The Search for Another Earth

Sujan Sengupta

Is there life anywhere else in the vast cosmos? Are there planets similar to the Earth? For centuries, these questions baffled curious minds. Either a positive or negative answer, if found one day, would carry a deep philosophical significance for our very existence in the universe. Although the search for extra-terrestrial intelligence was initiated decades ago, a systematic scientific and global quest towards achieving a convincing answer began in 1995 with the discovery of the first confirmed planet orbiting around the solar-type star 51 Pegasi. Since then, astronomers have discovered many exoplanets using two main techniques, radial velocity and transit measurements. In the first part of this article, we shall describe the different astronomical methods through which the extrasolar planets of various kinds are discovered. In the second part of the article we shall discuss the various kinds of exoplanets, in particular about the habitable planets discovered till date and the present status of our search for a habitable planet similar to the Earth.

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Introduction

Why do we need to search for another Earth? Why "The World is not enough"? It is an eternal curiosity of mankind to know "Is anybody out there?" Is there life elsewhere outside the Earth? Or are we alone in the vast arena of the cosmos? As soon as Aristotles concept of a geocentric world was abandoned and it was confirmed that the Sun is a star and the planets including the Earth are orbiting the Sun, many scholars realized that the millions of stars in the night sky should also

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Almost all kinds of stars except the extremely hot ones are found to have planets and planetary systems. A few planets are found to be floating freely while some planets are discovered around binary stars.

have similar planetary systems. So there could be many planets similar to the Earth. Since we know the environment of the Earth enabled life to originate and evolve, it is quite rational to speculate that some of those planets orbiting other stars might be habitable. The search for planets outside the solar system, termed as extrasolar planets or exoplanets, started during the nineteenth century. But the necessary technology to detect even a large planet similar to Jupiter orbiting a star other than the Sun was not available. All the early claims of discovery of exoplanets, when analyzed carefully, turned to be erroneous or considered as false alarms. So the search continued.

A second very speculative reason for the search of another Earth is to find out a suitable place to migrate if in the far future, the environment of the Earth becomes completely uninhabitable due to natural or manmade disasters. Although it is very rare, a catastrophic event such as a collision by a comet or a large asteroid may cause a drastic change in the atmosphere. It is now believed that such a catastrophic event that occurred about 63 million years ago caused the extinction of dinosaurs. Manmade catastrophic events such as a full-scale nuclear war may also cause irreversible damage to the environment of the Earth.

For astronomers, the discovery and characterization of exoplanets provide important knowledge on the formation of planets or planetary system apart from knowing the wide range of physical properties such as mass, size, chemical composition etc. In fact the discovery of more than 3000 exoplanets to date has revolutionized our understanding of planets.

Discovery of Exoplanets

We all know that a planet does not have its own source of energy. It only reflects a part of the starlight received. Therefore, planets are extremely faint. However, the main obstacle in detecting a planet is the glare of the star. Because of the brightness of the star, a planet orbiting it is very difficult to see even with a sufficiently large telescope. Another reason is the wave nature of light. If the apparent separation of the star and the planet is too small, the planet cannot be resolved due to the limitation of the instrument known as 'diffraction limit'. If θ (in radian) is the diffraction-limited resolution, λ is the wavelength (in cm) of the light from the star and D is the diameter (in cm) of the lens or the mirror of the telescope then $\theta = 1.22\lambda/D$. A planet can be resolved by the telescope, only if $\theta < a/d$, where a is the distance between the star and the planet and d is the distance of the star from the telescope. For example, the Hubble space telescope with a diameter of 2.4 meters can resolve a planet orbiting at a distance of less than 1 AU (AU is the distance between the Sun and the Earth) around a star that is less than about 65 light years away from us, but not further. Because of these difficulties, astronomers use indirect methods to detect the exoplanets.

Most of the exoplanets are detected indirectly, through their effects on their parent stars. These include dynamical and photometric effects.

