Probing Life with Planet Searching and Habitat Evaluation: Evidence from Moon, Mars and WASP-96b

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Abstract: Contemporarily, evaluation for the habitability of planet remain an extreme challenging task though plenty of advanced techniques have been proposed and implemented in astrophysics observation. So far, more than 4 thousand extra-planets have been observed while only about less than 10 planets show similar habitat like earth in terms of the state-of-art measurement tools, indicating the possibility for existence of life. With this in mind, this study will systematically discuss and analyse the probing life process with the demonstration of planet searching (the five common methods) and habitat evaluation based on sampling as well as spectrum analysis. To be specific, three most investigated celestials are selected as typical examples to discuss the probing life results, i.e., Moon, Mars and WASP-96b. According to the analysis, the current collected results will be evaluated and the limitations for the current methods will be discussed. These results will offer a guideline for further exploration regarding to life probing in universe.

1 INTRODUCTION

The probing life in planets remains a tough issue even under the rapid developments of astrophysics observation techniques (Cockell, 2020). Among various challenges, two tasks are identified as the first rank issues that need to be addressed, i.e., nonluminous celestial searching and habitat evaluation for the celestials. As for nonluminous celestial searching, different from stars that emits light, they can only be detected based on indirect measures or relevant direct events. Typically, there are more than 5 methods to achieve the goal including transit, radial velocity based on Doppler effects, gravitational lensing, etc. (Rice, 2014). With regard to habitat evaluations, it can only be inferred from the orbits information or emission spectrum for most of planets, which offers the elements distributions and possible atmosphere (Kaltenegger, 2017; Seager, 2014). For some nearby celestials, it is available to collects some soils or shadow images to retrieve more details information, e.g., the Moon (Glavin et al., 2010) and Mars (Joseph et al., 2019).

In recent years, exoplanets have been the fastest growing discipline in astronomy. More than 700 confirmed and more than 3,000 unconfirmed planets have been found using five further developed precision observation methods. Their universality and diversity not only challenge the classical planetary origin models, but also provide clues for new conceptual theories. In addition, one can look at the atmospheres, the densities, the elliptical shapes of some of the planets. The key conclusions include that planets begin with nuclear accretion, that many planets undergo large scale migrations, that habitable planets are common, that water-filled planets exist, and that planetary systems generally evolve dynamically. In the near future, observations and theoretical developments in this area will continue to advance rapidly, uncovering the secrets of the origin of life.

In the 21st century, the astronomical community has taken exoplanet detection, habitable planets and life signal search as a major strategic goal (The Project Team of Research on Development Strategies 2021-2035, 2023; National Academies of Sciences, Engineering, and Medicine, 2021).

The discipline of exoplanets is a new subject which has developed rapidly in the several decades. The study of exoplanets is important for answering questions such as whether there is other life in the universe and the place and significance of human beings in the universe (Zhou et al. 2024).

Under the circumstances of the novel discoveries for new planet or updated information of the celestials

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based on various state-of-art facilities, it is necessary to present a comprehensive analysis for the searching methodology and judgement criteria for evidence of habitability. On this basis, the planet searching methodology as well as habitat evaluation methodology will be discussed and introduced. Subsequently, probing life for three specific celestials will be discussed (i.e., Moon, Mars and WASP-96b), which are also the most investigated one nowadays. Based on the analysis, the current limitations and further developed techniques will be discussed.

2 PLANET SEARCH METHODOLOGY

The main methods of exoplanet detection at present including apparent velocity, transit, microlensing, direct imaging, astrometry, etc. With the rapid developments of data retrieving and system analysis techniques. Machine learning techniques are also applied to cross validation the search results and help to filer data, The crystallization of science and technology development. Exoplanet detection involves optics/red. Outer astronomy, space science and space technology, the development of this discipline will be straight. Connected to push space ultra high precision photometry technology, high sensitivity of weak spectral signal, detection technology, high-performance imaging detection technology, ultra-high contrast imaging technology, ultra-high precision astrometry technology, space light interferometry technology, satellite, attitude control technology and satellite formation flight technology have made new progress breakthrough (Santos, 2008; Zhou et al. 2024). Detecting Earth 2.0, discovering a second solar system, extraterrestrial life

