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THE SEARCH FOR HABITABLE PLANETS

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RESUMEN

Uno de los más grandes retos en Astrobiología es entender la distribución de vida en el Universo basándose en sólo un ejemplo: la Tierra. Con el objetivo de abordar esta limitación, diversos catastros observacionales llevados a cabo en las últimas tres decadas han monitoreado ciento de miles de estrellas y han encontrado más de 4900 planetas alrededor de ellas. Si bien aún no se ha identificado un sistema análogo al sistema Tierra-Sol debido a limitaciones técnicas, muchos de los exoplanetas descubiertos se encuentran en la zona habitable de sus estrellas anfitrionas y pueden ser proclives a poseer vida como la conocemos. En esta contribución presento una breve revisión sobre los métodos más exitosos para la detección de exoplanetas, las propiedades planetarias que de éstos se pueden derivar y sobre como estas propiedades pueden ser utilizadas para estimar si un planeta es potencialmente habitable. Tambien presentaré una lista de los mejores candidatos para albergar vida y una discusión sobre las perspectivas de detectar biomarcadores en sus atmósferas usando infraestructuras observacionales en el espacio y en tierra que iniciarán operaciones en el futuro cercano.

ABSTRACT

One of the greatest challenges in Astrobiology is understanding the distribution of life in the Universe based on a single example: Earth. In order to address this limitation, several astronomical surveys monitored hundreds of thousands of stars over the three past decades and found more than 4900 exoplanets around them. Although a perfect Earth-Sun analog system remains elusive due to technical limitations, many of the discovered exoplanets lie within the habitable zones of their host stars and could be suitable for life as we know it. In this contribution, I will briefly review the most successful methods for detecting exoplanets, what planetary properties can be inferred and how these can be used to estimate if the planet is potentially habitable. I will also present a list of the best candidates for hosting life and discuss perspectives for detecting biosignatures in their atmospheres using space and ground-based telescopes that will start operating in the near future.

Key Words: exoplanets — habitability — methods: radial velocity — methods: transit — planets: fundamental parameters

1. INTRODUCTION

Are we alone in the Universe? Despite being one of the oldest and most fascinating open questions in Astronomy and Sciences in general, the search for an answer is hampered by two fundamental limitations. First, the Solar System is the only known example of a planetary system that has a habitable planet in which life as we know it arose and prospered during 3.8 − 4.3 billion years (Dodd et al. 2017). Second, we are still not able to directly detect life in other planets with current technology. Thus, the search for habitable planets and biosignatures (molecules such as water, oxygen, ozone and methane which might provide evidence for the existence of living beings) in their atmospheres are currently our best tools to search for life in the Universe (Deming & Seager 2017; Kaltenegger 2017).

The search for habitable planets is focused on the detection of planets similar to Earth that are located within the habitable zones of their host stars. During the last three decades, several astronomical surveys have been monitoring hundreds of thousands of stars, resulting in the discovery of more than 4900 exoplanets orbiting more than 3600 stars in the Milky Way[2]. Although no twins to the Earth-Sun system were detected so far due to technical limitations of the main exoplanet detection methods (radial velocity and transit), tens to hundreds of potentially habitable planets are already known[3].

The process of discovering exoplanets, determining their properties and then narrowing down from almost 5000 planets to dozens of candidates that can be considered as habitable is very challenging and requires an enormous interdisciplinary effort. In this

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[2]As of 17 January 2022, according to NASA Exoplanet Archive and The Extrasolar Planets Encyclopaedia.

[3]See the Habitable Exoplanets Catalog and NASA Exoplanet Archive.

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contribution, I will provide a brief overview of this process from an astronomical perspective. In Section 2, I will present the radial velocity and transit methods, which are currently the most successful in detecting exoplanets. I will also explain what planetary properties can be inferred from these observations. In Section 3, I will discuss how these properties can be used to determine if the planet is potentially habitable and show some examples of the best candidates for hosting life as we know it as well as the perspectives for detecting biosignatures in their atmospheres. I will present the conclusions in Section 4. The readers should note that this contribution is not intended to be exhaustive and addresses the previous topics on an introductory level since it is tailored to the wider audience that attended the III Congreso Latinoamericano de Astrobiologa (3CLA).

