The Search for Another Earth – Part II

Sujan Sengupta

In the first part, we discussed the various methods for the detection of planets outside the solar system known as the exoplanets. In this part, we will describe various kinds of exoplanets. The habitable planets discovered so far and the present status of our search for a habitable planet similar to the Earth will also be discussed.

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1. Introduction

The first confirmed exoplanet around a solar type of star, 51 Pegasi b was discovered in 1995 using the radial velocity[1] method. Subsequently, a large number of exoplanets were discovered by this method, and a few were discovered using transit and gravitational lensing methods. Ground-based telescopes were used for these discoveries and the search region was confined to about 300 light-years from the Earth.

On December 27, 2006, the European Space Agency launched a space telescope called CoRoT (Convection, Rotation and planetary Transits) and on March 6, 2009, NASA launched another space telescope called Kepler[2] to hunt for exoplanets. Consequently, the search extended to about 3000 light-years. Both these telescopes used the transit method in order to detect exoplanets. Although Kepler's field of view was only 105 square degrees along the Cygnus arm of the Milky Way Galaxy, it detected a whooping 2326 exoplanets out of a total 3493 discovered till date. Apart from discovering a large number of exoplanets of different kinds, Kepler has also provided important statistics about the distribution of planets in our galaxy. It is now believed that our galaxy has at least 100 billion planets which means that on an average, every two stars have one planet. It is known that 80% of the stars in the extended solar neighborhood are red dwarfs[3] Analysis of the data obtained by Kepler indicates that 0.51 planets per red dwarf stars (on an average each couple of red dwarf

[1] The movement of the star towards the observer due to the gravitational effect of the planet. See Sujan Sengupta, The Search for Another Earth, *Resonance*, Vol.21, No.7, pp.641–652, 2016.

[2] Kepler Telescope has a primary mirror of diameter 0.95 meter and the spacecraft orbits the Sun in 372.5 days.

Keywords
Exoplanets, earth, super-earth, diamond planet, neptune, habitability, extra-terrestrial life.

[3]The solar neighborhood, a small region of the galaxy containing the sun is scanned and the number of stars are counted. Out of these stars, the number of red dwarf stars is determined from their spectra. Thereafter, statistical method is used to determine the average number of red dwarf stars among all the stars.

stars should have one planet) are small and rocky and hence similar to the Earth.

During the last two decades, both the ground-based and space-based telescopes have discovered a wide variety of exoplanets that are beyond our imagination. The size, mass, surface gravity, and surface temperature of these planets as well as their proximity to their parent stars have revolutionized our understanding of planetary properties and formation mechanisms.

2. The New Worlds

The physical properties of a planet are mainly determined by its mass, size, orbital distance from the parent star, and the brightness of the star. Mass and size give the surface gravity and the mean density of the planet which in turn determines whether the planet is rocky or gaseous. Accordingly, in our solar system, we have four kinds of planets : (1) terrestrial or Earth-sized planets such as the Earth and Venus, (2) subterrestrial planets such as Mercury and Mars, (3) giant gas planets such as Jupiter and Saturn, and (4) icy gas planets such as Uranus and Neptune.

On the other hand, the large number of exoplanets needs as many as 18 groups in order to describe them on the basis of their size, mass and surface temperature. These 18 groups are made of six different sizes and three different surface temperatures depending on the brightness and orbital distance of the parent star. Although in the solar system we know about four different planetary sizes, e.g., sub-Earth, Earth, Neptunian and Jovian, exoplanets are discovered with two more sizes, namely, super-Earth and mini-Neptunian. Super-Earths are rocky planets slightly heavier and larger than the Earth. Mini-Neptunes are the intermediate phase between rocky and gaseous planets. So they are smaller than Neptune but at least double the size of the Earth. They have a rocky core but an extended gaseous atmosphere. On the other hand, the three temperature regimes are (1) hot, (2) warm, including habitable and (3) cold or icy. We shall discuss a few of the remarkable exoplanets that were unknown to us just a decade ago.

