10-4	5.4513x10-5
b	1.7063x10-9	1.6558x10-9	2.9875x10-9	1.5313x10-9
c	-4.3241x10-12	-3.0045x10-12	-7.5702x10-12	-2.7786x10-12
d	-6.6462x10-16	-5.2983x10-16	-1.1635x10-15	-4.8997x10-16

Table 4: Coefficients for the above formula.

The above estimated(optimistic) borders of the habitable zones are bounded by the recent Venus (0.72AU) and the early Mars (1.67AU).

Rushby et.al(2013) defined the habitable zone borders in two formulas for a :

$HZ_{inner}=[HZ_{innersun*AU}-(2.7622*10^{-5}*(T_{eff}s-5700)^2)]*(L_{star}/L_{sun})^{0.5}$
$HZ_{outer}=[HZ_{outersun*AU}-(1.3786*10^{-4}*(T_{effs}-5700)^2)]*(L_{star}/L_{sun})^{0.5}$

They calculated two scenarios, a 50% cloud coverage scenario and a 100% cloud coverage scenario. The boundaries of a 50% cloud coverage is $HZ_{innersun}$=0.72AU and $HZ_{outersun}$=1.67AU. For a 100% cloud coverage the values for the $HZ_{innersun}$=0.49AU and $HZ_{outersun}$=2.4AU.

For the star Gliese 581, which has in minimum 3 identified planets, with a T_{effs}=3480 and a luminosity of $0.002L_{sun}$ the boundaries of the habitable zone can be calculated with a 50% cloud coverage by:

HZ_{inner}=0.0322AU

HZ_{outer}=0.075AU.

This means that the planets Gliese 581b(0.04AU) and Gliese 581c(0.0735AU) lay calculated with the 50% cloud coverage model from Rusby in the habitable zone. The 100% cloud coverage model results in

HZ_{inner}=0,022AU

HZ_{outer}=0,11AU

With the model from Kopparapu the moisture greenhouse zone lays for Gliese 581 at 0.048AU average diameter and the maximum greenhouse zone at 0.24AU average diameter.

The results from Kopparapu and from Rushby look by the assumption of a moisture greenhouse, in comparison with a 50% cloud coverage in a same dimension. By a maximum greenhouse is the model from Kopparapu for the habitable zone optimistically than the model from Rushby.

The results and calculations from Rushby et. al (2013) look consistent with the result from Pintr (2014) and that the age of an exoplanet host star is important for understanding of the habitability of an exoplanet.

Figure 3 shows the habitable zone of the solar system and at Gliese 581, and in case of that dependence of the luminosity of the star and so the ESI and the PHI values can be altered. (287 words)

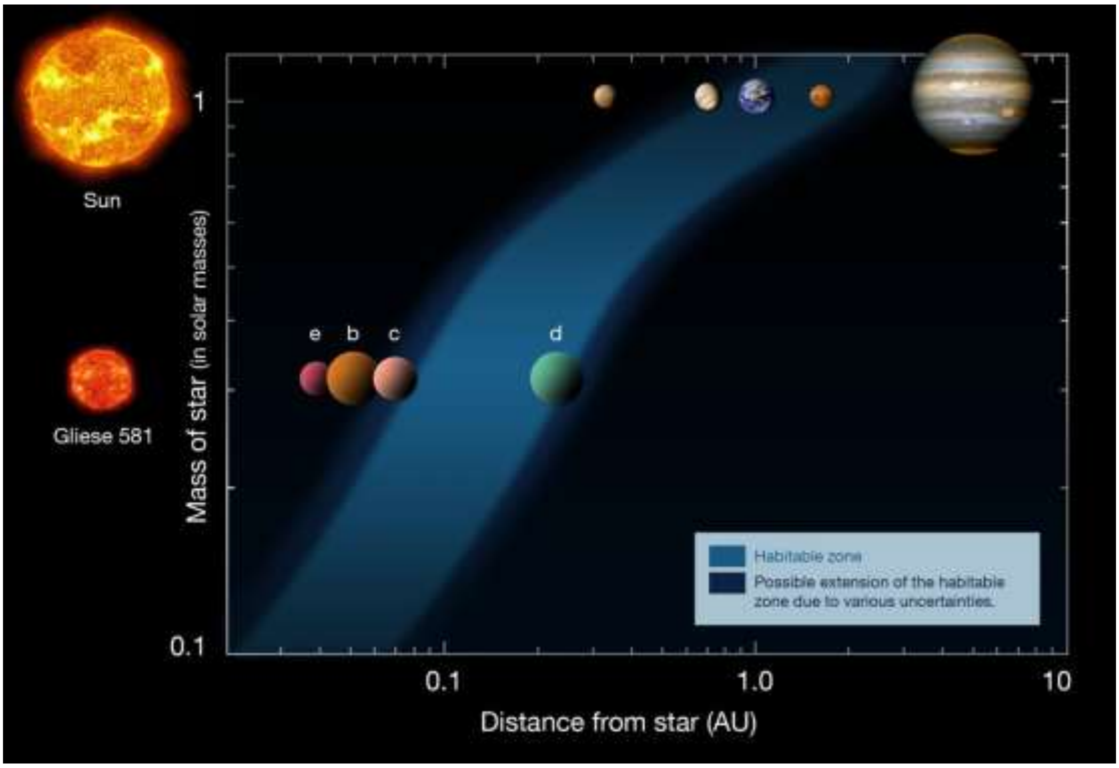

Figure 3: Habitable zone, Solar system and Gliese 581 (ESO, 2015)

Pintr (2014) finds two trends in his paper, first the greatest occurrence of exoplanets in habitable zones for main sequence star with spectral class G. The second astounding result is the finding that the occurrence of exoplanets in habitable zones increases with the life length of the host star.