During the early stage of planet hunting, the anomaly in the orbital motion of a binary star system was considered. Thus from the orbital anomaly or the deviation in the predicted motions of the binary star system Ophiuchi 71 monitored by using the erstwhile Madras Observatory in India, Captain William S Jacob in 1855 reported the possible presence of a planetary mass object in that binary system. However, careful analysis by other astronomers rejected the claim. But, historically this was the first false alarm for extrasolar planets. Subsequently, many astronomers claimed to have discovered planets orbiting other stars. Unfortunately none of the claims could be confirmed. Finally, in 1995, Michel Mayor and Didier Queloz of Geneva Observatory discovered a planet around a star known as 51 Pegasi. Two American astronomers, Geoffrey Marcy and Paul

Similar to the transit of Venus across the Sun, the transit of exoplanets across their parent stars blocks a tiny portion of the starlight. The reduction in the brightness of the star during transit can be detected by even small telescopes.

Butler confirmed this discovery immediately. However, in 1988, Bruce Campbell, G A H Walker and S Yang discovered a planet around the star Gamma Cephei but this discovery was confirmed only in 2003 after the precision of the instrument improved significantly. On the other hand, in 1992, Aleksander Wolszczan and Dale Frail discovered a planetary system consisting of two planets around the pulsar PSR 1257+12 but the discovery was confirmed only after the confirmation of the discovery of the planet around 51 Pegasi. It is worth mentioning here that pulsars are the end product of a massive star while 51 Pegasi is a star similar to the Sun.

How are these small and extremely faint exoplanets detected out of the intense glare of their parent stars? They are not seen or imaged directly but their influence on the star is detected through various methods.

Detection Methods

Astronomers use various methods and instruments attached with a telescope to detect exoplanets. Sometimes, more than one method is used to confirm the detection. Here, we shall describe only a few methods that are quite popular among the astronomers.

Transit Method

Most of the exoplanets are detected by using a method known as the Transit Method. When a large planet orbiting very close to its parent star passes the line of sight between the star and the observer, it blocks a tiny part of the stellar disk causing a slight decrease in the brightness of the star (see *Figure* 1). A periodic change in the apparent brightness of the star indicates the presence of a planet. The transit method provides the size of a planet accurately if the radius of the star is known. If ΔL is the decrease in the brightness L of a star, $\Delta L/L = R_P^2/R_S^2$ where R_P is the radius of the planet and R_S is the radius of the star. The transit method[1]

[1] Transit method not only confirms the presence of the planets around a star, but also provides the orbital period and inclination angle as well as the radius of the planet. From the transit duration, the orbital separation can be determined. Hence by using Kepler's law, the mass of the planet can also be estimated if the mass and the radius of the star are known. Therefore, transit method alone helps in estimating the mean density and surface gravity of the planet.

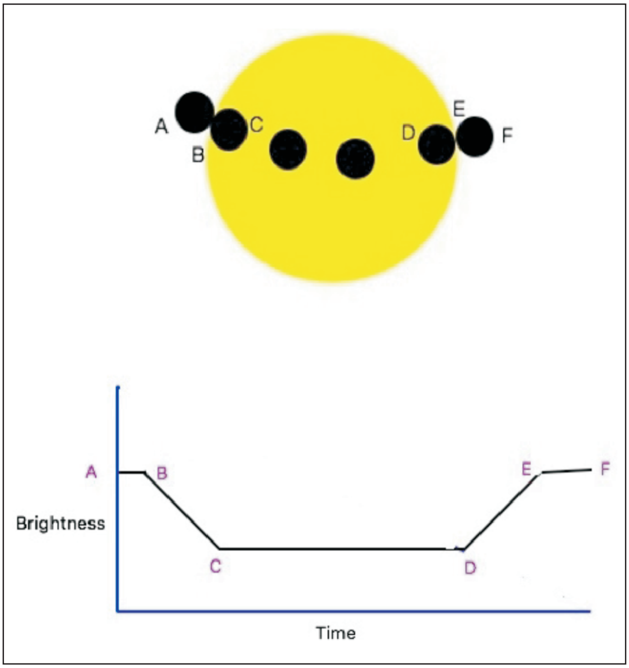
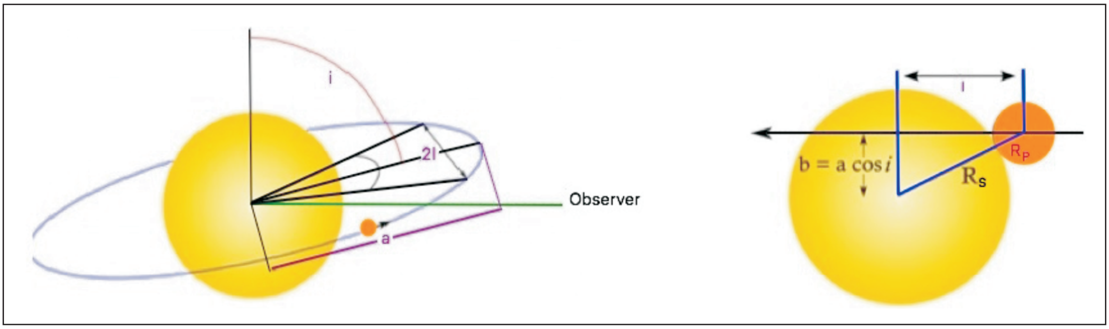