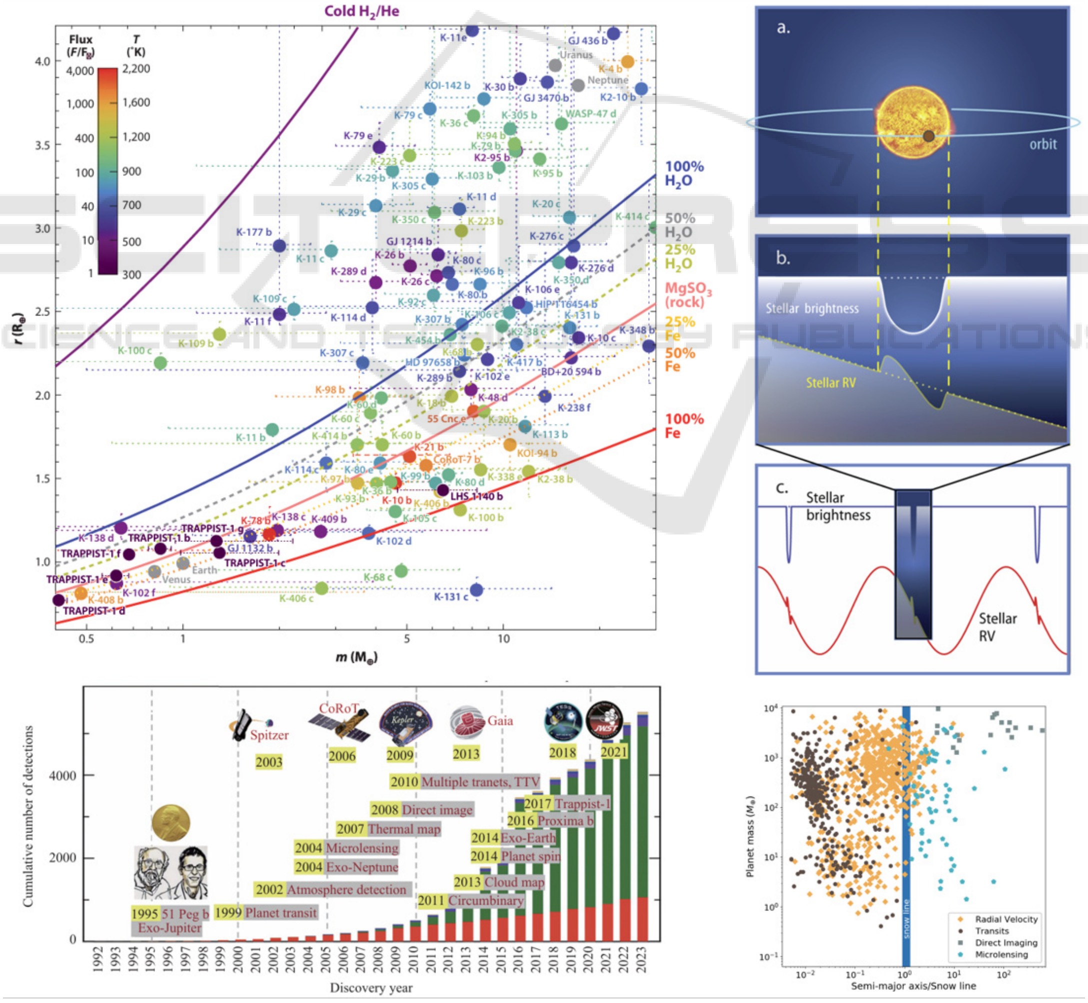

Figure 1: Footprint, progress and cross validation of different planet searching schemes (results are combination of Zhou et al. 2024; Kaltenegger 2017; Howard 2013 and Tsapras 2018).

and more Exocivilizations are all breakthroughs from zero to one in the progress of human civilization as well as making major breakthroughs in astronomy, it also promoted geology and planetary science, astrochemistry, astrobiology, and atmospheric science. The intersection of these disciplines to astronomy and related sciences as well as the development and breakthrough in the field of science and technology has acted as a catalyst.

To be specific, there are at least 7 methods to realize planet searching and the relevant milestones as well as principles for the methodology are presented in Fig. 1. Astrometry, the earliest method used to search for exoplanets, focuses on precisely measuring the motion of a star to determine where planets are being dragged by its gravity. The advantage of astrometry is that it can calculate planetary masses with relatively high accuracy, and it is particularly sensitive to planets with large orbits. However, this method requires very high accuracy, requiring years or even decades of observation to confirm the results. HD176051b, discovered in October 2010, is the only confirmed astrometric exoplanet to date (Ginski et al., 2012). Hopes are pinned on the European Space Agency's Gaia space astrometry project, which launched in December 2013. Not long ago, the project released its second batch of scientific data. Gaia has determined the brightness, spectral signature, three-dimensional position and motion of more than a billion stars and created the most accurate three-dimensional map of the Milky Way to date. Researchers estimate that the new astrometry is expected to help them find tens of thousands of new exoplanets.