2. DETECTION OF EXOPLANETS

In general terms, exoplanets are planets that orbit stars other than the Sun. There is no widely accepted definition for an exoplanet and astronomers usually adopt the working definition recommended by the International Astronomical Union (IAU) Working Group on Extrasolar Planets (WGESP) in 2003 (Boss et al. 2007). It states that, regardless of how they formed, planets are objects that orbit a star or a stellar remnant and have true masses below the limit for the thermonuclear fusion of deuterium, which corresponds to ∼13 M_J (Jupiter masses) for objects with solar metallicity[4].

Direct observation of exoplanets is a very challenging task since they are obfuscated by the brightness of their host stars. For the Earth-Sun system, for instance, the ratio between the planet and the stellar brightness is 10^{-10} (Perryman 2018). For exoplanets, ratios can be as high as 10^{-5} if observations are performed in the infrared (IR) (Perryman 2018), since planets are brighter in this region of the electromagnetic spectrum than at visible wavelengths. If coronographs are used during observations to block the light from the star, it is possible to obtain direct images of some exoplanets. For a few systems (e.g. HR 8799, β Pic and 51 Eri), several images were taken at different moments, allowing astronomers to actually follow the orbits of the planets around their parent stars[5]. Unfortunately, the technical challenges involved in the direct imaging method are considerable and only a small fraction of exoplanets (∼1%) were discovered by this method so far.

The majority of the known exoplanets were thus detected by a variety of indirect methods, including radial velocity, transit, astrometry and microlensing. In this contribution, the focus will be on the first two, which are the most successful ones to date. Together, they are responsible for more than 95% of current exoplanet discoveries.

2.1. *Radial velocity*

In a given star-planet system, both objects orbit around the center of mass (barycenter). The movement of the star is caused by the gravitational attraction of the planet and has observable effects, thus allowing the presence of the planet to be inferred. As the star moves away from Earth in the radial direction (i.e. in the line of sight of the observer), the spectral lines are shifted towards the red end of the spectrum due to the Doppler effect (see Figure 1). Similarly, the spectral lines are displaced to the blue end of the spectrum when the star is moving towards Earth (see Figure 1). By monitoring the periodic variation of the stellar radial velocity, it is possible to not only detect the exoplanet, but also to estimate a minimum mass for the object. Using the observable quantities radial velocity semi-amplitude (K), orbital period (P) and an estimate for the stellar mass (from an independent analysis), a function can be fitted to the data and the values for the planetary minimum mass ($M_p \sin i$) and orbital eccentricity (e) that best describe the observations can be found. This method only allows to infer a minimum mass because the inclination i of the planetary orbit is unknown in principle.

The radial velocity method yielded the first discovery of an exoplanet orbiting a star similar to the Sun[6]. In 1995, Mayor & Queloz (1995) discovered a planet with a minimum mass of 0.47 M_J orbiting the star 51 Peg with a period of only 4.2 days. Due to its enormous observational (confirming that reliable detection of exoplanets was feasible with the instruments available at the time) and theoretical (since giant planets are not expected to orbit that close to their parent stars) impact on Astronomy, this discovery was awarded the Nobel Prize in Physics in 2019. The radial velocity method remained as the most successful one until 2013 and is currently responsible for the discovery of ∼18% of all known exoplanets (see Figure 2).

[4] In Astronomy, metallicity is the logarithmic abundance of all chemical elements heavier than hydrogen and helium, collectively referred to as "metals", with respect to the solar value.

[5] https://jasonwang.space/orbits.html

[6] The first three confirmed exoplanets were detected around the pulsar PSR B1257+12 (Wolszczan & Frail 1992; Wolszczan 1994).

