RESEARCH ARTICLE

An Examination of Habitability in Exoplanet Systems

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ABSTRACT: By reviewing what is known and describing future research directions, this paper explores the qualities that make a planet habitable and the environment it may create. We consider two planetary systems — TRAPPIST-1 and Kepler-62 — and develop a metric to rank the likelihood of habitability on their respective planets. Our guideline for habitability includes the capability of sustaining liquid water, reasonable environmental conditions, and the presence of molecules known to sustain life. Previous research has determined specific values and rankings within each system for planet density, obliquity, effective temperature (T_{eff}) of the planet, equilibrium temperature (T_{eq}) of the planet, and semimajor axes (among others) that increase the likelihood of habitability. After compiling these system properties from the literature, we rank the planets in each system based on their expected probability of habitability. The two systems are compared to demonstrate how different environments might affect habitability. The rankings, system comparisons, and other information lead us to conclude that Kepler-62 f and TRAPPIST-1 e are likely the most habitable planet in each system. We compare these planets to each other and individually to Earth. We conclude by placing these findings into the broader context of exoplanet discovery and discussing future constraints on planetary habitability.

KEYWORDS: Physics and Astronomy, Astronomy, Planetary Systems, Exoplanets, Habitability, Kepler-62, TRAPPIST-1.

Introduction

Currently, there are over 5,000 known exoplanets, and more continue to be discovered.[1] In a grander sense, little is known about them; however, this does not mean the absence of information entirely. While we cannot physically go to these planets, we can collect critical data through various methods and compile them to form conclusions about individual systems and/or planets. These planets can be broadly categorized as falling into one of four categories: high-mass gas giants, sub-Neptunes, super-Earths, and terrestrial planets.[2] They are all located in a relatively small region of the Milky Way that surrounds Earth.[1] Being hundreds or thousands of light years away, there are two main ways of finding exoplanets: transit and radial velocity.[3] The transit method uses the light a planet blocks as it goes in front of its star to detect an exoplanet. The radial velocity method observes a slight change in the color of a star when it wobbles slightly due to an exoplanet hinting toward an orbiting planet. Collectively, the transit and radial velocity methods (along with other complementary measurements) are used to deduce the key properties of planetary systems.

This paper explores how various properties of a planet and its system come together to produce a unique environment. Through the data available, we study individual parameters and their implications for habitability, focusing on one parameter at a time for simplicity before considering each planet's properties as a whole. Our primary comparison point is the Earth, the only planet on which life has been confirmed to date. In other words, we use the life we know of as a baseline to identify the possibility of life elsewhere.

Habitability is not clearly defined by one decisive set of qualities, as we base it solely on life as we know it on Earth and do not know of the other forms in which it might manifest. This paper considers a planet most likely to be habitable if it has a solid surface, is capable of hosting liquid water, has no sign of abnormal climate conditions, and has a protective atmosphere.[3] Evidence related to these requirements can be collected through measurements of a variety of qualities such as planet density, semimajor axis, formation history, obliquity, etc., that have a cumulative impact on the planet. We acknowledge that some shortcomings are inherent to this definition of habitability, discussed later in this work, along with possible pathways to more robustly evaluate our candidates' likelihood of habitability.

This work demonstrates that Kepler-62 f and TRAPPIST-1 e are the most likely habitable planets in their respective systems. We first discuss the reasoning behind choosing the Kepler-62 and TRAPPIST-1 systems to focus on. We then define each of the parameters used to rank the planets. After providing a ranking, we analyze the results and determine each system's most likely habitable planet. Then, we compare (1) the properties of the two systems, (2) the most likely habitable planets to each other, and (3) each potentially habitable planet with Earth.

Lastly, we outline our conclusions' broader implications for habitability and discuss future research.

Materials and Methods

How systems were selected:

As a general guideline, certain qualities were considered when looking for systems to study. We favored systems with at least 4-5 rocky planets, at least 1-2 planets in the habitable zone (area in the system in which liquid water can exist), and relatively well-characterized properties from existing data/research. We differentiate between the optimistic and conservative habitable zone when possible and use these characterizations to aid in considering habitability.[9] Most quantitative data on planet properties were taken from the NASA Exoplanet Archive. We ultimately selected two promising systems, outlined below.