Figure 1. Schematic diagram of transit light curve of a star produced by a planet. B is the ingress and E is the egress point. Transit of the planet causes reduction in the brightness of the star.

also provides the period and the orbital inclination angle of the planet from the transit duration and from the ingress and egress times of the transit. However, the method is applicable only if the orbit of the planet is inclined to a large angle so that it is viewed almost edge on. *Figure* 2 presents the transit geometry. Transit of a planet can occur only if the orbital inclination angle i is greater than $\cos^{-1}[(R_S + R_P)/a]$. The transit length $2l = 2[(R_S + R_P)^2 - b^2]^{1/2}$, where $b = a\cos i$. The total transit duration is given by $T = P\sin^{-1}(l/a)/2\pi$, where P is the orbital period of the planet.

Figure 2. Transit geometry. In the figure, *a* is the orbital separation between the star and the planet, *i* is the orbital inclination angle, 2*l* is the transit length and b/R_S is the transit impact parameter.



Astronomers measure the brightness of the star continuously by using a photo-imager and detect the periodic variation in the brightness of the star. Although this is a simple photometric method, the detection of the planet is usually confirmed by using other methods because the change in brightness of the star may occur due to reasons other than the transit of a planet. For example, a small component in a binary or triple star system may also give rise to periodic decrease in the brightness of the primary star. On the other hand, a giant dark spot (similar to Sun spots) may also cause a transit-like phenomenon. The space telescopes Kepler and CoRoT have detected a large number of exoplanets by using the transit method. Ground-based telescopes also have detected a good number of exoplanets. Multiple planets around the same star are detected by Transit Timing Variation or by Transit Duration Variation.

Radial Velocity or Doppler Method

When starlight is passed through a spectrograph, the spectrum of light shows several vertical dark lines. These lines are produced due to the absorption of light by different chemical species present in the atmosphere of the star. Each line at different wavelength corresponds to the absorption by a specific element. When the wavelength changes, the position of each line changes. This is called Doppler shift because the change in wavelengths is caused by Doppler effect. When the source moves towards the observer, the wavelength decreases and the lines shift towards the blue region of the spectrum. When the source moves away from the observer, the wavelength increases and the lines shift towards the red region. These are known as blue and red shifts respectively (see *Figure* 3).

Radial velocity method enables detection of exoplanets but it provides only the projected mass and the orbital period of the planet.