Direct imaging is another common method, which works like taking spectra of exoplanets based on the facilities directly and analysis the typical peak. Nevertheless, it requires the planet satisfying certain size that it is not so close to its parent star that it is obscured by its light, and requires a high observer. Not only are they equipped with advanced photography equipment, but they also have powerful coronagrameters, which can effectively block out the dazzling light of their parent stars and ensure clear images. Due to the difficulty of direct imaging, only 40 exoplanets have been found by this method so far.

Unlike direct imaging methods, most exoplanets are found through indirect methods. The radial velocity method is a widely adopted indirect method in terms of Doppler effect, which was used for the first extrasolar planet, 51b Pegasi (Wang and Peng, 2015). The planets also exert a pull on the star as they orbit it, and the spectrum of light emitted by the star is shifted red and blue accordingly, from which the radial velocity of the star can be obtained. Thousands of exoplanets have been discovered based on advanced astronomical equipment such as the HARPS and the HIRES. There is a well-known empirical formula for RV method (Lovis and Fischer, 2010):

$$RV = \frac{28.4ms^{-1}}{\sqrt{1-e^2}}\frac{m_d sini}{M_J}\left(\frac{m_s}{M_s}\right)^{-\frac{2}{3}}\left(\frac{P}{1yr}\right)^{-\frac{1}{3}} \tag{1}$$

Here, RV is the measure value, e corresponds to the value of eccentricity, P is the cycling period, i is the inclination angle, m_s, M_s, M_J and m_d corresponds to the mass of system, solar, Jupiter and measure celestial, respectively.

Another method is transit, in which an exoplanet passes between its parent star and Earth, blocking some of the light from the star, causing a slight decrease in the brightness of the star one observes. The detection of such slight variations in light can be used to predict the presence of exoplanets. On account of the rare feature for transits, as many stars as possible must be monitored in order to find as many exoplanets as possible. Kepler space telescope since the launch in March 2009, the search for exoplanets harvest, so far human found nearly 3800 exoplanets, 70% is found by it, it is called "planet hunter" reputation (Howard, 2013). Although Tess also uses the transit method to search for exoplanets, its search strategy is different from its predecessors. Unlike Kepler, which monitors a small patch of the sky for years on end, Tess will be in "survey" mode, surveying almost 90 percent of the entire sky for two years, focusing on the solar system neighbours.

In addition to the above methods, there are some other approaches including gravitational microlensing (Tsapras, 2018), pulsar counter, special relativity method (Wolszczan, 2012). For the gravitational microlensing method, when a star moves in front of a background star observed from the Earth, the light emitted by the star will be refracted and amplified by the gravitational action as if it were passing through the lens, and a light curve will be generated. If the star had planets, it would have a second-order light curve. Thus, once a second-order light curve is found, the existence of a planet can be proved. This approach is most likely to be fruitful when looking at stars between the Earth and the galactic centre, which can provide many background stars. For the pulsar timing method, it is particularly suitable for finding planets moving around pulsars. Pulsars are extremely dense remnants of supernova explosions that emit intense pulses of radiation as they spin at high speeds. The first confirmed planets were found using this method (the two planets of pulsar PSR1257+12). The special relativity method is a new method that uses Einstein's special theory of relativity to guide the discovery of exoplanets. Changes in the star's brightness as a result of the planet's motion, I,e,m the latter's gravitational pull triggers relativistic effects that cause the photons that make up light to "pile up" which helps the discovery of the Kepler-76b.

3 PLANET HABITAT EVALUATION METHODOLOGY

At present, the detection and research of exoplanets are very active, forming a development trend of finding exoplanets, accurate characterization of planetary systems (mass, orbital parameters, atmospheric composition, etc.), discovery of habitable planets and characterization of habitable planets. A large quantity of space and ground telescope projects have been planned and carried out around this idea of exoplanet discipline development, and some important progress has been made in observation and theory (Madhusudhan, et al., 2020).

