Searching Extra-Planet Based on Radial Velocity, Transit and Direct Imaging

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Abstract: In reality, the extra planet searching has always been one of the ultimate targets for astrophysics and cosmology research. With the extremely rapid development speed of high accuracy searching tools and facilities, human beings have witnessed thousands of extra planets which has been verified by various methods. With this in mind, this study will systematically analyse searching scenarios and choose three typical types among the 7 mostly used types (i.e., radial velocity, transit as well as direct imaging) for further discussions. According to the analysis and based on the evaluations, the basic principles of the different methods as well as the advance facilities and detection results will be demonstrated. The available properties for searching are discussed at the same time. In the meantime, the current limitations for the different schemes will be clarified and the future development trends for better searching will be proposed. To sum up, the analysis presented in this study paves a path for deeper investigation for extra-planet searching.

1 INTRODUCTION

There are billions of galaxies existing in the vast universe, with numerous planets inside each of galaxies. As an unique planet, the Earth is the only planet with life in solar system. This lifts people a question that: whether there are another planet containing life within the complete cosmos, which motivates the beginning of the search for exoplanets. The search for exoplanets has a long history and has evolved over time. When early astronomers like Giordano Bruno appeared in the 16th century, the idea that there might be other worlds in the universe came to people’s view. However, until the end of the 20th century when technology made great advances, people were able to discover distant planets for the first time. In 1995, radial velocity has been reported implemented successfully (Batalha, et al. 2013), which is important and marks a key step for the searching. Models of planet-star evolution and interaction can be improved by searching for exoplanets due to much information provided by them (Borucki, et al. 2010). The search also offers the opportunity to clarify the question of whether there are other living beings in the universe. Discoveries of exoplanets with Earth-like conditions provide compelling materials (Johnson, et al., 2022).

Recently, scholars have come up with many effective methods to detect exoplanets. Therefore, with improvements in observation techniques, significances have been proposed and achieved. In 2009, with the help of NASA's launch of the Kepler Space Telescope, scientists have found thousands of exoplanets using the transit method based on the data obtained in the Kepler mission, helping people to better understand the distribution of planets (Kreidberg, 2018). One of the most notable discoveries made by Kepler is Earth-like planets found in the habitable zones (Macintosh, et al., 2015). Likewise, the radial velocity method is an effective tool for exoplanet identification. Numerous low-mass planets have been found as a result of the improvement in radial velocity measurements with contribution made by instruments like the HARPS spectrograph (Mayor, et al., 1995). The knowledge of planetary system and the range of planetary types that exist has increased with the help of the results. Similarly, the direct imaging method has also made notable advancements. The SPHERE instruments have imaged some massive exoplanets and confirmed their existence, which enables in-depth studies of their atmospheres (Pepe, et al., 2011). These observations have illustrated the physical properties of exoplanets.

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The purpose of this paper is to present a detailed analysis of the three approaches for locating exoplanets: radial velocity, transit and direct imaging. In order to offer a analytically and systematically sumamry of the current state of exoplanet detection research as well as possible directions for future development, this paper examines the guiding principles, detector structures and current results of these methods. The main part of the paper introduces the three exploration methods in detail, including the principle of each method, the structure of the probe and the specific results in recent years. In addition, the limitations of current planetary research and the future prospects of this field are analysed.

2. DESCRIPTIONS OF PLANET SEARCHING

Planet searching involves many aspects to be analyzed and studied, and they provide important information to further analyze the characteristics and potential habitability of newfound planets. The elements to be determined include the planetary properties and the potential habitability of discovered exoplanets. Planetary properties include radius, mass, density and atmospheric composition of a planet. Both radius and mass are measured at the first to further obtain the density and atmospheric composition. For the measurement of the radius, scientists usually use transit method. When a planet transits, it causes dimming of the star's light. By transit, the planet's size relative to the star can be determined. Regarding to the measurement of mass, velocity method is used in most cases.