When two massive objects orbit each other, they rotate around a common center of mass situated at the line joining the centers of the two objects. This is known

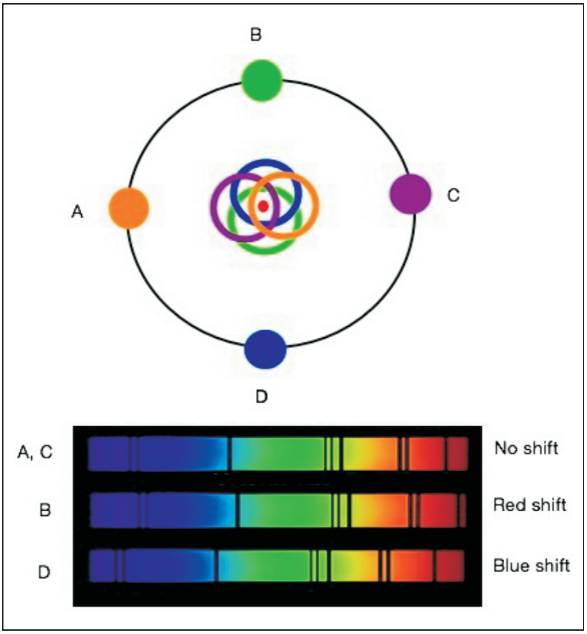


Figure 3. Illustratioan of radial motion of a star due to a planet and the Doppler shift caused by the radical velocity. The red dot is the barycenter of the system around which both the objects rotate. Small solid circles are various positions of the planet and the rings represent various positions of the star. The observer is towards D.

as barycenter of the system. This center of rotation is different from the center of any of the two objects. If M_1 and M_2 are the masses of two objects at a distance of r_1 and r_2 respectively from a reference point, then the distance of the barycenter from that reference point is $(M_1r_1+M_2r_2)/(M_1+M_2)$. If the mass of one object is reduced, the barycenter moves towards the heavier object. Therefore, if the mass of one object is extremely small compared to the other object, the barycenter goes inside the heavier object and this is the case for a small planet orbiting a massive star. Both the objects rotate around the barycenter of the system that is not exactly the center of the star. As a consequence, the star wobbles. If the orbital plane is such that the star moves periodically towards and away from the observer, it gives rise to the Doppler effect. So, when the starlight is passed through a spectrograph, the spectrum shows periodic red and blue shift of the absorption lines. The movement of the star induced by the planet is called radial velocity of the star. The shift of a particular absorption line therefore provides the radial velocity of the star through the relationship $\Delta\lambda/\lambda = v/c$, where $\Delta\lambda$ is the shift in the emitted wavelength λ, v is the radial velocity and c is the velocity of light.

Both the radial velocity and the transit methods can detect planets that have very high orbital inclination angle.

Now,

$$v = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{M_P \sin(i)}{M_S^{\frac{2}{3}}} \; (M_P \ll M_S),$$

where M_P and M_S are the mass of the planet and the star respectively, P is the orbital period of the planet, i is the orbital inclination angle and G is the universal gravitational constant. Therefore, from the Doppler shift $\Delta\lambda$, we can derive v and from the above relationship we can derive the projected mass $M_P \sin\,(i)$ if P and M_S are known. Thus, the radial velocity of the star derived from the Doppler shift of the stellar absorption line confirms the presence of the planet and it provides the projected mass of the planet. That is why this method is also called Radial Velocity Method. However, the radial velocity imparted by even a giant planet very near to the star is not very high. The planet 51 Pegasi b is ten times heavier than Jupiter and is orbiting about 0.05 AU from the star. It imparts a radial velocity of 56.0 ms^{-1} on the star. Jupiter imparts a radial velocity of 12.7 ms^{-1} and the Earth imparts a radial velocity of only 0.09 ms^{-1} on the Sun. But the movements of the detector and the telescope and the thermal fluctuations usually produce much larger shift in the observed absorption lines than that due to the wobble of the star. Therefore the Doppler shift due to such small radial velocity cannot be distinguished by an absolute measurement. So, the astronomers pass the starlight through a gas absorption cell that produces a reference spectrum of a chosen absorption line. The shift of the lines in the stellar spectrum is compared to this reference spectrum. Mayor and Queloz used an iodine cell to monitor the shift in the iodine absorption lines of the spectrum of 51 Pegasi. Radial velocity method can only provide the projected mass of the planet. It cannot determine the actual mass or the radius of the planet. However, this method was the most popular among the astronomers before the space telescopes Kepler and COROT (COnvection ROtation and planetary Transits) were launched. Before these two space missions were launched, the ground-based telescopes could search for exoplanets within a region of sky extending to only 300 light years. But after their launch, the search region got enhanced to about 3000 light years.