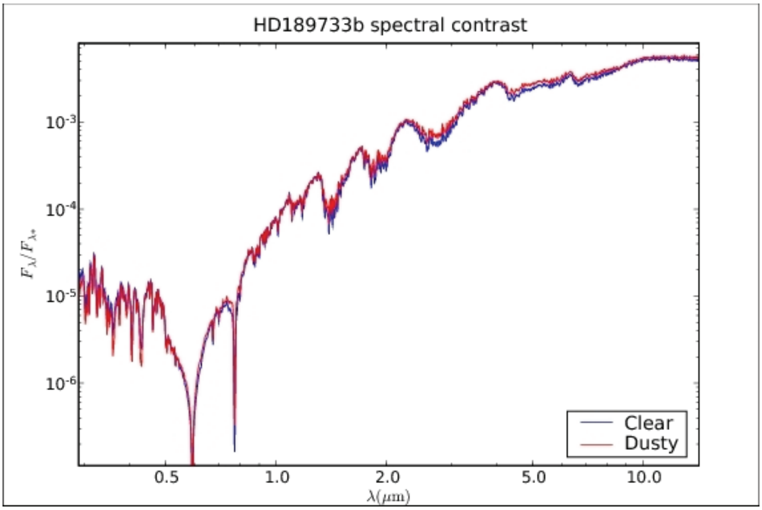

Figure 1. Theoretical spectra of hot gas giant planet HD 189733b with and without silicon cloud.
(Credit: Derek Homeier.)

Hot Jupiters or Roasters

The average distance between the Sun and the Earth is called an Astronomical Unit or AU and it is 1.496×10^8 km. Mercury, the closest planet to the Sun is about 0.4 AU away from the Sun. But several exoplanets have been discovered which are orbiting their parent stars at a distance as close as 0.01 AU. In fact, the first exoplanet discovered to be orbiting (with a period of just 4 days) around the main sequence star 51 Pegasi is at a distance of 0.05 AU. The star is slightly brighter than the Sun and hence the surface temperature of the planet is estimated to be about 1000°C. Immediately after the first discovery, a large number of such exoplanets were reported because it was easier to measure the high radial velocity of the star imparted by such nearby planet. Besides 51 Pegasi b, HD 209458b and HD 189733b are two well-studied hot gas giant planets. Astronomers take the spectra of the star during the transit and secondary eclipse (when the planet is behind the star). A comparison of these two spectra with theoretical model spectra enables determination of the presence of various molecules in the atmosphere of such giant planets (*Figure* 1). It is believed that at such high atmospheric temperatures, the atmosphere should be clouded by silicon condensates.

Mini-Neptunes

The presently available observational facilities cannot detect small exoplanets that are more than 1–2 AU away from their stars. Therefore, an icy planet like our Neptune is beyond the present observational capacity. However, a large number of Neptune-sized planets have been discovered orbiting very close to their parent stars. While Jovian planets are 8–22 times larger than the Earth, the Neptunian planets are only 2–8 times larger than the Earth. They too are gaseous in nature. A few planets that are about 2–4 times larger than the Earth have been discovered and this type of planets are not present in our solar system. These are called mini-Neptunes and they must be at the transition of rocky and gas planets; their core is made up of rock and they have an extended gaseous envelope. Gliese 436b, a planet orbiting a red dwarf star Gliese 436 is about 4 times larger than the Earth and is about 22 times heavier. Kepler 11b is another mini-Neptune. All these planets are so close to their parent stars that their surface temperature could range from 400–2000^{o}C, depending on the temperature of the parent star.

Super-Earths

In our solar system, we have Earth and Venus that are almost the same in size. These are called terrestrial planets. The size of terrestrial planets varies from 0.75–1.25 times the size of the Earth. Mercury and Mars are much smaller than the Earth or Venus. These are sub-Earths. Both terrestrial and subterrestrial planets are also found outside the solar system. Some exoplanets have sizes ranging between 1.25–1.75 times the size of the Earth. These are called super-Earths and our solar system does not have such a planet. Super-Earths are also rocky like the Earth and are 2–6 times heavier than the Earth. Depending on their proximity to the parent star, their surface temperature may be high enough to evaporate the gaseous atmosphere. Mercury is believed to have lost its gaseous atmosphere due to strong solar irradiation. Therefore, although the subterrestrial, terrestrial and super-terrestrial exoplanets (*Figure* 2) are geologically very similar, they may have environments much different than that of the Earth.