By knowing the planet's mass and radius, the density of the planet can be calculated using density formula. Besides, the density can also provide the information of an exoplanet's composition. A planet's atmosphere absorbs some starlight as it passes through its star, which can be used to determine the composition of the atmosphere. As for detailed atmospheric condition, missions like the JWST will provide strong support (Pepe, et al., 2020).

The factors to assess whether a planet could support life include the planet's location within the habitable zone, surface temperature, and geological activity. With measurement of the star's luminosity and the planet's distance from the star, whether its location is within the habitable zone can be determined. However, even if a planet's location is determined as the habitable zone, it doesn't mean a guarantee of habitability since it merely indicates the signature of water.

Surface temperature can be affected by several factors including the distance, its atmosphere, and its reflectivity. For those planets with thick atmosphere, closer distance and smaller reflectivity, their surface temperature is greater; and vice versa (Shields, et al., 2016). Geological activity is also very important to maintain a planet's habitability in the long run. It generally includes two main factors: volcanism and plate tectonics. They both contribute to producing and recycling carbon and other elements, which is crucial for climate stability and nutrient distribution.

3 RADIAL VELOCITY

Because of the planet's gravitational pull, a star with planets orbiting it moves in a small orbit, making it impossible for the star to remain stationary. This movement is caused by the Doppler effect, which periodically shifts the star's spectral lines. The star's light spectrum has redshift when it moves away from Earth and blueshift when it moves closer to the planet. This observation forms the basis of the approach. The existence of a planet and details about it, like its mass and orbit, can be determined by measuring those changes in the star's color lines (Ribas, et al., 2018; Smith, et al., 2021).

The velocity change (Δv) can be calculated using the Doppler formula:

$$\Delta v = Ksin(i)\cos\frac{2\pi(t-t_0))}{P} \tag{1}$$

$$K = \left(\frac{2\pi G}{p}\right)^{\frac{1}{3}} \frac{M_p \sin(i)}{(M_* + M_p)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}} \tag{2}$$

where i is the inclination of the orbit, t is the time of observation, t_0 is the time of periastron, and P is the orbital period, G is the gravitational constant, M_p and M_* are the mass of the planet and star, and e is the eccentricity.

Detection using radial velocity measurements basically depends on the spectrograph. There are three important components of the spectrograph. These fibers maintain a steady and uniform light delivery while guiding starlight into the spectrograph. In order to preserve the accuracy required for radial velocity measurements, stabilized optical fibers are used to reduce any possible signal loss or distortion. Accurate measurements of radial velocity require extremely stable wavelength calibration. Reference light sources, such as Th-Ar (thorium-argon) lamps and laser frequency combs, are used to achieve this. To measure the star's spectrum, these calibration systems provide a set of recognized spectrum lines. If any shifts in the star's spectral lines are found, they can be assured that the star's motion is the cause because these calibration sources are stable but not instrumental errors. Spectral light from the spectrograph is detected by sensors called charge-coupled devices (CCDs). The smallest alterations in the star's spectrum can be recorded by these detectors because of their extreme sensitivity to variations in light intensity. Acquiring the necessary precision in radial velocity measurements requires high-quality CCDs with low noise and high resolution.

The radial velocity method has been used in the discovery of various types of exoplanets. The following charts from recent research demonstrate the efficacy of the method and the level of detail analysis it allows:

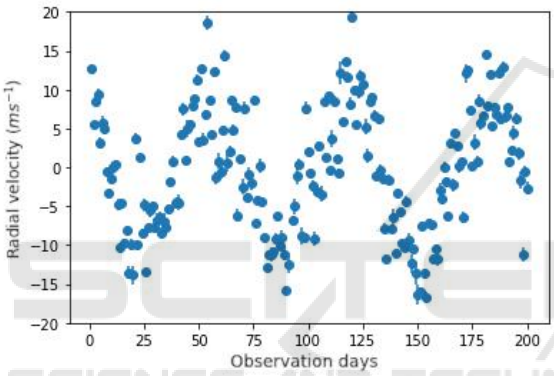

Figure 1: Radial velocity measurements of a star over time (Wang, 2023).