The habitability of a planet can be measured in a number of ways, but typical indicators are as follows. ESI stands for Earth Similarity index and is an index that measures how similar other planets are to the Earth, ranging from 0 to 1, with the Earth's own similarity index represented by 1. The Earth Similarity Index is designed for planets, but can also be used for large natural satellites and other celestial bodies (Schulze-Makuch, et al., 2011). The Earth similarity index can be calculated by plugging in the planetary radius, density, detachment velocity and surface temperature. Some typical results for ESI metric are presented in Fig. 2. SPH is an index of suitability for vegetation growth, ranges from 0 to 1 and depends on surface temperature and relative humidity. HZD indicates how far a planet is from the centre of the star's Habitable zone. Values range from -1 to 1. A value of -1 indicates the innermost part of the habitable zone, while a value of 1 indicates the outermost part of the habitable zone. It depends on the brightness and temperature of the star, and of course on the radius of the planet's orbit. HZC denotes the amount of planetary composition. A value close to 0 means the planet is likely to be iron-stone-water, a value below -1 means it's likely to be mostly iron, and a value above 1 means it's likely to be gas. HZC depends on the mass and radius of the planet. HZA is used to measure and assess the potential of a planet to have a Habitable Atmosphere. A value below -1 indicates a thin or almost no atmosphere, a value above 1 indicates a very likely thick hydrogen atmosphere (like a gas giant planet), and a value between -1 and 1 indicates an atmosphere potentially suitable for life. Whereas, it's important to note that 0 doesn't mean the ideal atmosphere for life. HZA depends on the mass of the planet, the radius, the orbit size and the brightness of the star (Méndez, et al., 2021).

The most common and power tools to analyse the habitat with maximum likelihood is spectrum estimations. However, the intensity is much smaller for planet compared to stars. Hence, the transit schemes should be considered to collect the spectrum signals of the planet. In fact, researchers need to find some kind of quick assessment score that they can use as a metric to list promising planets, to determine which of the billions of celestial bodies out there are more suitable. The habitability of exoplanets is a challenging problem. At present, researchers have proposed new classification schemes (machine learning) for the existing habitability indicators and exoplanets. Currently, astronomers can use computational intelligence techniques to assess habitability scores and automate the exoplanet classification process. They investigated how solving convex optimization techniques can cross-validate ML-based exoplanet classification. Examples include computing new metrics, e.g., the CDHS and CEESA. Despite recent criticism of exoplanet habitability rankings, human beings are convinced that the field must continue to evolve to use all available astroinformatics, artificial intelligence (AI), and machine learning mechanisms (Safonova et al., 2021).

Indeed, the most direct method to estimate the planet habitat is sending detectors as close as possible to the orbits or even collecting the sample (gas, soil, elements, etc.) directly. Nevertheless, in consideration of the distances, the scenarios are tough to fulfil. In the subsequent sections, three cases will be discussed, where two of them (i.e., Moon and Mars) are feasible to achieve the goal to direct analysis.

4 SPECIFIC CASES ANALYSIS

4.1 Moon

As a matter of fact, Moon is a satellite instead of planet, whereas it is the closest celestial for human beings. On this basis, the searching life schemes of