Overview of TRAPPIST-1:

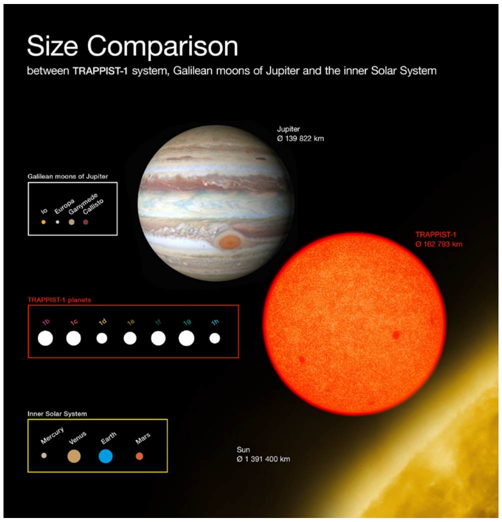

Figure 1: Visualization of the size of TRAPPIST-1's planets and host star alongside our Sun, the inner solar system, Jupiter, and its moons. European Southern Observatory. (2017). Comparison of the sizes of the Trappist-1 planets with Solar System bodies. European Southern Observatory. Retrieved July 1, 2022, from https://www.eso.org/public/images/eso1706d/.

TRAPPIST-1 was selected due to its extensive set of promising terrestrial planets, which have cooler than our Sun, at 0.1192 R⊙ and 2566K.[5] Figure 1 contains a scaled depiction of TRAPPIST-1 and our Sun; evidently, our sun is much larger, and TRAPPIST-1 is more comparable in size to Jupiter. While this difference from the Sun might make TRAPPIST-1 initially seem, unlike the solar system, all seven planets orbit much closer to TRAPPIST-1, at a distance of 0.0619 au at most.[5] This places a total of 2 planets in the optimistic, conservative, and/or tidal habitable zones (TRAPPIST-1 d & e) and another in the optimistic and tidal habitable zones. The system is predicted to be slightly younger (TRAPPIST-1 f).[6] The inner six planets are also believed to be rocky based on planet density.[7] Figure 1 demonstrates that the TRAPPIST-1 planets are all near the size of the planets in our inner solar system. In a more general sense, the system's parameters (other than star size and temperature) are similar to or near Earth's. These include planet density—that is, the system consists of a large number of small, rocky planets— and the expected temperature of the planets. The combination of promising qualities (parameters that are promising for studying habitability) and a system relatively similar to our own solar system distinguished TRAPPIST-1 from other planetary systems. As mentioned before, the TRAPPIST-1 system has extensive research on it in the form of data, analysis, and predictions. As a well-studied system with desired qualities, TRAPPIST-1 was ideal for the ranking and analysis conducted within this paper.

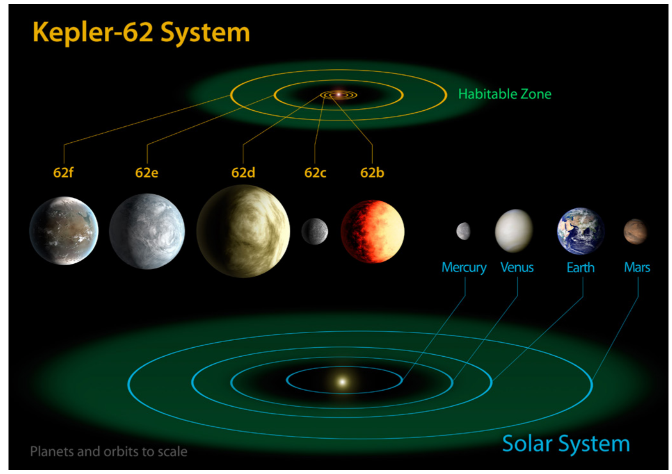

Figure 2: Size comparison of individual Kepler-62 planets to our solar system's planets. NASA Ames/JPL-Caltech. (2013). Kepler-62 and the Solar System. NASA. NASA. Retrieved July 1, 2022, from https://www.nasa.gov/content/kepler-62-and-the-solar-system.