Gravitational microlensing method can provide only the mass of the planet as compared to the mass of the host star. It is a chance process, so the detection cannot be repeated.

Gravitational Microlensing Method

We all know that the light from a distant star travels to us in a straight line. It needed the genius of Albert Einstein to perceive that the space–time surrounding a massive object is curved due to the strong gravitation of the object. As a consequence, when light passes near a massive object, it bends towards the object. When a distant star passes near the line joining an observer and a nearby star, the bending of light from the distant star by the intervening nearby star gives rise to lensing effect. As a result, the brightness of the distant star gets magnified gradually and reaches a maximum value when the three objects are aligned in a straight line. Subsequently, the brightness starts reducing as the source star moves away (see *Figure* 4). This is known as gravitational microlensing. The whole process occurs in a period of 2-4 days. Now if the lens star has a planet, it too acts as a lens. Consequently, the brightness of the

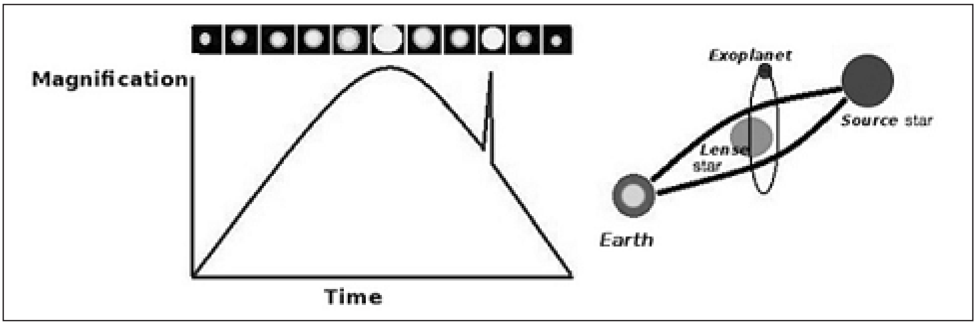


Figure 4. Diagram showing gravitational microlensing of a source star by a lens star and its planet. The sharp peak in the light curve is due to the lensing by the planet.

source star again increases sharply albeit for a small period when the source crosses the line joining the observer and the planet. The change in the brightness is recorded by a photo-imager. Since observation cannot be made during daytime, the entire event is observed by using an array of telescopes placed at different geographical locations of the Earth. Even a small planet orbiting far away from its parent star can be detected through the gravitational microlensing effect. However, neither the period nor the mass of the planet can be determined by this method. It can only provide the ratio of the mass between the planet and its parent star. Also, since the brightness of the planet-hosting star is not involved in this method, a planet around a distant star can also be detected. However, unlike the transit method and the radial velocity method, microlensing is a chance event and cannot be observed again.

Direct Imaging

We have already mentioned that exoplanets cannot be observed directly because of the intense glare of the star and because of the small apparent distance between the planet and the star. However, recently a few exoplanets have been imaged directly by astronomers. These planets are far away from their parent stars, at a distance of 10–30 AU or more and so they can be resolved easily. They are very young, about 10–100 million years old and so they are very hot. An instrument called a Coronagraph is used to block out the starlight. *Figure* 5 presents the first directly imaged exoplanets 2MASS 1207b. Both the objects in this system are quite interesting. We know that the stars are massive enough to ignite and sustain nuclear burning of hydrogen at their core and this nuclear burning is the source of energy emitted from the stars. Interestingly the parent of this directly imaged planet is not a star because although it has sufficient energy to ignite deuterium, an isotope of hydrogen, it fails to ignite hydrogen due to the lack