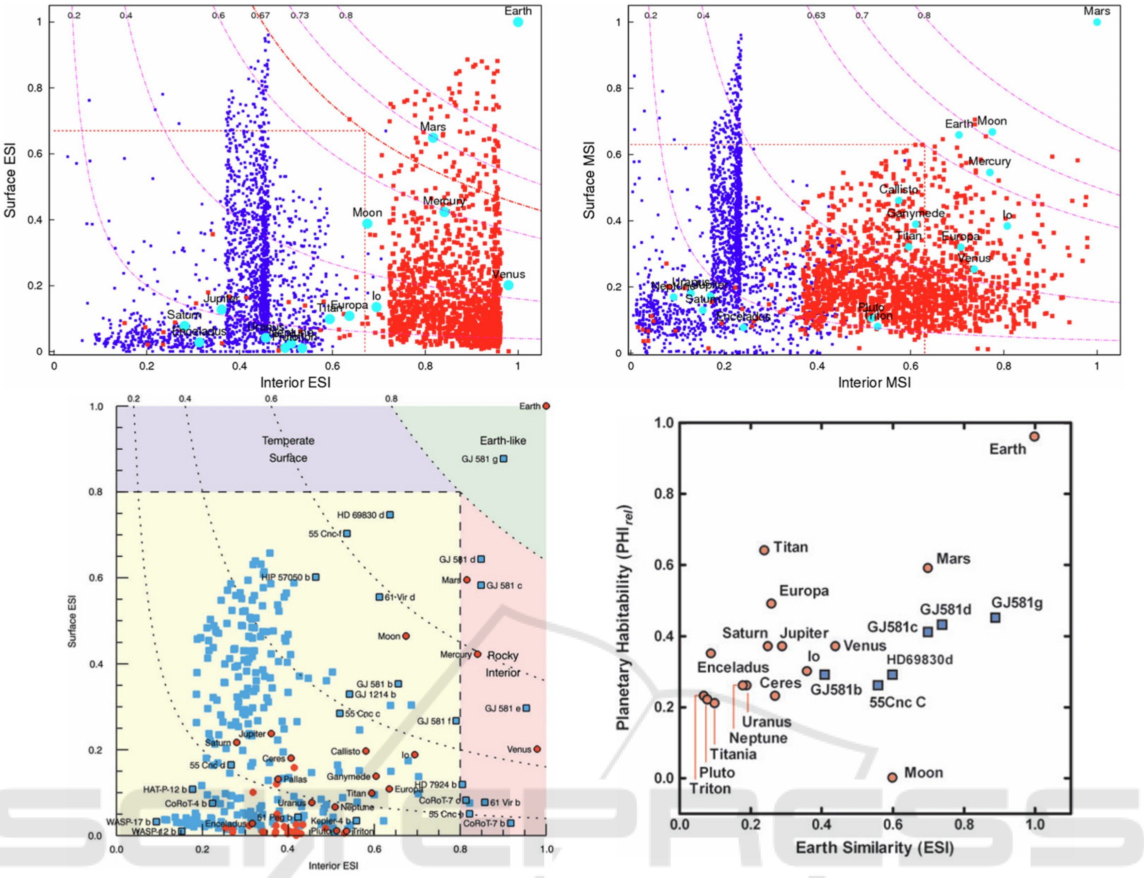

Figure 2: Typical examples of ESI metric and habitability (Data collected from: (Madhusudhan, et al., 2020; Safonova et al., 2021 and Schulze-Makuch, et al., 2011).

Moon could offer insights for probing life for others. If one wants to explore the solar system, it has to open the door of the moon. For the moon, which is as large as a whole continent, man has left only a few steps on it. As Earth's closest planetary neighbour, the moon holds great potential as a new source of scientific progress and economic growth. In fact, NASA's Lunar Orbital Reconnaissance Vehicles have been imaging and mapping the moon for more than a decade to conduct scientific research and prepare for humans to land on the moon again. In the future, NASA will deliver its next lunar Exploration robot, the VIPER, which will conduct a scientific investigation of lunar volatiles at the South Pole of the moon. The data generated by VIPER will inform future lunar in situ resource utilization (ISRU) technologies.

In recent years, with China's lunar exploration program, some lunar soil has been brought back (Li, et al., 2022), but the conclusions obtained are the same as satellite observations, and there is no evidence of life on the moon. The reasons are as follows. First, the moon has no atmosphere. Its surface atmospheric pressure is only one billionth of Earth's, and it is almost a vacuum. Due to the lack of atmospheric protection, the lunar surface temperature varies greatly between day and night. The maximum temperature of the lunar surface detected by Apollo 15 at its landing site was 374K and the minimum was 92K. In addition, the lunar surface ultraviolet radiation and other strong, especially during the solar storm, the sun's ultraviolet rays directly into, played a role in eliminating. Second, liquid water has never been found on the moon's surface. Like the Earth, the moon is covered with a layer of loose, granular rock called the lunar regolith. Through the analysis of lunar exploration and lunar samples, there are hydrogen enrichment phenomena in the polar regions of the Moon. The hydrogen enrichment may be caused by hydrogen injected by the solar wind or hydroxyl groups contained in some minerals. It may also be caused by water ice (ice solidified by water or meltwater at low temperature) mixing with the lunar soil in the form of fine particles. Liquid water has not yet been found on the moon. Finally, lunar soils lack elements that are currently known to be essential for carbon-based life. Scholars have analysed the data obtained by the APXS of the CE3 Yutu lunar rover. Some typical results of elements are illustrated in Fig. 3, which denote that the lunar soil of the landing site mainly includes Si, Ca, Al as well as other 10 elements (Guo, et al., 2022). However, it lacks elements such as C and N, which are essential for life. So overall, the chances of native life on the moon are slim. In other words, the possibility of microbial life on the moon is extremely small.