Fig. 1 show the periodic shifts corresponding to the presence of an orbiting planet. The consistent sinusoidal pattern is a clear signature of the planet's gravitational effect on the star. Proxima Centauri b is a significant discovery detecting by using the radial velocity method due to its proximity to Earth and its potential for having life. Fig. 2 gives the results of detecting Proxima Centauri b using the radial velocity method.

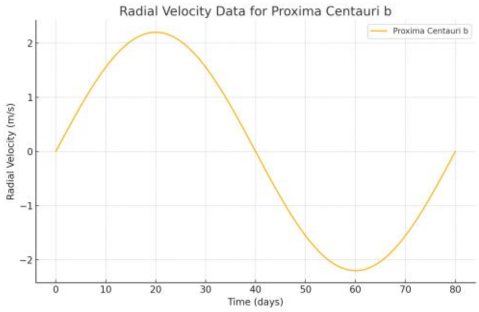

Figure 2: radial velocity data for Proxima Centauri b.

4 IMAGING

Unlike the majority of the current exoplanet detection methods, which are predominately indirect due to the vast distances, imaging offers a visualized manifestation and represents the most straightforward and intuitive way of detecting an exoplanet. This method simply means to capture photons from exoplanets directly, also involving the use of instruments including coronagraphs, adaptive optics (AO), in addition to telescopes. Direct imaging can be employed when a planet is large enough to reflect sufficient light from its host star, combined with its own thermal emission, for detection, and when the separation is sufficiently large for their respective lights to be distinguished (Wright & Gaudi, 2012). The discovery of planet 2M1207 b in July 2004, imaged by the VLT), marked the first detection of an exoplanet using direct imaging. 2M1207 b is a Jupiter-like brown dwarf with a mass five times that of Jupiter's. Extremely low brightness ratio and small angular separations are two big challenges in imaging exoplanets. Therefore, the biggest challenge is the removal of the overwhelming starlight, given the typically minute brightness ratio between planets and stars. Planets are generally much dimmer and smaller than their host stars. The brightness ratio at wavelength λ can be represented as:

$$\frac{f_{\alpha}(\alpha,\lambda)}{f_{*}(\lambda)} = p(\lambda)\left(\frac{R_p}{\alpha}\right)^2 g(\alpha) \tag{3}$$

where $p(\lambda)$ is the geometric albedo, and $g(\alpha)$ is the phase function of the planet (Dai et al., 2021). For example, it means stars can sometimes be billions of times brighter than the planets (Li et al., 2021). One approach to remove the overwhelming glare of the star is to use coronagraph, which simply means to insert a device in the telescope that blocks the starlight from reaching the detector, while also removing the diffraction pattern (Fischer et al., 2015). Some typcal results are shown in Fig. 3 (ESO Figures, 2018; NASA, 2019).