Safonava (2015) found in his paper that it is successful to search for extraterrestrial life around old metal poor population II stars. But most of the confirmed exoplanets orbits around relatively young population I stars, which has a limited time to develop life. So that the argument to search for extraterrestrial life around metal poor population II is a good advise to search in these systems. Old Population II stars (9-13 Gyr) had enough time to build the necessary chemical reactions on habitable planets in the habitable zone around the host star. This theory is necessary to search for planets around the habitable zone of a specific host star and to determine a possible research star. (176 words)

4.0 The change of the ESI and the PHI over the lifetime of main sequence stars

4.1 Lifecycle of a star

Stars have like creatures a development process. For example we take our Sun the next star, which can be studied very well. The simplified process will be explained in the next few sentences. Our Sun was formed out of a molecule cloud for about 4.6 billion years ago. The collapse of the molecule cloud is mostly gravitational driven. By this collapse the temperature of the cloud will increase and forms a protostar. The protostar builds an accretion disk and cumulates material out of the molecule cloud. If the energy out of the contraction of the protostar is greater than the energy out of the accretion disc a pre-main-sequence star is developed. If the nuclear fusion from hydrogen starts the main-sequence branch is reached. A star like the Sun remains of 10-11 billion years on the main-sequence branch. Figure 4 shows the life cycle of our Sun. (167 words)

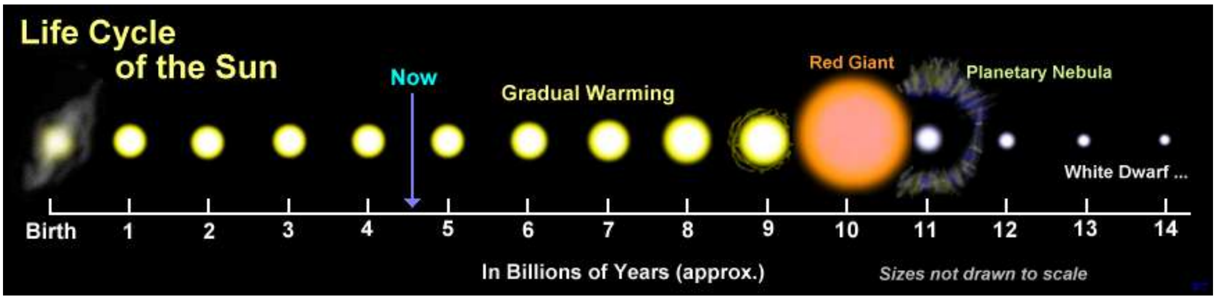

Figure 4: Lifecycle of the Sun (wikicommons, 2006)

After these 10-11 billion years of remaining on the main sequence, the star will inflate to a red giant. This second to last phase has a duration of about 600 million years. The last phase is after repelling the outer hull of the star the arising of a white dwarf. The outer hull around the dying star forms a planetary nebula. This described way is similar for a star with the same mass like our sun. For stars with a lower mass the life cycle is longer, it can be some 100 billion years. (Stars with a mass<0.2M_{Sun} do not evolve a red giant stage). For stars with much more mass the life cycle is shorter, it can be only some 100 million years. (Laughlin, 1997;Vanbeveren, 1998;Clark et.al, 2012)

The stellar lifecycle has an important influence of holding an exoplanet in a habitable orbit around a star. Like described in Chapter 2, liquid water is necessary for carbon based life-forms like we know. The Sun or a similar star is of about 4.6 billion years old, the average surface temperature of the Earth or a similar planet is 15°C (Nasa, 2015a). In case of the stellar evolution in about 900 million years the surface temperature of the Earth or a similar planet will reach the temperature of 30°C which is an estimated limit for higher life. After further 1 billion years the surface temperature of the examined planet will reach 100°C. This described scenario is a result of the stellar evolution and that the star will increase in its radius and its will increase its luminosity. (Ribas, 2010).

The size of the habitable zone clearly depends on the luminosity of the host star. If the luminosity of the star does change, the habitable zone change and also the ESI value and the PHI value changes. Figure 5 shows the comparative life zones of stars, red areas are areas which are too hot, green areas shows the habitable zone and blue are too cold. (341 words)

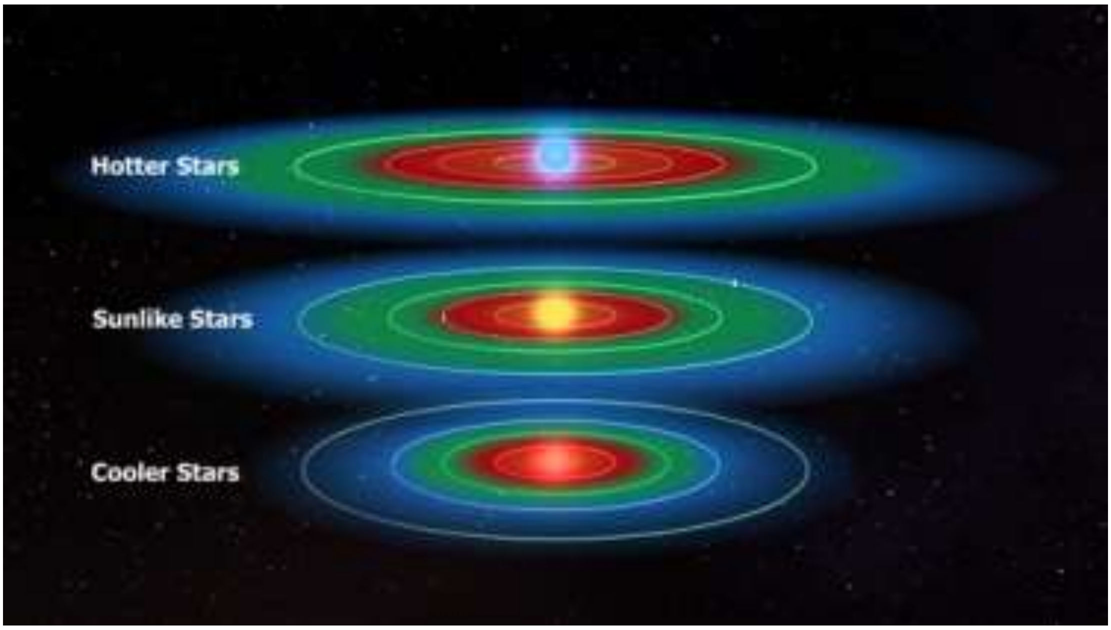

Figure 5: Comparative life zones of stars (NASA, 2015b)