Overview of Kepler-62:

Similarly, Kepler-62 possesses qualities that make it optimal to study for potential habitability. Kepler-62 is smaller and cooler than our sun at 0.73 R⊙ and 4842K.[8] The system has five planets, each orbiting at 0.05-0.718 au.[8] Figure 2 shows a scaled comparison of all five planets to the planets in our own inner solar system. One of the planets is in the optimistic habitable zone (Kepler-62 e), while a second is in the conservative habitable zone (Kepler-62 f).[9] While the other planets within this system have high temperatures, Kepler-62 e & f are more temperate. These two planets provide a chance for more in-depth study and have potential in terms of habitability. Overall, the Kepler-62 system is well-studied, with rare constraints on planetary obliquities and potential atmospheric properties. Overall, the qualities of the Kepler-62 system make it optimal for this paper.

Parameters used in rankings:

It is vital to understand the reason behind each category used to rank and evaluate these planets, along with the impact they can have on habitability. The categories used are equilibrium temperature (T_{eq}) of the planet, orbital semimajor axis (which we use as a proxy for the distance from the host star), planet density, and obliquity. Unless otherwise stated, rankings for each category were made in direct comparison with Earth, and a higher ranking denoted greater similarity with Earth's properties. The motivation behind our inclusion of each of these properties is as follows:

- T_{eq}: As per the definition of habitability used in this paper, T_{eq} is essential to knowing whether liquid water can exist on the planet. If the planet cannot sustain liquid water, it will likely be unable to maintain or create an environment full of life. Water, a versatile and key molecule for different cellular reactions, is needed to enable cell growth and the existence of life on Earth more broadly.
- Semimajor axis: The distance of a planet from its star is directly related to its temperature. Previously determined habitable zones for each system were compared with the semimajor axis of each planet, measured in astronomical units

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(au; distance from the Sun to the Earth). If a planet was not in the conservative or optimistic habitable zone, it was determined that it could not support liquid water.

- Planet density: Planet density, derived from planetary radius (R_p) and mass (M_p), determines the planet's gravitational pull. A planet's density is directly related to its expected ability to retain an atmosphere, and it is crucial to characterize whether a planet is rocky or gaseous. Because it is assumed that a rocky planet is best for habitability, density and its implications were considered during the analysis, as stated in referenced papers.
- Obliquity: Data on obliquity (degree of tilt to a planet) was used as another way to predict environmental conditions. The obliquity of the Earth is known to partially drive the long-term climate variations of the planet, producing different seasons in the northern and southern hemispheres. An obliquity close to 0° or one that is unusually high can cause adverse wind patterns and highly varying temperatures throughout a planet of interest.

Results and Discussion

The results of our rankings are provided in Table 1 (Kepler-62) and Table 2 (TRAPPIST-1), together with all properties used in this study for reference. Rankings are provided from top to bottom (top: most similar to Earth; bottom: least similar to Earth).

Table 1: Overview of Kepler- 62 properties, in order of most favorable for each parameter. T_{eq} and semimajor axis, planet radius, and mass (radius and mass values were used to calculate planet density) were obtained from https://exoplanetarchive.ipac.caltech.edu/overview/Kepler- 62. Obliquity rankings were obtained from https://doi.org/10.1017/s1743921415007832.

Kepler-62			
T_{eq}(K) [Earth: 255 K]	Semimajor axis Conservative: 0.48-0.85 au Optimistic: 0.36-0.92 au [Habitable zones specific to this system]	Planet density (g/cm^3) [Earth: 5.51 g/cm^3]	Obliquity (°) [Earth: ≈23.4°]
e: 270±15	f: 0.718±0.007	f: 5.5±2.02	f
f: 208±11	e: 0.427±0.004	b: 5.2±3.83	e
d: 510±28	d: 0.120±0.001	e: 6.0±0.78	b, c, & d
c: 578±31	c: 0.09±0.009	d: 4.1±0.60	
b: 750±41	b: 0.05±0.0005	c: unconstrained	

Table 2: Overview of TRAPPIST-1 properties, in order of most favorable for each parameter. We exclude obliquity from our parameter list in this table because this parameter has not been measured for the TRAPPIST-1 planets. T_{eq}, semimajor axis, and planet density were obtained from https://exoplanetarchive.ipac.caltech.edu/overview/TRAPPIST-1. Semimajor axis rankings were decided with predictions made in https://doi·org/10.1093/mnras/stx2980.