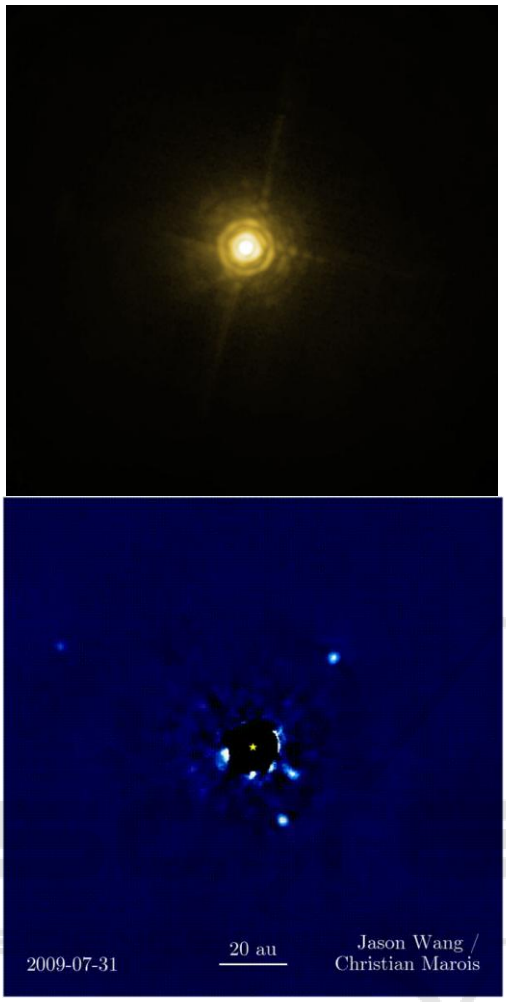

Figure 3: The frame of the system around HR 8799. The left image represents the original frame of system HR 8799. The right one is the image after removing the dazzling light of HR 8799, which shows the existence of 4 planets (ESO Figures, 2018; NASA, 2019).

The principle of coronagraph can be described in Fig. 4 (Galicher & Mazoyer, 2023). The phase and amplitude of the incoming wavefront can be modified by a pupil apodizer in plane A to optimize the shape of diffraction. Plane A and plane B make sure that most of the on-axis source light is blocked, and the remaining part of light is mostly blocked by plane C. Whereas, most of the off-axis light reaches the final imaging plane almost without being altered (Galicher & Mazoyer, 2023). This could also be achieved by utilizing external occulters (Levine and Soummer, 2009). According to Rayleigh Criterion, the limit of resolution (or diffraction limit), is defined as $\theta_{\min} = 1.22\lambda/D$. However, the resolution calculated by this equation is not achieved in reality due to optical imperfections, which can scatter the light. Under the effect of these imperfections, space-based telescope or AO (it uses deformable mirror (DM) to correct. As a result, although with the help of various techniques, detecting exoplanets by direct imaging remains difficult due to factors above, as well as small angular separations, vast distances, and other factors.

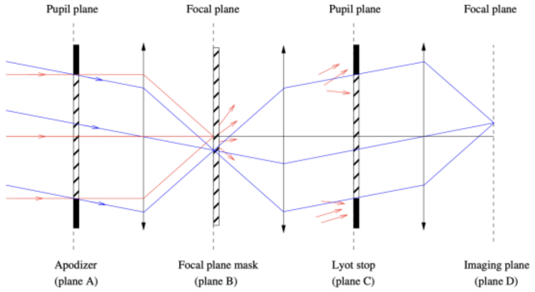

Figure 4: Schematic optical design of a stellar coronagraph (Galicher & Mazoyer, 2023).

5 TRANSIT

For a star and its planet that are aligned at a specific angle, when the planet is in the position between its host star and the earth, some starlight would be blocked, leading to periodic dips in the brightness curve. The period is the time interval between 2 transits. Larger planets would result in deeper dips. The width of the dips indicates the transit duration. As shown in Fig. 5, one can see different depths and widths in brightness curves for different planets. The presence of multiple planets would form more complex geometrical patterns in the brightness curve. For example, likely, there would be a bulge on the curve when different planets overlap. Moreover, once it causes a signal that we can detect, more information can be obtained utilizing spectroscopy through studying the molecular absorption features. This method can be used when the impact parameter b is less than 1, which allows transit to occur.

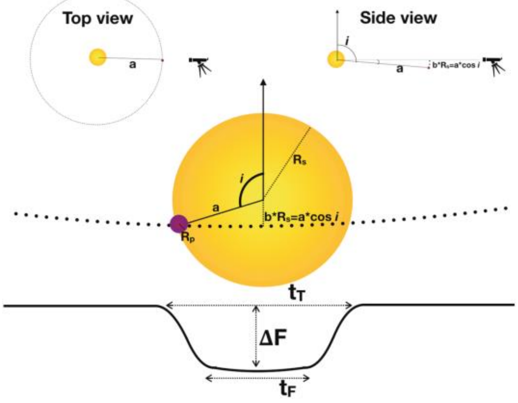

Figure 5: A sketch of the transit.