4.2 The ESI and PHI value in respect of the life cycle of a star.

By changing the luminosity this results in lowering of the ESI value and the PHI value of the examined planet. Especially that the surface temperature is relatively high weighted. Other planets which orbit this star (or the sun) will increase their ESI value, so that e.g. Mars becomes more Earth like and Earth becomes more Venus like, and Venus becomes more Merkur like and perhaps Merkur disappear in the Sun atmosphere.

Now we see that the ESI value is a very earth-centric index and in case of that also an anthropocentric index.

The above scenario is also be described in a paper from Underwood (2012), which looks how long a star can hold a planet in the habitable zone, that carbon-based extraterrestrial life outside of the solar system can be developed. For the earth the lifetime to develop life is about 5.2 billion years (1 billion to develop life from forming the Earth and of 6.2 billion years from the beginning to become too hot for life). This shows that at normal G2V star like our sun the habitable lifetime is about 5 to 5.5 billion year. For other main sequence stars like M dwarf stars the habitable lifetime is longer and can be reach tenths of billion years, so that an exoplanet can be habitable for that long time. The sun´s main sequence effective temperature, luminosity and radius are shown in figure 6 against the time. (261 words)

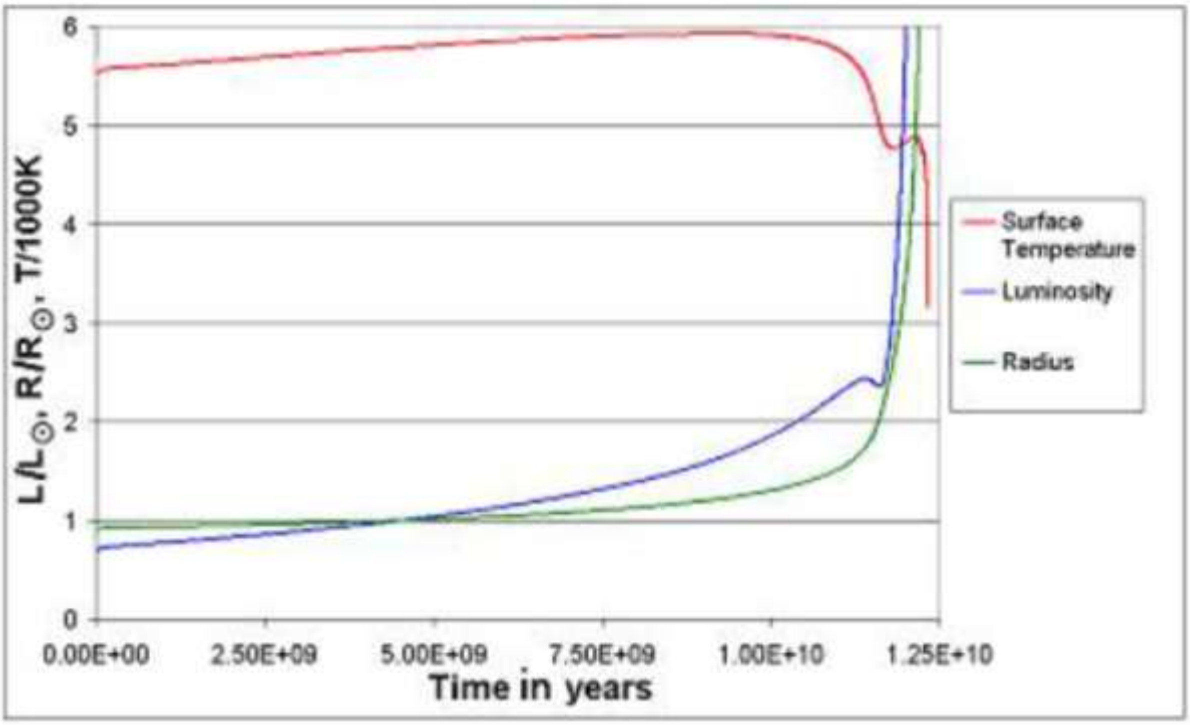

Figure 6: Sun´s main sequence effective temperature, luminosity and radius (Underwood, 2012)

Like above described the lifetime and the possible habitability of a star with lower mass is higher than that of the sun, so that if an earth like planet is found around that star the possibility of habitability could be higher.