4.2 Mars

Mars is a great planet to study and a promising candidate for signs of life, and humans have sent several landers and rovers to search for evidence of life. Nevertheless, the planet's barren surface might actually not the appropriate location for observations as well as analysis, since telescopes and probes have proven. Instead, shielded places underground is the best bet for finding well-preserved evidence of alien life. However, the nature of these shields makes detection and detection difficult. Moreover, Mars is full of caves formed by millennia of lava flows, hence the caves are difficult to reach and rovers. To address the issue, NASA worked with collaborators to create a four-legged, four-legged hiking mechanical utility robot, or LEMUR. It will allow it to explore areas that are simply not possible with the rovers currently exploring the surface of Mars (Joseph et al., 2019). Some typical detections results based on such scheme are presented in the left panel of Fig. 4.

In addition to LEMUR, PIXL is also a suite of rovers onboard the Mars 2020 Perseverance rover to search for signs of ancient life. The probe's X-ray Instrument, called PIXL, stands for Planetary Instrument for X-ray Lithochemistry, and it delivered surprisingly strong scientific results during testing. It is used to test the instrument setup and would be capable of determining the composition of Martian dust attached to the matters. In addition to analysing the rock based on the high energy photons, it will zoom in on tiny fragments of the rock's surface that could show evidence of past microbial activity. To obtain a detailed picture of rock texture, contour, and composition, PIXL maps of rock chemistry can be combined with mineral maps produced by the SHERLOC as well as WATSON (Lawson, et al., 2024). A typical detector diagram and detection results are shown on the right panel of Fig. 4.

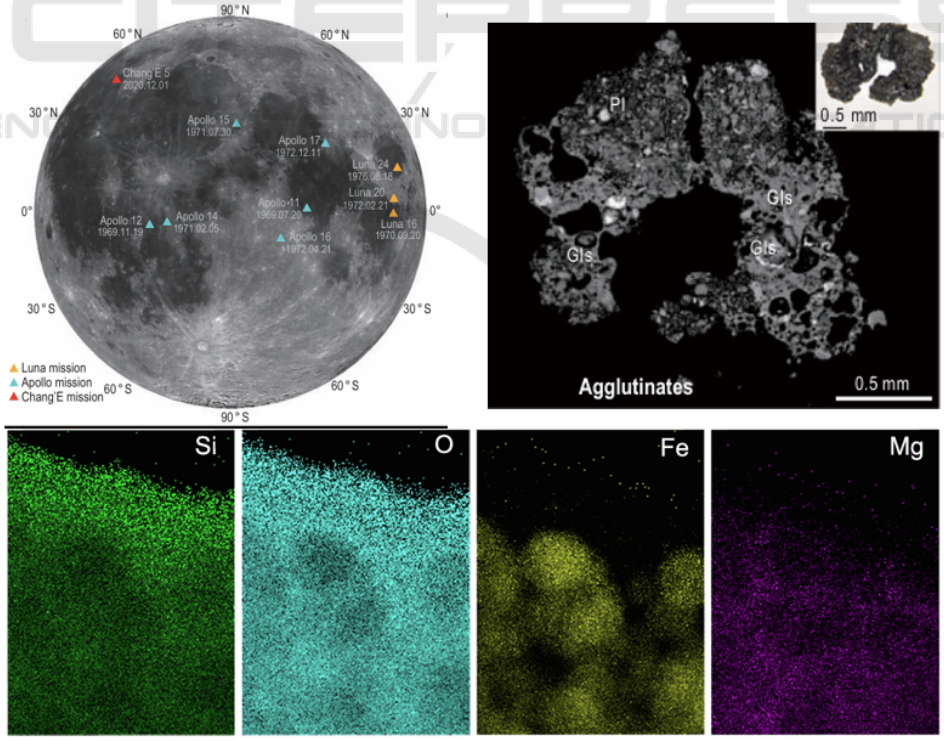

Figure 3: Elements analysis of Moon from the soil sample (data collected from Guo, et al., 2022; Li, et al., 2022).

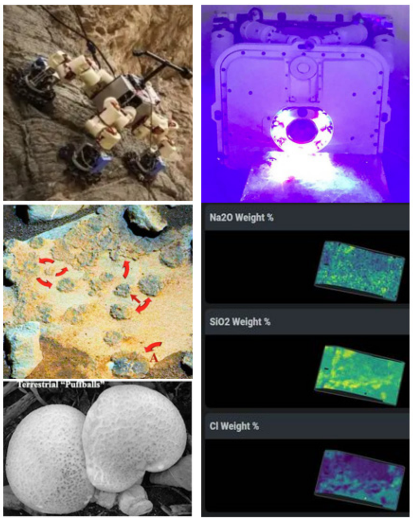

Figure 4: Probing life on Mars based on typical detectors (data collected from Joseph et al., 2019; Lawson, et al., 2024; Mars Nasa and NASA/JPL-Caltech).