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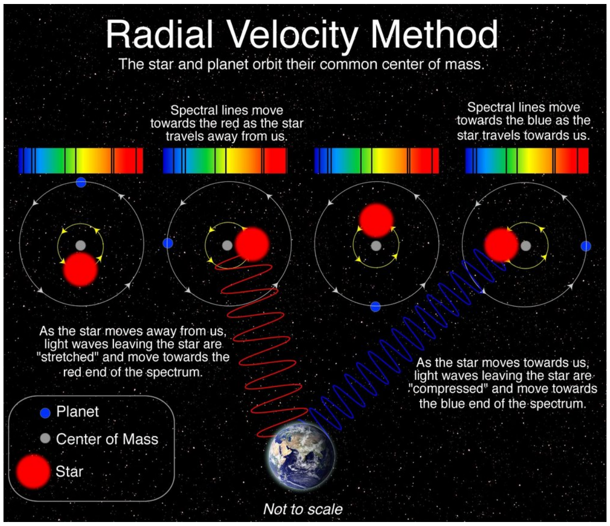

Fig. 1. Schematic representation of the radial velocity method. When the star is moving away from (towards) Earth, the spectral lines are shifted to the red (blue) end of the spectrum, thus allowing the presence of the planet to be inferred. Credit: Las Cumbres Observatory. Available at `https://lco.global/spacebook/exoplanets/radial-velocity-method`.

2.2. *Transit*

The title of most successful exoplanet finder is currently held by the transit method, having contributed with an impressive ∼77% of all discoveries (see Figure 2). Most of them were detected by the Kepler mission (Borucki et al. 2010), which remains as the most prosperous exoplanet survey to date.

As seen from Earth, the planet will temporarily block a fraction of the star's light when it passes in front of it (see top part of Figure 3). This fraction is usually small (a few percent), but by monitoring the stellar brightness, it is possible to measure the temporary periodic dimming caused by the planet (the transit depth) and build a light curve (see bottom part of Figure 3). The transit depth depends on the relative sizes of the planet and the parent star and, if we have previous information about the stellar radius (from an independent analysis), it is possible to determine the planetary radius. For a hypothetical star with a given radius, larger planets will block larger fractions of the stellar light. Similarly, for a hypothetical planet with a given radius, it will cause a greater dimming when passing in front of a smaller star. As this method requires a favorable alignment, it is necessary to monitor thousands of stars in order to obtain a significant number of exoplanet detections. For instance, the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) has been monitoring ∼200,000 stars near the Sun since 2018 and already discovered more than 170 exoplanets[7].

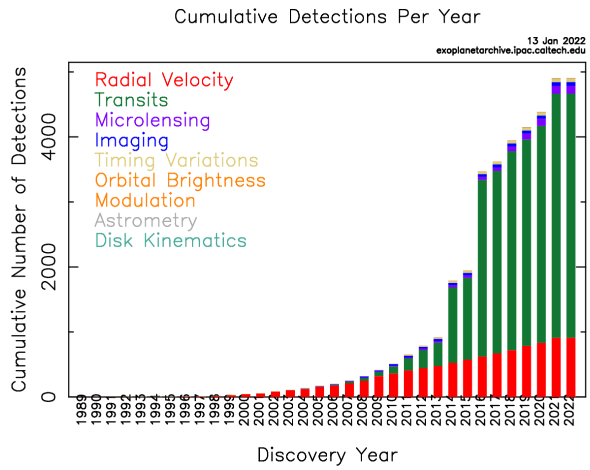

Fig. 2. Cumulative numbers of exoplanets discovered by each method per year. Radial velocity and transit, which are discussed in this contribution, are shown in red and green, respectively. Credit: NASA Exoplanet Archive. Available at `https://exoplanetarchive.ipac.caltech.edu/exoplanetplots`.

3. HABITABLE EXOPLANETS

The ever increasing sample of exoplanets discovered by radial velocity, transit and other methods revealed a diversity of worlds, including some planet classes that do not exist in our Solar System, like Hot Jupiters, Mini-Neptunes and Super-Earths. Although they are fundamental to fully understand the processes involved in planetary formation, the quest for habitable worlds is focused on the search for planets that could support life as we know it. As a key ingredient to life on Earth is liquid water, astronomers look for rocky planets that are located within the habitable zones of their stars.

The habitable zone is a region around a star where liquid water can exist on the surface of a rocky planet (e.g. Kaltenegger 2017). Since its distance depends on the incident stellar flux, cooler and less luminous main-sequence[8] stars will have closer habitable zones, while they will be located farther away for hotter and more luminous main-sequence stars (see Figure 4). Hundreds of exoplanets within the habitable zones of their parent stars are currently known (see NASA Exoplanet Archive). However, it

[7]As of 17 January 2022, according to NASA Exoplanet Archive.