Rushby et.al (2013) presents a relatively simply model about habitable zone around main sequence stars. The model describes the lifetime of a planet in that habitable zone. The underlying model from Rushby et.al estimates for example a habitable lifetime of the Earth between 6.29 and 7.79 Gigayears, ending between 1.75 and 3.25 Gigayears from present. With these results a comparison of the lifetime of exoplanets can be done. The exoplanets Gj581d and Gj581g and HD40307g a prediction of their lifetime in the habitable zone can be done. The lifetime in the habitable zone of an exoplanet is dependent of the mass of the host star. Table 5 shows this relation. (163 words)

Mass of host star		Main Sequence		Typ.hab. Zone	
Msun		Lifetime/ Gyr		Lifetime/Gyr	
0,2		436,3		42,16	
0,3		296,6		25,34	
0,4		225,6		21,24	
0,5		115,1		14,42	
0,6		59,5		11,07	
0,7		34,2		9,63	
0,8		21,2		8,56	
0,9		14,9		7,86	
1,00		10,9		6,77	
1,10		8,2		5,62	
1,20		6,3		4,57	

Table 5: Relation between mass of host star, Lifetime of a planet and lifetime in the habitable zone (Rushby et.al, 2013)

Table 5 shows it impressive, that the lifetime of a planet around his host sun, is dependent of the mass of the sun and in cause of that the luminosity of that sun.
(54 words)

5.0 Suggest ways to improve the ESI and the PHI for further discoveries

First the question arises, do we mean habitability for earth like organism or is habitability a general term for the possibility of life on an exoplanet. I would define habitability in that work as a possibility for a planet to hold life similar to Earth life. But this includes life in a very broad spectrum, from life at black smokers to life in the Antarktis.

The ESI value and the PHI value are indices which uses as comparison and as reference the average Earth. Principle the two indices covers a big spectrum of habitability. But life is very adaptable to the environment through the evolution process. Dependent of the life time of a star the star increases in their luminosity, so that the habitable zone drifts to the outside of the system. This means for the solar system Venus becomes Merkur, Earth becomes Venus and Mars becomes Earth. So that the ESI and the PHI values which are use now Earth as a reference alters, but in that scenario Earth is not habitable in our sense.

So it makes sense to add to the two indices more parameters. I would suggest these additional parameters:

1) A parameter for the lifetime of the star. This should be a factor in the ESI value, to adapt the weighting of the surface temperature. Also the PHI value needs an additional factor in the surface-temperature.

2) If we decide to expand the term “habitable planet” for extremophile life-forms an additional parameter also in the parameter surface-temperature in all two indices.

3) The last adaption, which is a very unusual adaption but a necessary adaption for other exotic life-forms, like silicon based life. This should be happened also in the surface-temperature in all two indices.

The additional parameters should be so constructed, that if not needed or wished the originally term is not altered. This must be additional multiplicators by the weighting figure. (331 words)

6.0 Discussion

In case of that is a literature based project the discussion is a relatively short one, but by the analysis of the two parameters ESI and PHI and of the two tier approach of Schulze-Makuch, the three approaches makes sense and had minor gaps. Only the earth-centric/human-centric approach could make problems, so that I suggest in that work some additional parameters, especially for the surface-temperature to cover the lifetime of a star, extremophile organism and last but not least exotic life-forms.

The spectral class of a star and the luminosity states the position of the observed star in the Hertzsprung-Russel-diagram, so that principle a star with more mass has more luminosity as a star with lower mass. This effect results in different habitable zones diameter and in case of that in other ESI and PHI values. At this work we look only at F,G,K and M stars so that the possibility of earth similarity is higher. There are some different approaches, from the authors Kopparapu, Rushby, Kane/Gelino and Pintr which had principle as base the luminosity of the star.

Pintr calculates only the luminosity as base and calculates only an average diameter of the habitable zone. Kane/Gelino uses for the calculation also the luminosity, but calculates a lower and an outer limit of the habitable zone.

Kopparapu uses for the calculation a 1-D radiative-convective, cloud-free climate model, but this model gives additional parameters for 50% cloud coverage and 100% cloud coverage. The model from Kopparapu calculates and outer and inner limit of the habitable zone. Rushby use for the calculation the greenhouse effect, the model calculates also an outer and an inner limit of the habitable zone.

The result of the two models especially from the 50% cloud coverage and the moist greenhouse effects gives similar results. The difference between the 100% cloud coverage model and the maximum greenhouse effect is existing, but perhaps not essential. The two models look very consistent.

Finally the lifetime of a planet in the habitable zone is analysed, so that a habitable zone alters with the age and the mass of the host star. This includes the statement, that if a star gets more luminosity through their development, the habitable zone alters.

All this parameters should get more respect in the ESI and the PHI values like suggested.(386 words)

7.0 Conclusions

As conclusion out of that work we can determine that one of the essential parameter is to define the habitable zone of an exoplanet is the luminosity of the host star.

The luminosity depends of the mass of the star or of the lifecycle position of the star.

An altering luminosity results in a shifting of an exoplanet out or in this habitable zone.

The two values ESI and PHI have also as an essential parameter the surface temperature of that planet. Some other parameters are used by these two indices, but the greatest weighting lies on the surface temperature, which is depend of the luminosity of the host star. The greatest critique on the two indices is that the Earth is the comparison planet. The two parameters do not respect other exotic life-form, extremophile life-forms and the natural shifting of the habitable zone in case of the life-cycle of a star. In that work some suggestions of a correction of that circumstance will be given. (168 words)

Sum: 4979 words

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Appendix 1

The following data are from the University of Puerto Rico at Arecibo
http://phl.upr.edu/projects/earth-similarity-index-esi Last access 19.07.2015