TRAPPIST-1		
T_{eq}(K) [Earth: 255 K]	Semimajor axis [Earth: 1.000 au]	Planet density (g/cm^3) [Earth: 5.51 g/cm^3]
e: 251.3±4.9	e: 0.02925±0.00250	c: $5.464^{+0.221}_{-0.237}$
f: 219±4.2	f: 0.03849±0.00033	b: $5.442^{+0.265}_{-0.276}$
d: 288±5.6	d: 0.02227±0.00019	g: $5.06^{+0.14}_{-0.16}$
g: 198.6±3.8	c: 0.01580±0.00013	f: $5.02^{+0.14}_{-0.16}$
h: 173±4	g: 0.04683±0.00040	e: $4.90^{+0.17}_{-0.18}$
c: 341.9±6.6	b: 0.01154±0.00010	d: $4.37^{+0.15}_{-0.17}$
b: 400.1±7.7	h: 0.06189±0.00053	h: $4.16^{+0.33}_{-0.30}$

Discussion of rankings:

Kepler-62:

Rankings listed in Table 1 suggest that Kepler-62 f and Kepler-62 e are most likely habitable since they are the two highest ranked for all individual parameters. In all parameters, Kepler-62 f is ranked above Kepler-62 e, aside from the Teq(K). Kepler-62 f has a Teq of 208 K, which is lower than the 255 K of Earth and 270 K of Kepler-62 e.[8] Kepler-62 e & f are predicted to have less evolving obliquity (degree of tilt) through time relative to the other planets in the Kepler-62 system.[10]

However, Kepler-62 e is predicted to have reached pseudo-synchronization, where the frequency of the planet's spin and orbital velocity at its closest approach ("periastron") are very close or the same.[11] This would mean that the planet only shows one face to its host star for the majority of the time. This would cut off an entire half of the planet from sunlight and create a hostile environment for the side facing away. The side facing the sun would be extremely warm, while the side facing away would be extremely cold.

Kepler-62 e is also predicted to have a slower rotation period in comparison to Kepler-62 f.[12] This may have contributed to an unusual and varying environment across the planet, with no longitudinal circulation. Kepler-62 f has an obliquity close to Earth's, along with a more rapid rotation period (20-40 hours) based on model predictions.[12] This may produce similar wind patterns to those on Earth due to a similar heating pattern for Kepler-62 f. By these criteria, we conclude that Kepler-62 f is the most likely habitable planet in the Kepler-62 system.

TRAPPIST-1:

Rankings for the TRAPPIST system in Table 2 show that TRAPPIST-1 e and TRAPPIST-1 f are the most similar to Earth in terms of T_{eq} and semimajor axis rankings based on model predictions.[13] We also know that the outer planets (beyond TRAPPIST-1 d) have lower ion escape rates ($<10^{27}$ s $^{-1}$) that would have helped them to retain their atmospheres if the planets formed further out and migrated closer to the TRAPPIST-1 star as the system evolved.[14] So, TRAPPIST-1 e, f, g, & h are most likely to have retained their atmospheres. TRAPPIST-1 b and c are likely completely dry due to X-ray and UV irradiation. At the same time, TRAPPIST-1 d is predicted to be hot and dry, with minimal water in limited regions.[15] On the other end of the scale, TRAPPIST-1 g and h are too cold (T_{eq} is too low) to be likely habitable. The estimated masses of the planets indicate that the six inner planets are probably rocky.[7]

Furthermore, we use tidal parameters to examine a planet's properties further. The tidal parameter describes how resilient a planet is to distortion by tidal interactions. For instance, the Earth experiences a change in rotation rate due to our moon's tidal tug.[13] Any gravitational force exerted on a planet often plays some role in determining its climate and rotation, an effect that the tidal parameter measures. Simulations show that when Q', the tidal parameter, is equal to 100, TRAPPIST-1 e & f are in the conservative habitable zone. However, when Q'=103, TRAPPIST-1 e was the only planet in the conservative habitable zone.[13]

Considering the tidal parameter, T_{eq}, predicted atmospheres, and likely formation history, we determine that TRAPPIST-1 e is the most likely habitable planet in the system.