4.3 WASP-96b

Hot Saturn WASP-96b is the latest discovery of an exoplanet atmosphere without clouds, marking a major breakthrough in the search for planets beyond our solar system. WASP-96b's atmosphere was studied by Chile using the European 8.2 Million Telescope. As a matter of fact, based on the state-of-art observations for the emission spectrum of WASP-96b, a complete sodium fingerprint is obtained under the special circumstance without clouds with a typical 1300K hot gas giant (McGruder, et al., 2022). Earth's periodic transiting sun-like star is located 980 light-years in the southern constellation Phoenix, between the southern jewels (α Austrini) and αEridani. The presence of sodium of hot gas giant exoplanets has long been predicted to produce a spectrum similar to the shape of a camping tent in such special situation.

As the transit method explained earlier (Sec. 2), when a planet passes in front of a star, blocking some of the light, some of the starlight is transmitted through the planet's atmosphere. Because different components of the atmosphere absorb different spectra, the observation of subtle differences in transmitted light can help astronomers determine the composition of a planet's atmosphere. Being the only completely cloud-free exoplanet discovered so far, and showing such a clear spectrum feature for Na element. So far, sodium has been found to be either a very narrow peak or missing altogether. This is because the characteristic "shape" profile can only be produced deep in a planet's atmosphere, and for most planets, clouds appear to block its direction. A better understanding can be gained by looking at a variety of possible atmospheres similar to WASP-96b (Radica, et al., 2023). The sodium signature indicates the absence of clouds in the atmosphere. It will also provide us with a unique opportunity to determine the abundance of other molecules. Typical observations are shown in Fig. 5.

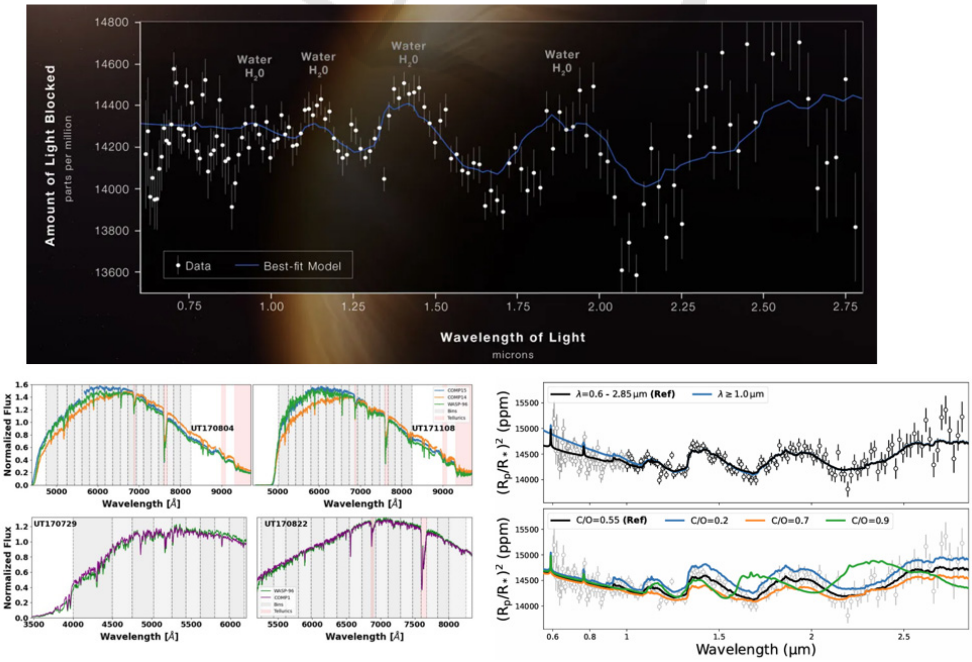

Figure 5: WASP-96b spectrum (data collected from McGruder, et al., 2022; Radica, et al., 2023 and NASA WEBB).

5 DISCUSSION

As a matter of fact, it should be noted that though thousands of new planets have been detected based on advanced techniques and the state-of-art facilities, no strong evidence or sufficient supporting materials confirming the existence of Earth 2.0. Whether human beings are alone in the universe, this is a basic question that almost everyone wants to know the answer to, and it is also one of the most cutting-edge scientific questions that can be solved today. The search for extraterrestrial life will finally answer this question. However, the search for extraterrestrial life must first find the most likely host of life, Earth 2.0. To date, no Earth 2.0 has been discovered. The first discovery of Earth 2.0, and subsequent determination of its habitability through observation of the atmosphere, will be a major scientific event in the field of exoplanets. Finding a number of Earth 2.0's could determine the incidence of such planets, answering the key question of how common Earth 2.0 is in the universe.