ESI value for the solar planets and solar moons

Planet Name	mass (EU)	radius (EU)	density (EU)	g (EU)	ve (EU)	a (AU)	Tsurf (K)	Teq (K)	ESIi	ESIs	ESIg
Earth	1.00	1.00	1.00	1.00	1.00	1.00	288.	254.	1.000	1.000	1.000
Mars	0.107	0.53	0.71	0.38	0.45	1.52	227.	210.	0.815	0.595	0.697
Mercury	0.0553	0.38	0.98	0.38	0.38	0.39	440.	434.	0.840	0.422	0.596
Moon	0.0123	0.27	0.60	0.17	0.21	1.00	220.	255.	0.674	0.464	0.559
Venus	0.815	0.95	0.95	0.90	0.93	0.72	730.	232.	0.979	0.201	0.444
Io	0.0150	0.29	0.64	0.18	0.23	5.20	130.	112.	0.694	0.188	0.362
Callisto	0.0180	0.38	0.33	0.13	0.22	5.20	134.	112.	0.580	0.197	0.338
Jupiter	318.	10.97	0.24	2.64	5.38	5.20	152.	110.	0.360	0.238	0.292
Ganymede	0.0248	0.41	0.35	0.15	0.25	5.20	110.	112.	0.604	0.138	0.289
Ceres	0.000159	0.08	0.36	0.03	0.05	2.77	167.	153.	0.406	0.180	0.271
Europa	0.00803	0.25	0.55	0.13	0.18	5.20	102.	112.	0.635	0.108	0.262
Vesta	4.38e-05	0.04	0.59	0.02	0.03	2.36	166.	166.	0.414	0.158	0.256
Saturn	95.2	9.14	0.12	1.14	3.23	9.54	134.	81.	0.280	0.217	0.246
Titan	0.0225	0.40	0.34	0.14	0.24	9.54	94.	83.	0.594	0.099	0.242
Pallas	3.53e-05	0.04	0.44	0.02	0.03	2.77	153.	153.	0.376	0.132	0.222
Iapetus	0.000330	0.11	0.23	0.03	0.05	9.54	130.	83.	0.372	0.120	0.211
Uranus	14.5	3.98	0.23	0.92	1.91	19.19	76.	58.	0.455	0.077	0.187
Neptune	17.1	3.87	0.30	1.14	2.11	30.07	72.	47.	0.509	0.067	0.184
Hygiea	1.00e-05	0.03	0.37	0.01	0.02	3.14	144.	144.	0.318	0.101	0.179
Dione	0.000183	0.09	0.27	0.02	0.05	9.54	87.	83.	0.374	0.050	0.137
Rhea	0.000390	0.12	0.23	0.03	0.06	9.54	76.	83.	0.376	0.040	0.123
Titania	0.000590	0.12	0.31	0.04	0.07	19.19	60.	58.	0.433	0.025	0.104
Oberon	0.000500	0.12	0.29	0.03	0.06	19.19	61.	58.	0.418	0.025	0.103
Enceladus	1.81e-05	0.04	0.31	0.01	0.02	9.54	75.	83.	0.316	0.028	0.094
Umbriel	0.000200	0.09	0.26	0.02	0.05	19.19	61.	58.	0.371	0.023	0.092
Haumea	0.000690	0.12	0.43	0.05	0.08	43.34	50.	39.	0.486	0.017	0.091
Ariel	0.000220	0.09	0.29	0.03	0.05	19.19	58.	58.	0.390	0.021	0.090
Tethys	0.000103	0.08	0.18	0.01	0.04	9.54	64.	83.	0.309	0.023	0.085
Charon	0.000250	0.09	0.29	0.03	0.05	39.48	53.	41.	0.395	0.017	0.082
Pluto	0.00220	0.18	0.37	0.07	0.11	39.48	40.	41.	0.512	0.011	0.075
Triton	0.00359	0.21	0.38	0.08	0.13	30.07	38.	46.	0.535	0.010	0.074
Mimas	6.30e-06	0.03	0.21	0.01	0.01	9.54	64.	83.	0.254	0.017	0.066
Miranda	1.10e-05	0.04	0.22	0.01	0.02	19.19	59.	58.	0.269	0.015	0.064
Varuna	6.20e-05	0.05	0.53	0.03	0.04	43.13	43.	39.	0.415	0.009	0.062
2005 QU182	0.000200	0.08	0.36	0.03	0.05	113.58	41.	24.	0.415	0.009	0.061
Quaoar	0.000170	0.08	0.35	0.03	0.05	43.60	41.	39.	0.405	0.009	0.060
2002 TC302	0.000260	0.09	0.36	0.03	0.05	55.24	38.	34.	0.422	0.008	0.057
Ixion	5.00e-05	0.05	0.38	0.02	0.03	39.68	43.	40.	0.370	0.009	0.057
Orcus	0.000100	0.08	0.24	0.02	0.04	39.42	42.	41.	0.340	0.009	0.054
Eris	0.00270	0.19	0.39	0.07	0.12	67.67	30.	31.	0.530	0.006	0.054
2005 UQ513	0.000100	0.07	0.25	0.02	0.04	43.31	41.	39.	0.344	0.008	0.053
Proteus	8.44e-06	0.03	0.23	0.01	0.02	30.07	46.	46.	0.270	0.008	0.048
2007 OR10	0.000300	0.09	0.36	0.03	0.06	55.24	30.	34.	0.429	0.004	0.043
Makemake	0.000670	0.14	0.23	0.03	0.07	45.79	30.	38.	0.399	0.005	0.043
2007 UK126	0.000100	0.07	0.30	0.02	0.04	73.74	32.	30.	0.369	0.005	0.041
Sedna	0.000500	0.12	0.29	0.03	0.06	525.86	12.	11.	0.418	0.000	0.013

Appendix 2

The following data are from the University of Puerto Rico at Arecibo http://phl.upr.edu/projects/earth-similarity-index-esi. Last access 19.07.2015