Supposing the spherical shape of the star and the planet, the uniform brightness over the star, and the negligible flux from the planet. The radius of the planet could be derived from the brightness curve. This could be represented as:

$$\frac{\Delta \mathrm{F}}{\mathrm{F}} \approx \left(\frac{\mathrm{R_p}}{\mathrm{R_s}}\right)^2 = \mathrm{k}^2 z \tag{4}$$

where △F is the change while F represents for the total stellar flux, and k the brightness ratio (Deeg & Alonso, 2018). R_p and R_s are the radius of the planet and the star respectively. Thus, one derives key value b:

$$\mathrm{b} = \frac{a\cos \mathrm{i}}{\mathrm{R_s}} = \sqrt{\left\{\frac{(1-\mathrm{k})^2-\left[\sin^2\left(\mathrm{t_F}\frac{\pi}{P}\right)/\sin^2\left(\mathrm{t_T}\frac{\pi}{P}\right)\right](1+\mathrm{k})^2}{\cos^2\left(\mathrm{t_F}\frac{\pi}{P}\right)/\cos^2\left(\mathrm{t_T}\frac{\pi}{P}\right)}\right\}} \tag{5}$$

In this equation, a is the semi-major axis of the orbit, i the orbital inclination, and P the orbital period. $\mathrm{t_F}$ and $\mathrm{t_T}$ are the full transit duration and the total transit duration, respectively. For the planet to be in front of the star, the sky-projected distance (perpendicular to the line of sight) of the planet higher (or lower) than the center of the star should be smaller than the radius of the star, which means b should be less than 1. Thus, the ratio between the semi-major axis and the radius can be derived (Deeg & Alonso, 2018):

$$\frac{a}{R_s} = \left[\frac{(1+\mathrm{k})^2-\mathrm{b}^2\cos^2(\mathrm{t_T}\pi/\mathrm{P})}{\sin^2(\mathrm{t_T}\pi/\mathrm{P})}\right]^{1/2} \tag{6}$$

This ratio would be used in the calculation of the mass and density of the star. As a matter of fact, one has

$$M_s = \frac{4\pi^2 a^3}{\mathrm{P^2 G}} \tag{7}$$

Thus:

$$\rho_s = \left(\frac{a}{\mathrm{R}}\right)^3 \frac{3\pi}{\mathrm{P^2 G}} \tag{8}$$

The path of the planet can be approximately considered as a horizontal straight line; t_T, the total transit duration, is the time between the moment the planetary disc touches the stellar disc for the first time and the moment the planetary disc loses contact with it. It could be expressed as:

$$t_T \approx \frac{2R_s\sqrt{1-b^2}+2R_p}{2\pi a/P} \tag{9}$$

The total distance travelled in this time includes two parts: the distance travelled over the stellar disc (this could be represented as $2\sqrt{\mathrm{R_s}^2-\mathrm{b}^2\mathrm{R_s}^2}$) and the planet's own diameter it travelled; t_i and t_e , the ingress duration and egress duration, is the time period, the brightness curve going down, and on opposite case and situation, the brightness curve going up, respectively. The ingress and egress duration are the same and can be represented as:

$$t_i = t_e \approx \frac{2R_p}{2\pi a/P} \tag{10}$$

Here, t_F, defined as the full transit duration, is the the time between the two moments when the planetary disc is tangent to the stellar disc when it's inside of the stellar disc, the time when the brightness curve is roughly horizontal. However, the brightness curve drawn using the actual data observed is not the same as what we assumed. The bottom part is concave up rather than being flat.

This this because the brightness over the stellar disc is not uniform due to the effect of limb darkening, which refers to the phenomenon that the center of a star tends to be brighter than its limb. This is caused by stars′ structure of multiple layers. For example, the sun includes three layers, which are corona, chromosphere, and photosphere from outside to inside. When we observe the limb of the sun, we only see the outermost layer, while when we observe the center, the see all the way down to the deepest interior of the sun with the highest temperature and the lightest emitted. Thus, the rate at which the brightness decreases (or increases) tend to be higher when the planet approaches the center of the stellar disc, and the brightness curve is at its lowest when the planet is at the center because it blocks the area that is most luminous. There are also other factors that can affect the shape of the brightness curve.