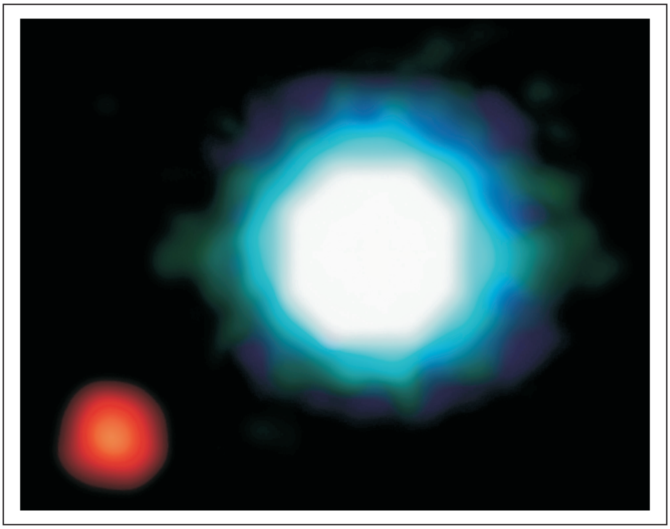


Figure 5. The first directly imaged exoplanet (red) around a brown dwwarf 2MASS 1207.
Credit: NASA/ESO

of sufficient mass. Hence, it cannot sustain the nuclear burning process. In that sense, it is a failed star. It is, however, born in the same way as a normal star, i.e., through the collapse of a huge interstellar cloud. This type of object is known as a brown dwarf. They inhabit the realm between the least massive stars and the most massive planets. On the other hand, a planet is formed by the accumulation of material in a protoplanetary disc that is formed during the formation of the star. Planets do not have sufficient mass to even ignite deuterium. So, the primary object in this system fails to become a star while the secondary object fails to become a brown dwarf. We cannot tell how they were formed, and the range of mass of the objects that are formed like a star overlaps with the range for those which are formed like a planet. This poses a question on the definition of planets or planetary mass objects. At present, an object that is less than thirteen times heavier than Jupiter is considered as a planet.

Brown dwarfs were theoretically predicted by an Indian origin astrophysicist Shiv S Kumar during the early 1960's and was discovered in 1995 by a group led by S Kulkarni, another Indian origin astrophysicist. The first confirmed brown dwarf is Gliese 229B, a component of the binary star system Gliese 229.

Other Methods

Besides the above-mentioned detection methods, astronomers have been using a few other methods such as astrometry, timings, etc. Most of these methods are effective in detecting large planets that have high orbital inclination. The author has suggested that time resolved imaging polarimetry[2] can be a potential technique to detect even small Earth-sized planets. The intensity of unpolarized natural light or starlight is the same in all directions but the intensity of polarized light changes in different directions. Therefore, although, the light of a normal star is unpolarized, the light reflected from a planet should be polarized and the amount of polarization, a measure of the anisotropy in the radiation field, can be detected by a polarimeter. On the other hand, Earth-sized rocky planets around brown dwarfs and exomoons around directly imaged self-luminous planets can also be detected in future through polarimetry.

About 3000 exoplanets have already been detected mainly by using transit and radial velocity methods and more than 3000 detections are awaiting confirmation. In future, very large ground-based telescopes such as European Extra-Large Telescope, Thirty Meter Telescope and Giant Magellan Telescope along with James Webb Space Telescope are expected to discover a large number of exoplanets including the small rocky planets. The discoveries of a large variety of planets have not only enhanced our understanding about the nature of planets but also have posed challenges to our existing knowledge on the formation of planets and planetary systems. The ultimate goal has been to detect the planets that have potential to harbor life. Therefore, the focus is now shifted towards the detection of rocky planets that has appropriate temperature for water to exist in liquid state. We shall discuss all those fascinating developments in the next part of this article.

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Suggested Reading

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[2] **C A Scharf, *Extrasolar Planets and Astrobiology*, University Science Books, Sausalito, California, 2009.**

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[2] Polarization of light is an electromagnetic phenomenon caused either by the presence of strong magnetic field or by scattering of light with atoms, molecules and cloud particles. When a randomly oscillating wave of starlight gets scattered or reflected, it starts oscillating in a particular direction. This is called polarization of light, and the measurement is called polarimetry.