Comparison between systems:

To further examine the most likely habitable planets from each system, we will compare the systems as a whole and their host stars. The findings from these comparisons will be considered when comparing the most likely habitable planets themselves. This comparison broadens our understanding of each system and, most likely habitable planet.

Host star comparison:

The two host stars must also be compared to understand their influence on their companion planets. TRAPPIST-1 has an effective temperature of 2566 K, a stellar mass of 0.0898 $M_\odot$, and a stellar radius of 0.1192 $R_\odot$.[5] Kepler-62, at 4842 K, has a stellar mass of 0.79 $M_\odot$, and a stellar radius of 0.73 $R_\odot$.[8] For reference, our sun has an effective temperature of 5778 K. These parameters classify Kepler-62 as a K-type main sequence star and TRAPPIST-1 as an M-type main sequence star. While the two host stars and our sun are different, both of their most likely habitable planets lie within their respective liquid-water habitable zones. Furthermore, our analysis focuses on the incident thermal radiation that reaches the planet rather than just the planet's distance from the host star. Therefore, the size and temperature differences in host stars do not strongly affect our analysis beyond what has already been included in this study.

Non-thermal radiation from the host star:

The TRAPPIST-1 planets do, however, receive intense X-ray and extreme ultraviolet (EUV) radiation from the star. An analysis of this radiation demonstrates that the inner three planets would receive tens to thousands of times more radiation than present-day Earth.[15] As a result, TRAPPIST-1 b and c are predicted to be completely dry from radiation, while TRAPPIST-1 d, e, and f each have a chance of retaining some of their initial water.[15] Kepler-62 does not emit analogous high-energy radiation in problematic amounts.

Atmospheric properties:

TRAPPIST-1 has an age of ~3-8 Gyr, while Kepler-62 has an age of 7 Gyr.[7,9] This has implications for each system's formation history and atmosphere (discussed in the next section). The Kepler-62 planets are expected to have varying obliquities, yet none are considerably higher than Earth's. This allows us to predict that the planet's wind patterns and temperatures are not extreme. The obliquities of the TRAPPIST-1 planets are not yet well-constrained. TRAPPIST-1 b and c have been observed to have clouds and/or hazes; however, it is unknown what they are composed of.[16]

Expected formation mechanism:

The formation history of TRAPPIST-1 has been particularly well-studied. The TRAPPIST-1 planets likely formed further from the star, then migrated inwards to their current orbits.[13] More specifically, simulations revealed that the inner two planets must have migrated separately from the others to allow the present-day system to exist.[13] The formation history of Kepler-62 has not yet been well-constrained.

Comparison of the most likely habitable planet from each system:

We concluded from the data we have that the planets predicted to be most similar to Earth in each system are Kepler-62 f and TRAPPIST-1 e.

Similarities between planets:

Kepler-62 f and TRAPPIST-1 e have some similarities, despite being from different solar systems. Both are in their systems' conservative habitable zones and are the only planets in their respective systems within this zone. They are predicted to most likely have atmospheres capable of maintaining agreeable temperatures and weather. Lastly, the planets have similar eccentricities. Kepler-62 f is consistent with an e=0, circular orbit for 267 days.[17] TRAPPIST-1 e has an eccentricity of <0.085.[7] Since these eccentricities are close to zero and close to each other, both planets likely experience minimal net heating variations over their orbits.

Differences between planets:

Kepler-62 f and TRAPPIST-1 e do, however, differ in their temperatures and sizes. Kepler-62 f is 208 K, while TRAPPIST-1 e is 251.3 K. TRAPPIST-1 e is also slightly smaller than Kepler-62 f at 0.92 $R_\oplus$, while Kepler-62 f is 1.41 $R_\oplus$.[17]

Kepler-62 f comparison with earth:

In comparison with Earth, Kepler-62 f has a cooler temperature at 208 K, while Earth has an equilibrium temperature of 255 K. The planet also has an obliquity close to Earth's, meaning it will experience seasonal effects.[12] Its predicted rapid rotation period (20-40 hrs.) means stronger wind patterns.[12] This is a positive sign for its habitability, confirming that the planet may have Earth-like weather.