The transit probability is:

$$P_{tra} \equiv \left(\frac{R_s \pm R_p}{a}\right)\frac{1+e\sin\omega}{1-e^2} \tag{11}$$

For this equation, ω is the argument frequency of the stellar orbit. It's typically easier to detect exoplanets with transit method than the other. For example, through transit method, we can get much more strong signals that suggest the existence of a planet than using direct imaging can, due to the fact that the size ratio is typically much bigger than their brightness ratio. However, the probability for transit to occur is low.

6 LIMITATIONS AND PROSPECTS

As a matter of fact, the rate of exoplanet discovery has shown a distinct increase in recent years, notably attributed to the contributions of the Kepler mission and TESS employing the transit method. So far, more than 3000 exoplanets have been confirmed. However, current exoplanet detection methods are still largely reliant on the inherent properties of the planets themselves. Discovered planets tend to exhibit characteristics such as larger size, greater brightness, greater orbital distance, and higher mass, resulting in stronger signals. Consequently, most exoplanets remain undetected. For instance, employing the transit method may only yield a one in two hundred success rate for discovery, indicating that most exoplanets go unnoticed. This would also probably lead to biased outcomes in our understanding of planetary systems. For example, most exoplanets discovered are gas giant, super-earths, or Neptune-like planets, whereas terrestrial planets (or rocky plants) like the earth only occupy a small fraction. However, it doesn’t necessarily mean there are more of them and fewer terrestrial planets.

For direct imaging, the range where we can detect exoplanets is limited since we are not able to capture photons from places that are to distant from us currently. Secondly, although we can use coronagraphic instruments to block out the starlight, certain separation between the planets and the stars and enough size of the planets are still required for the light to be distinguished. As shown in Fig. 6, most exoplanets discovered through transit method are relatively larger. Moreover, AO is necessary for distinguishing exoplanets from stars, limiting our study (Lee, 2018). The problem associated with transit method is the relative low probability for transit to happen. Plus, high photometric accuracy is required to detect the slight decrease in the total stellar flux. Space-based telescopes are advantages for this as they eliminate the effect of atmospheric seeing but at the same time, being high-cost. Furthermore, exoplanets discovered through transit method tend to have shorter period. Illustrated in Fig. 5, discovery of exoplanets through this method is the densest at where the separation is smaller (which means shorter period). Besides these methods, the other methods also have their own drawbacks.

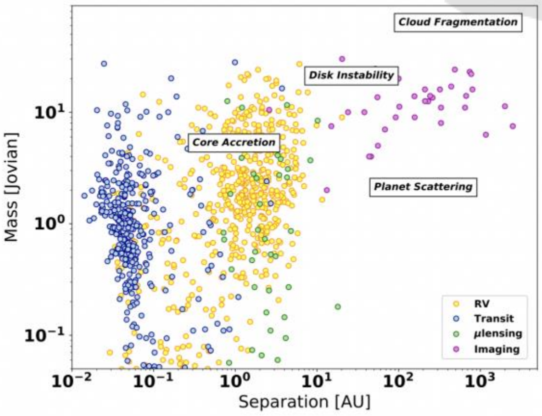

Figure 6: Mass as a function of Separation in terms of NASA data (Lee, 2018).

However, although under the limitations associated with the present detection methods, the new frontier indicates a positive prospect of future planetary studies. For direct imaging, new AOs are on the arrival. These include comprehensive exoplanet surveys (GPIES10) conducted by the GPI. New techniques include the PIAA Coronagraph, which will be able to deliver high contrast. For transit method, the Kepler is now transforming into K2 mission, TESS3 and PLATO4 mission. The radial velocity method is especially having major development.

7 CONCLUSIONS

To sum up, this study discusses how to search exoplanets based on three methods: radial velocity, direct imaging, and transit. Their basic principles, also including the structure of apparatus and mathematical expressions to obtain the properties of exoplanets, are explained in this paper. This also includes research history, significance, and results of exoplanet exploration, as well as the limitations and prospects of exoplanet exploration. With the emergence of new techniques and emissions, the improvement of varies detection methods, and the accelerating development of exoplanet exploration are expected.