[8]The main sequence is the stage in a star's life in which energy is produced by thermonuclear fusion of hydrogen in the stellar core.

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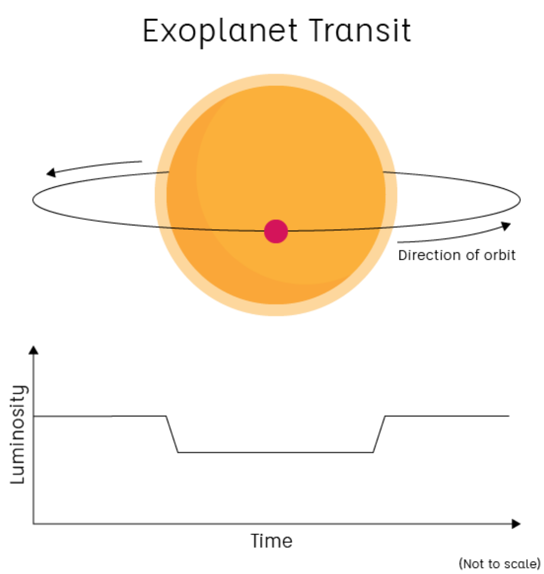

Fig. 3. Schematic representation of the transit method. When the planet passes in front of the star (top), its presence can be inferred by the dimming of the stellar brightness observed in the light curve (bottom). Credit: Las Cumbres Observatory. Available at `https://lco.global/spacebook/exoplanets/transit-method`.

is clear from Figure 5 that most of the known planets located within the habitable zones of stars similar to the Sun (with stellar effective temperatures close to 5777 K) are the size of Neptune or larger, while planets similar to Earth are mainly found within the habitable zones of the cooler M stars. This fact is directly related to the limitations of current detection methods, since it is easier to find Earth-like planets orbiting around M stars, since they are smaller, and more difficult to discover systems similar to Earth-Sun.

The location within the habitable zone is not enough, however, to make a planet habitable. As can be seen in Figure 6, habitability is very complex and is affected by multiple stellar and planetary properties. For instance, planetary masses and radii provide valuable information about the interior structure of the planet, while data about the incident stellar flux is essential to modelling the planetary climate (e.g. Kaltenegger 2017). Using these parameters, the Planetary Habitability Laboratory

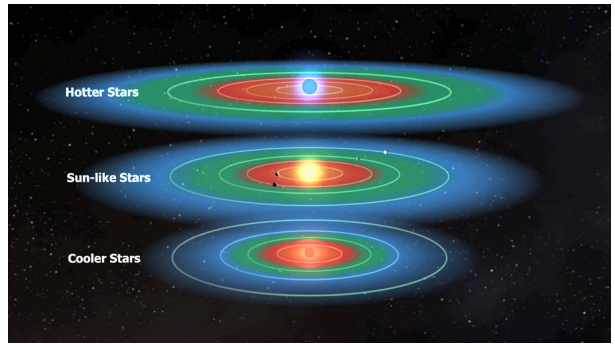

Fig. 4. Habitable zones (green regions) for the Solar System (center) and both hotter and more luminous (top) and cooler and less luminous (bottom) main-sequence stars. Credit: NASA/Kepler Mission/Dana Berry. Available at `https://www.nasa.gov/ames/kepler/habitable-zones-of-different-stars`.

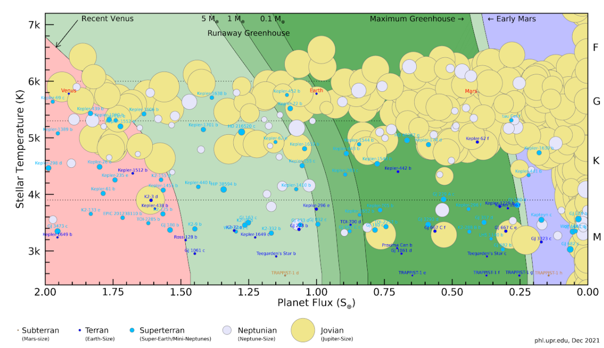

Fig. 5. Planets within the optimistic (light green) and pessimistic (dark green) habitable zones of their host stars. Symbol sizes correspond to the radii of the planets. Solar System planets are labeled in red. Credit: PHL @ UPR Arecibo. Available at `https://phl.upr.edu/projects/habitable-exoplanets-catalog`.