ESI Value for known exoplanets

Planet Name	mass (EU)	radius (EU)	density (EU)	g (EU)	ve (EU)	a (AU)	Tsurf (K)	Teq (K)	ESIi	ESIs	ESIg
GJ 581 g	3.100	1.36	1.22	1.67	1.51	0.15	278.	248.	0.901	0.877	0.889
GJ 581 d	5.600	1.60	1.36	2.18	1.87	0.22	232.	202.	0.849	0.643	0.739
GJ 581 c	5.600	1.60	1.36	2.18	1.87	0.07	380.	350.	0.849	0.583	0.703
HD 69830 d	18.434	3.36	0.49	1.63	2.34	0.63	312.	282.	0.636	0.747	0.689
55 Cnc f	45.768	4.91	0.39	1.90	3.06	0.78	310.	280.	0.536	0.703	0.614
61 Vir d	22.884	3.68	0.46	1.69	2.50	0.48	375.	345.	0.612	0.555	0.583
GJ 581 e	1.700	1.16	1.10	1.27	1.21	0.03	591.	561.	0.954	0.297	0.532
HIP 57050 b	94.714	6.64	0.32	2.15	3.78	0.16	250.	220.	0.464	0.602	0.528
mu Ara d	165.876	8.38	0.28	2.36	4.45	0.92	327.	297.	0.413	0.588	0.493
HD 142 b	327.367	11.12	0.24	2.65	5.43	1.00	286.	256.	0.357	0.657	0.484
GJ 581 b	15.600	3.14	0.51	1.59	2.23	0.04	499.	469.	0.656	0.353	0.481
HD 37124 b	203.412	9.13	0.27	2.44	4.72	0.53	332.	302.	0.395	0.564	0.472
HD 96167 b	216.126	9.36	0.26	2.47	4.81	1.30	334.	304.	0.390	0.555	0.465
HD 108874 b	432.251	12.49	0.22	2.77	5.89	1.05	294.	264.	0.336	0.632	0.460
GJ 581 f	7.000	2.16	0.70	1.51	1.80	0.76	139.	109.	0.790	0.267	0.459
HD 210277 b	390.933	11.98	0.23	2.73	5.72	1.10	275.	245.	0.343	0.614	0.459
HD 147513 b	317.832	10.99	0.24	2.63	5.38	1.26	263.	233.	0.359	0.586	0.459
HD 69830 c	12.078	2.82	0.54	1.52	2.07	0.19	549.	519.	0.686	0.304	0.457
HD 188015 b	400.468	12.10	0.23	2.74	5.76	1.19	274.	244.	0.341	0.608	0.456
HD 142415 b	514.888	13.43	0.21	2.85	6.19	1.05	288.	258.	0.323	0.639	0.454
HD 114729 b	260.622	10.12	0.25	2.55	5.08	2.08	245.	215.	0.375	0.537	0.448
HD 82943 b	556.206	13.87	0.21	2.89	6.34	1.19	287.	257.	0.318	0.631	0.448
HD 34445 b	251.087	9.96	0.25	2.53	5.02	2.07	240.	210.	0.378	0.522	0.444
HD 216435 b	400.468	12.10	0.23	2.74	5.76	2.56	264.	234.	0.341	0.577	0.444
61 Vir c	18.212	3.34	0.49	1.63	2.33	0.22	541.	511.	0.638	0.303	0.440
HD 3651 b	63.566	5.63	0.36	2.01	3.36	0.28	450.	420.	0.502	0.381	0.437
HD 11964 c	193.877	8.95	0.27	2.42	4.66	3.34	221.	191.	0.399	0.468	0.432
HD 4203 b	657.912	14.87	0.20	2.97	6.65	1.16	299.	269.	0.306	0.594	0.426
HD 30562 b	410.003	12.22	0.22	2.75	5.80	2.30	251.	221.	0.340	0.534	0.426
HD 170469 b	212.947	9.30	0.26	2.46	4.79	2.24	219.	189.	0.391	0.459	0.424
mu Ara b	532.686	13.62	0.21	2.87	6.26	1.50	262.	232.	0.321	0.558	0.423
GJ 1214 b	5.689	2.71	0.29	0.77	1.45	0.01	548.	518.	0.542	0.329	0.423
HD 216770 b	206.591	9.19	0.27	2.45	4.74	0.46	383.	353.	0.394	0.452	0.422
HD 16141 b	73.101	5.96	0.34	2.06	3.50	0.35	462.	432.	0.489	0.361	0.420
HD 10647 b	295.584	10.66	0.24	2.60	5.27	2.03	228.	198.	0.365	0.476	0.417
kappa CrB b	572.097	14.03	0.21	2.91	6.39	2.70	319.	289.	0.316	0.548	0.416
HIP 14810 d	181.164	8.70	0.28	2.40	4.57	1.89	206.	176.	0.405	0.421	0.413
HD 73534 b	365.507	11.65	0.23	2.70	5.60	3.15	230.	200.	0.348	0.474	0.406
HD 134987 b	505.353	13.33	0.21	2.85	6.16	0.81	339.	309.	0.324	0.506	0.405
HD 164922 b	114.419	7.18	0.31	2.22	3.99	2.11	185.	155.	0.446	0.367	0.404
HD 153950 b	867.681	16.69	0.19	3.12	7.21	1.28	304.	274.	0.288	0.565	0.403
HIP 14810 c	406.825	12.18	0.23	2.74	5.78	0.55	358.	328.	0.340	0.475	0.402
HD 196885 b	820.006	16.30	0.19	3.09	7.10	2.37	267.	237.	0.291	0.551	0.401
HD 37124 d	198.327	9.03	0.27	2.43	4.69	1.64	202.	172.	0.397	0.404	0.400
HD 171028 b	581.632	14.13	0.21	2.91	6.42	1.29	337.	307.	0.314	0.504	0.398
HD 208487 b	143.024	7.88	0.29	2.30	4.26	0.49	440.	410.	0.426	0.371	0.397
HD 5319 b	616.594	14.48	0.20	2.94	6.53	1.75	334.	304.	0.310	0.508	0.397
HD 12661 b	731.013	15.54	0.19	3.03	6.86	0.83	324.	294.	0.299	0.523	0.395
HD 92788 b	1226.831	19.27	0.17	3.30	7.98	0.97	290.	260.	0.266	0.586	0.395
HD 205739 b	435.430	12.53	0.22	2.78	5.90	0.90	362.	332.	0.335	0.463	0.394
HD 125612 b	1017.062	17.83	0.18	3.20	7.56	1.20	273.	243.	0.277	0.559	0.394
HD 19994 b	533.957	13.63	0.21	2.87	6.26	1.42	348.	318.	0.320	0.483	0.393
HD 73526 c	794.579	16.09	0.19	3.07	7.03	1.05	323.	293.	0.293	0.521	0.391
HD 4208 b	254.265	10.01	0.25	2.54	5.04	1.70	205.	175.	0.377	0.405	0.391
HD 9446 c	578.454	14.10	0.21	2.91	6.41	0.65	346.	316.	0.315	0.484	0.391
HD 114783 b	314.653	10.94	0.24	2.63	5.36	1.20	213.	183.	0.360	0.423	0.390