AUTHOR CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

REFERENCES

Batalha, N. M., Rowe, J. F., Bryson, S. T., et al. 2013. *Planetary candidates observed by Kepler. III. Analysis of the first 16 months of data.* The Astrophysical Journal Supplement Series, 204(2), 24.

Borucki, W. J., Koch, D., Basri, G., et al. 2010. *Kepler planet-detection mission: Introduction and first results.* Science, 327(5968), 977-980.

Dai, Z., Ni, D., Pan, L., Zhu, Y. 2021. *Five methods of exoplanet detection*. In Journal of Physics: Conference Series, 2012(1), 012135.

Deeg, H. J., Alonso, R. 2018. *Transit photometry as an exoplanet discov ery method*. arxiv preprint arxiv:1803.07867.\

ESO Figures. 2018. Retrieved from: https://www.eso.org/public/images/eso1002e/

Fischer, D. A., Howard, A. W., Laughlin, G. P., et al. 2015. *Exoplanet detection techniques.* arxiv preprint arxiv:1505.06869.

Galicher, R., Mazoyer, J. 2023. I*maging exoplanets with coronagraphic instruments*. Comptes Rendus. Physique, 24(S2), 1-45.

Johnson, J. A., Brown, T. M. 2022. *The formation and evolution of planetary systems.* Annual Review of Astronomy and Astrophysics, 60, 133-161.

Kreidberg, L. 2018. *Exoplanet atmosphere measurements from transmission spectroscopy and other planet star combined light observations*. Handbook of Exoplanets, 2291-2322.

Lee, C. H. 2018. *Exoplanets: past, present, and future.* Galaxies, 6(2), 51.

Levine, M., Soummer, R. 2009. *Overview of technologies for direct optical imaging of exoplanets*. Astro2010 technology development white paper call, 11.

Li, Z., Hildebrandt, S. R., Kane, S. R., et al. 2021. *Direct imaging of exoplanets beyond the radial velocity limit: Application to the hd 134987 system*. The Astronomical Journal, 162(1), 9.

Macintosh, B., Graham, J. R., Barman, T., et al., 2015. *Discovery and spectroscopy of the young Jovian planet 51 Eri b with the Gemini Planet Imager*. Science, 350(6256), 64-67.

Mayor, M., Queloz, D. 1995. *A Jupiter-mass companion to a solar-type star*. Nature, 378(6555), 355-359.

NASA. Direct Imaging. 2019. Retrieved from: https://science.nasa.gov/mission/roman-space-telescope/direct-imaging/

Pepe, F., Mayor, M., Queloz, D., et al. 2011. *The HARPS search for Earth-like planets in the habitable zone*. Astronomy & Astrophysics, 534, A58.

Pepe, F. A., Cristiani, S., Rebolo Lopez, R., et al. 2020. *ESPRESSO: The Echelle spectrograph for rocky exoplanets and stable spectroscopic observations*. Proceedings of SPIE, 7735, 77350F.

Ribas, I., Tuomi, M., Reiners, A., et al. 2018. *A candidate super-Earth planet orbiting near the snow line of Barnard's star*. Nature, 563(7731), 365-368.

Shields, A. L., Ballard, S., Johnson, J. A. 2016. *The effect of host star spectral energy distribution and ice-albedo feedback on the climate of extrasolar planets*. Astrobiology, 16(6), 443-464.

Smith, A., Johnson, B., Lee, C. 2021. *Exoplanet detection techniques and their efficiency*. Astronomical Journal, 162(3), 75.

Wang, M., Hu, Y., Zhang, J. 2023. *ExoplANNET: A deep learning algorithm to detect and identify planetary signals in radial velocity data*. Simulation data, 18.

Wright, J. T., Gaudi, B. S. 2012. E*xoplanet detection methods*. arxiv preprint arxiv:1210.2471.