TRAPPIST-1 e comparison with earth:

TRAPPIST-1 e is very close to Earth in temperature, at 251K compared to Earth's 255K. It has a planet density of 0.80±0.76 ρ_{Earth}[7]. While not an exact match, these parameters are all similar to Earth's. Models predict that TRAPPIST-1 e has been able to retain an atmosphere throughout time.[14] This is due to the low ion escape rate that prevents a loss of atmosphere. While TRAPPIST-1 e and Earth are similar in that they have atmospheres, the details of TRAPPIST-1 e's atmosphere are unknown and may not be comparable to Earth's.

Conclusions

Broader implications for habitability:

The Kepler-62 and TRAPPIST-1 planets are among the most promising for habitability compared to the 5,000+ confirmed exoplanets discovered. However, the scope is much larger than this. These confirmed exoplanets are relatively close to Earth and large enough to be detected by our technology. Even with various methods being used to find exoplanets, some limitations render us incapable of finding smaller, more distant planets. To summarize, the planets studied in this paper are the ones that are the most realistic ones known today to do further study on and are most likely habitable in comparison to other exoplanets that have been found.

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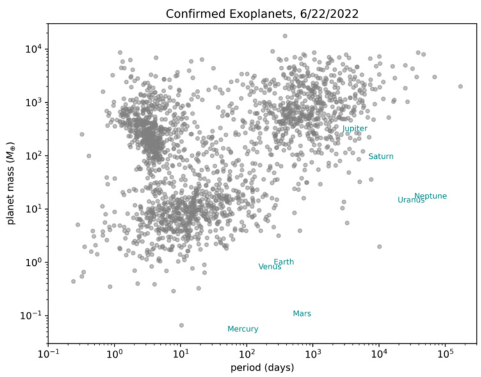

Figure 3: Distribution of all confirmed exoplanets and planets in our solar system, plotted with an x-axis of the period (days) and a y-axis of planet mass ($M_\oplus$). Rice, M. (2022, June 22). Confirmed Exoplanets, Retrieved June 22, 2022, from https://exoplanetarchive.ipac.caltech.edu/docs/acknowledge.html.

It is essential to keep in mind that, thus far, very few exoplanets have resembled any of the planets in our solar system, as Figure 3 displays. Figure 3 shows that the currently confirmed exoplanets are not similar to the inner solar system in terms of orbital period and planet mass. In fact, Figure 3 shows that not one exoplanet is plotted near Mercury, Venus, Earth, Mars, Uranus, or Neptune, and very few are plotted near Saturn and Jupiter. Despite having discovered more than 5,000 exoplanets, we can infer that we are not yet capable of discovering planets precisely like our inner solar system's and that there is more work to do in the field of exoplanet discovery.[1] It is essential to keep this in mind as a disclaimer when considering the findings and conclusions discussed in this paper.

Moreover, it is not feasible to consider a direct mission to any of these planets, as they are all light-years away. The TRAPPIST-1 system, which is about 40 light years from Earth[18], can be characterized in much greater detail with JWST and other upcoming space missions. However, the Kepler-62 system is relatively dim and is located about 1,200 light-years from Earth, making it substantially more challenging to characterize in comparison with the TRAPPIST-1 system.[19]

Specific molecules and biosignatures would help in verifying the habitability of a planet.

PH3, or phosphine, is produced only by anaerobic organisms on Earth (ex., bacteria, and microbes) and is thought to be difficult to form in the absence of life.[20] CH4, or methane, is produced by anaerobic organisms as a waste product.[20] CH3Cl, or methyl chloride, is a gas whose primary sources are oceanic algae, tropical/subtropical plants, certain aquatic and terrestrial planets, and the decay of organic matter.[20] The presence of these biosignatures, along with others, would provide convincing evidence pointing to some form of life or organism living on the planet. On the other hand, properties (beyond those mentioned in this paper) that make a planet highly inhabitable would also be useful to rule out the potential for habitability.

Final Takeaways:

This paper analyzes the available data to conclude that TRAPPIST-1 e and Kepler-62 f are the most likely habitable planets within their respective systems. Our findings are reached through an individual study of the planets of each system, comparisons with Earth, and an analysis of the environment within which each planet resides. We discuss how our findings fit into the demographics of exoplanets found thus far; the limitations of currently confirmed exoplanets; plans of characterization and observation for the TRAPPIST-1 system; and possible biosignatures that would be of use in future research.

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