developed an Earth Similarity Index (ESI) which is used to build a list of 59 potentially habitable exoplanets[9] as of January 2022 (see Figure 7). One of the best known examples in this list is Proxima b, which has a minimum mass of 1.17 $M_\oplus$ (Earth masses) (Suárez Mascareño et al. 2020) and is located within the habitable zone of Proxima Centauri (the closest star to the Sun).

Even if a rocky planet is located within the habitable zone and is considered to be habitable, it is still not guaranteed that it will be inhabited. There are currently no methods to directly detect life on exoplanets, but fortunately their atmospheres might contain important clues. During a transit, a small fraction of the stellar radiation is blocked by the

[9] https://phl.upr.edu/projects/habitable-exoplanets-catalog

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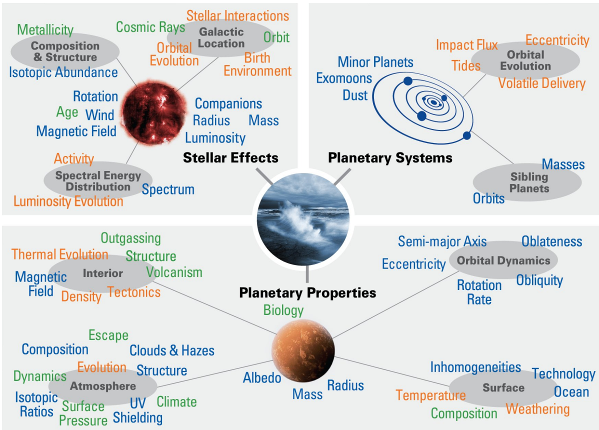

Fig. 6. Diagram showing the complex interplay of all factors affecting the habitability of a planet. Credit: Meadows & Barnes (2018).

planet, but also part of it is transmitted through the planetary atmosphere. Careful analysis of the resulting transmission spectrum might reveal absorption features caused by molecules in the planet's atmosphere such as water, oxygen, ozone and methane, which are associated with life on Earth. Observation of a combination of these biosignatures could be a strong evidence of the existence of life on the studied planet (e.g. Kaltenegger 2017). Important steps in this direction are being taken with the successful launch of the James Webb Space Telescope (JWST) on 25 December 2021, although the detection of some of the most interesting biosignatures will be extremely challenging (Lustig-Yaeger et al. 2019), and the construction of the next generation of extremely large telescopes (ELTs).

4. CONCLUSIONS

In the last three decades, the discovery of almost 5000 exoplanets revealed a wide variety of worlds and led to significant advances in the understanding of the processes involved in planetary formation. Despite all the technical challenges involved, astronomers were already able to identify among them dozens of potentially habitable planets whose atmospheres will be observed and analyzed in unprecedented detail in the next few years, which might result in the first confirmed detection of biosignatures. This is definitely an exciting time for us Astrobiologists in our search for life in the Universe!

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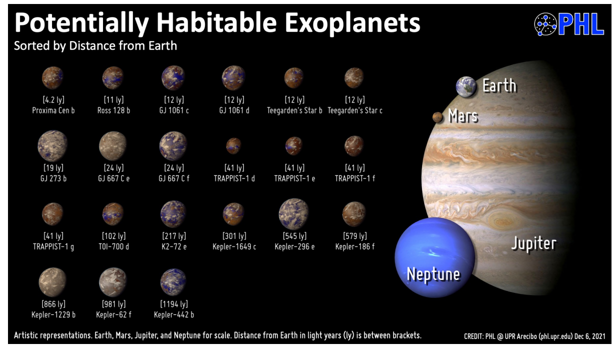

Fig. 7. Some of the 59 potentially habitable exoplanets sorted by increasing distance from Earth. Credit: PHL @ UPR Arecibo. Available at `https://phl.upr.edu/projects/habitable-exoplanets-catalog`.

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