Subsequently, one can determine whether there is life beyond Earth. The holy grail of the next exoplanet frontier after the discovery of Earth 2.0 will be the detection of extraterrestrial life, that is, the detection of biosignatures produced by life in the atmospheres of exoplanets to infer the existence of life. This would answer the fundamental scientific question of whether there is other life in the universe. There are two main methods to measure the atmospheric composition of planets in front of the eye: transit transmission spectroscopy and direct imaging. Spectral detection and atmospheric composition analysis of the atmosphere of Earth-like planets or super-Earth planets are expected to directly search for trace gases and compositions released in the atmosphere of planets by extraterrestrial life activities. The direct imaging method has become one of the most important scientific factors driving the development of new generation ground-based and space telescopes (e.g., ELT, TMT, GMT), which puts severe requirements on telescope aperture, adaptive optics and detector performance.

The detection of planetary atmospheres provides a crucial constraint for the formation, evolution and habitability of planets, and is an important means for the detection of planetary habitability and exolife. By 2030 or so, the next generation of space telescopes should have high-precision optical spectrometers capable of detailing the atmospheric composition and abundance of gas giants, and observing other properties. The atmospheric composition and abundance of multiple types of planets accompanying the evolution of stars are described in detail, and the atmospheric circulation and atmospheric escape are studied. Through the accurate measurement of the tracer gas element abundance and isotope abundance, it can be related to the important problems of planetary formation, orbital migration and evolution. Through the atmospheric modelling of small exoplanets (e.g., terrestrial planets and super-Earths), scholars study the transition evolution behaviour from primary atmosphere to secondary atmosphere, and the role of atmospheric escape in the habitability of terrestrial planets. Develop the next generation of large space telescope (>10m) star coronarometer, high-contrast direct imaging spectroscopy and optical interference technology, observe the habitable zone planets of a large number of neighbouring stars, confirm whether they are twin Earth from the planetary reflection spectrum or thermal emission spectrum, determine their habitability and search for potential life signs. In addition, as mentioned above, planetary habitability is an interdisciplinary frontier research topic. Astronomers are particularly concerned about the definition of life signals and the corresponding spectral characteristics, because this is the key to the future search for extraterrestrial life. At present, even the JWST can only detect the spectral characteristics of super-Earths around sun-like stars, which are larger than the Earth. In the future, LUVOIR and HabEx hope to use larger telescopes for direct imaging detection. In order to develop the space interference and imaging observation of exoplanets, mankind will search and characterize the nearby planetary system, expect to obtain the characteristics of the habitable zone terrestrial planets, and combine the research on the long-term activity of stars and the atmospheric model of exoplanets, as well as the development of interdisciplinary definition of life signals, etc., to reveal the habitability of terrestrial planets.

Although international deep space exploration has flourished in the decades since the launch of the Voyager spacecraft, almost all current research on exoplanets is based on passive observation rather than active exploration. Tiny detectors based on ground-based laser arrays or accelerated solar radiation called light sails could change that in the first half of the 21st century. Tiny probes weighing on the order of grams will be able to accelerate to solar escape velocity in a matter of minutes to explore small exoplanets such as' Oumuamua and analyse their activity, shape, and composition. With the further miniaturization of ground-based laser technology and materials science, as well as chips predicted by Moore's law, it will be possible for tiny probes to be accelerated to 10 percent of the speed of light, enabling interstellar travel to reach the solar system's close neighbour, the alpha Cen system, and image its planets up close for the first time.

6 CONCLUSION

To sum up, this study systematically analyses the planet searching schemes as well as habitat evaluation scenarios and indicators. To give specific examples, the life searching results of three celestials are detailly demonstrated and estimated. According to the analysis, though no life signs have been searched so far, it is witnessed that the searching tools have been expanded rapidly with more accurate. Nevertheless, it should be noted that the current advanced probing approaches still has some shortcomings, which are unable to present absolute accurate and direct information. Further study ought to focus on the updating of the precise spectrum detectors and signal extraction as well as collecting direct information and sample based on machine with collectors. Overall, these results offer a guideline for further exploration of Earth 2.0 and exoplanet habitat evaluation.

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