55 Cnc c	53.714	5.24	0.37	1.95	3.20	0.24	535.	505.	0.519	0.285	0.385
HD 16175 b	1398.460	20.35	0.17	3.38	8.29	2.10	283.	253.	0.258	0.571	0.384
HD 45350 b	568.919	14.00	0.21	2.90	6.38	1.92	231.	201.	0.316	0.460	0.381
HD 75898 b	797.758	16.11	0.19	3.07	7.04	1.19	338.	308.	0.293	0.488	0.378
HD 82943 c	638.842	14.69	0.20	2.96	6.60	0.75	354.	324.	0.308	0.463	0.378
HD 23079 b	829.541	16.38	0.19	3.09	7.12	1.65	246.	216.	0.291	0.489	0.377
HD 183263 b	1172.799	18.91	0.17	3.28	7.88	1.52	264.	234.	0.269	0.524	0.375
HD 99492 b	34.644	4.37	0.42	1.81	2.82	0.12	590.	560.	0.566	0.246	0.373
16 Cyg B b	533.957	13.63	0.21	2.87	6.26	1.68	221.	191.	0.320	0.430	0.371
HD 175541 b	193.877	8.95	0.27	2.42	4.66	1.03	461.	431.	0.399	0.334	0.365
HD 28185 b	1811.641	22.67	0.16	3.53	8.94	1.03	279.	249.	0.243	0.547	0.365
HD 20868 b	632.485	14.63	0.20	2.96	6.58	0.95	223.	193.	0.309	0.430	0.364
HD 154857 b	572.097	14.03	0.21	2.91	6.39	1.20	381.	351.	0.316	0.417	0.363
HD 108874 c	323.553	11.07	0.24	2.64	5.41	2.68	195.	165.	0.358	0.367	0.362
HD 177830 b	406.825	12.18	0.23	2.74	5.78	1.00	407.	377.	0.340	0.386	0.362
HD 95089 b	381.398	11.85	0.23	2.71	5.67	1.51	419.	389.	0.345	0.371	0.358
6 Lyn b	762.796	15.82	0.19	3.05	6.95	2.20	368.	338.	0.296	0.430	0.357
HD 136418 b	635.664	14.66	0.20	2.96	6.59	1.32	382.	352.	0.308	0.412	0.356
HD 213240 b	1430.243	20.54	0.16	3.39	8.35	2.03	256.	226.	0.257	0.493	0.356
HD 148427 b	305.119	10.80	0.24	2.61	5.32	0.93	443.	413.	0.362	0.344	0.353
HD 180902 b	508.531	13.36	0.21	2.85	6.17	1.39	407.	377.	0.324	0.379	0.351
HD 8574 b	670.625	14.99	0.20	2.98	6.69	0.77	386.	356.	0.305	0.403	0.350
CoRoT-9 b	266.979	11.78	0.16	1.92	4.76	0.41	407.	377.	0.297	0.409	0.349
HD 40979 b	1055.201	18.10	0.18	3.22	7.64	0.81	358.	328.	0.275	0.436	0.346
HD 4308 b	12.872	2.89	0.53	1.54	2.11	0.12	731.	701.	0.678	0.174	0.344
HD 11506 b	1093.341	18.37	0.18	3.24	7.72	2.43	231.	201.	0.273	0.433	0.344
HD 12661 c	498.996	13.26	0.21	2.84	6.14	2.56	198.	168.	0.325	0.361	0.343
HD 128311 b	692.873	15.20	0.20	3.00	6.75	1.10	208.	178.	0.302	0.383	0.340
HD 52265 b	359.150	11.56	0.23	2.69	5.58	0.49	458.	428.	0.350	0.321	0.335
HD 10697 b	2027.767	23.75	0.15	3.59	9.24	2.16	254.	224.	0.237	0.471	0.334
HD 196050 b	953.495	17.35	0.18	3.17	7.41	2.50	217.	187.	0.282	0.396	0.334
HD 6434 b	152.559	8.10	0.29	2.33	4.34	0.15	532.	502.	0.420	0.265	0.334
HD 167042 b	508.531	13.36	0.21	2.85	6.17	1.30	433.	403.	0.324	0.343	0.333
HD 222582 b	2463.196	25.76	0.14	3.71	9.78	1.35	263.	233.	0.227	0.488	0.333
HD 23596 b	2285.211	24.96	0.15	3.67	9.57	2.72	258.	228.	0.231	0.478	0.332
HD 231701 b	343.258	11.35	0.24	2.67	5.50	0.53	467.	437.	0.353	0.311	0.332
HD 86264 b	2224.823	24.69	0.15	3.65	9.50	2.86	256.	226.	0.232	0.474	0.332
HD 33564 b	2892.269	27.53	0.14	3.82	10.25	1.10	306.	276.	0.218	0.503	0.331
HD 169830 c	1284.040	19.64	0.17	3.33	8.09	3.60	226.	196.	0.263	0.412	0.329
HD 181342 b	1048.845	18.06	0.18	3.22	7.62	1.78	383.	353.	0.276	0.392	0.329
HD 50499 b	543.492	13.74	0.21	2.88	6.29	3.86	190.	160.	0.319	0.336	0.327
HD 73526 b	921.712	17.11	0.18	3.15	7.34	0.66	400.	370.	0.284	0.370	0.324
HD 216437 b	667.447	14.96	0.20	2.98	6.68	2.70	195.	165.	0.305	0.343	0.323
HD 192263 b	228.839	9.58	0.26	2.49	4.89	0.15	521.	491.	0.385	0.266	0.320
HD 114386 b	394.111	12.02	0.23	2.73	5.73	1.65	174.	144.	0.343	0.298	0.319
HD 38801 b	3400.800	29.45	0.13	3.92	10.75	1.70	311.	281.	0.210	0.483	0.319
HD 2039 b	1557.376	21.28	0.16	3.44	8.56	2.20	224.	194.	0.252	0.400	0.317
HD 206610 b	699.230	15.25	0.20	3.01	6.77	1.68	438.	408.	0.302	0.327	0.314
HD 89744 b	2539.476	26.08	0.14	3.73	9.87	0.89	338.	308.	0.225	0.438	0.314
30 Ari B b	3140.178	28.49	0.14	3.87	10.50	0.99	326.	296.	0.214	0.454	0.312
HD 202206 c	775.510	15.92	0.19	3.06	6.98	2.55	191.	161.	0.295	0.329	0.312
HD 37124 c	217.079	9.38	0.26	2.47	4.81	3.19	153.	123.	0.390	0.248	0.311
HD 69830 b	10.488	2.66	0.56	1.48	1.99	0.08	828.	798.	0.703	0.137	0.311
HD 7924 b	9.217	1.84	1.48	2.73	2.24	0.06	875.	845.	0.805	0.119	0.310
HD 190360 c	18.116	3.34	0.49	1.63	2.33	0.13	780.	750.	0.638	0.150	0.309
HD 89307 b	565.741	13.97	0.21	2.90	6.37	3.27	177.	147.	0.316	0.297	0.307
HD 141937 b	3082.968	28.28	0.14	3.86	10.45	1.52	245.	215.	0.215	0.431	0.304
HD 73267 b	972.565	17.50	0.18	3.18	7.46	2.20	191.	161.	0.280	0.322	0.301
HAT-P-13 c	4608.561	33.42	0.12	4.13	11.75	1.19	315.	285.	0.196	0.460	0.300
HD 50554 b	1557.376	21.28	0.16	3.44	8.56	2.38	209.	179.	0.252	0.356	0.299
HD 154672 b	1595.516	21.50	0.16	3.45	8.62	0.60	397.	367.	0.250	0.357	0.299
HD 210702 b	635.664	14.66	0.20	2.96	6.59	1.17	474.	444.	0.308	0.288	0.298
HD 169830 b	915.356	17.06	0.18	3.14	7.33	0.81	444.	414.	0.284	0.312	0.298
HD 190360 b	477.383	13.01	0.22	2.82	6.06	3.92	165.	135.	0.329	0.267	0.296
HD 39091 b	3289.559	29.05	0.13	3.90	10.65	3.29	240.	210.	0.212	0.413	0.296
HD 212771 b	731.013	15.54	0.19	3.03	6.86	1.22	465.	435.	0.299	0.293	0.296
HD 202206 b	5530.273	36.06	0.12	4.25	12.39	0.83	313.	283.	0.188	0.457	0.293

HD 11964 b	34.961	4.39	0.41	1.82	2.82	0.23	758.	728.	0.565	0.151	0.292
HD 72659 b	940.782	17.26	0.18	3.16	7.39	4.16	183.	153.	0.282	0.300	0.291
HD 117618 b	56.574	5.36	0.37	1.97	3.25	0.18	714.	684.	0.514	0.164	0.290
HD 4313 b	731.013	15.54	0.19	3.03	6.86	1.19	477.	447.	0.299	0.281	0.290
HD 192699 b	794.579	16.09	0.19	3.07	7.03	1.16	471.	441.	0.293	0.285	0.289
HD 134987 c	260.622	10.12	0.25	2.55	5.08	5.80	145.	115.	0.375	0.223	0.289
HD 117207 b	654.733	14.84	0.20	2.97	6.64	3.78	166.	136.	0.306	0.260	0.282
HD 102117 b	54.667	5.28	0.37	1.96	3.22	0.15	753.	723.	0.518	0.148	0.277
HD 9446 b	222.482	9.47	0.26	2.48	4.85	0.19	618.	588.	0.388	0.194	0.275
HD 106252 b	2164.434	24.41	0.15	3.63	9.42	2.61	197.	167.	0.234	0.315	0.271
HD 128311 c	1020.240	17.85	0.18	3.20	7.56	1.76	171.	141.	0.277	0.265	0.271
HD 13931 b	597.524	14.29	0.20	2.93	6.47	5.15	156.	126.	0.313	0.235	0.271
mu Ara e	576.547	14.08	0.21	2.91	6.40	5.24	154.	124.	0.315	0.232	0.270
HD 70642 b	635.664	14.66	0.20	2.96	6.59	3.30	157.	127.	0.308	0.237	0.270
HD 74156 c	2552.189	26.14	0.14	3.74	9.88	3.85	201.	171.	0.225	0.321	0.269
HD 187123 c	632.485	14.63	0.20	2.96	6.58	4.89	155.	125.	0.309	0.233	0.268
HD 62509 b	921.712	17.11	0.18	3.15	7.34	1.69	500.	470.	0.284	0.254	0.268
HD 38529 c	5625.623	36.31	0.12	4.27	12.45	3.69	234.	204.	0.187	0.379	0.266