The mantle of the Earth consist of a crystalline material called Perovskite. A region between the core and the mantle of the Earth consists of post-Perovskite. The entire mantle of a super-earth is made of post-Perovskite.

Figure 2. A size comparison of super-Earth, Earth and sub-Earth.
(Credit: NASA)

Diamond Planets

The solar system is oxygen rich because the interstellar cloud from which the Sun and the solar planets were born had double the amount of oxygen than carbon. Therefore, the solar system is abundant in oxides such as carbon dioxide, water, silicate oxide, etc. Also, the mantle of the rocky planets in the solar system is made of compounds of silicon and oxygen (such as granite). On the other hand, if the initial star-forming interstellar cloud contains equal amount of carbon and oxygen, then the stars and its planets would be carbon rich. Carbon combines with other elements also and if the amount of oxygen is equal to the amount of carbon, they cannot form as much oxides as in the case when amount of oxygen is double the amount of carbon. Such stars and planets are called carbon stars and carbon planets, respectively. The mantle of a rocky carbon planet, therefore, is made of carbon instead of oxides. Under high pressure and temperature, the entire mantle of such carbon planets may become diamond[4]. For example, the carbon star Cancri 55 should have a rocky planet Cancri 55e. The surface temperature of this planet is about 2000°C. Under such temperatures, the entire planet should become diamond if it is indeed rocky. This exoplanetary system is about 40 light-years away from us.

A diamond planet in the habitable zone of its parent stars may be a habitating planet if it has all the necessary conditions to harbour life.

[4]Diamond is an allotrope of carbon. Under tremendous pressure and temperature at 150–200 km below the surface of the Earth, carbon atoms form a lattice giving rise to a crystalline material known as diamond. Through volcanoes, diamonds come out to the surface of the Earth.

Planets in Multiple-Star Systems

A large number of stars in our galaxy are in binary systems or in multiple stellar systems where one star is orbiting the other (*Figure* 3). Although it is rare, there are quite a few planets discovered that are orbiting one of the two or more stars in the system. This

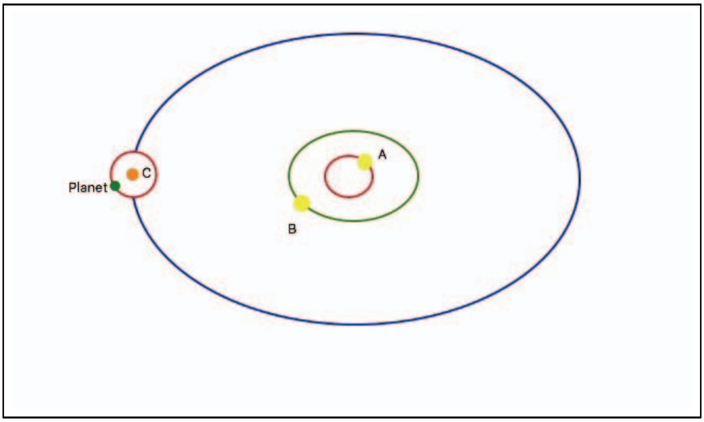

Figure 3. Schematic diagram of a planet orbiting a star in a triple star system such as our nearest star system Alpha Centauri A, Alpha Centauri B and Proxima Centauri (or Alpha Centauri C).
(Credit: Author)

means, a planet has more than one Sun appearing in its sky. The planet Kepler 16b orbits two stars, Kepler 16A, a K-spectral type star and Kepler 16B, an M dwarf star. Here the stars are separated by a distance of 0.2 AU and the planet is orbiting them at a distance of 0.7 AU. Similarly, Kepler 34b is orbiting two solar type of stars Kepler 34A and Kepler 34B. While the stars orbit each other in 27 days, the planet orbits the binary system in 288 days. HD 131399 is a stellar system with three stars, HD 131399A, HD 131399B and HD 131399C. A planet, HD 131399Ab is orbiting one of the stars HD131399A and the other two stars are orbiting this star and planet system.

Free-Floating Planets

A few planetary mass objects are found to be floating in space without being bound to any star. They are rogue planets and believed to be detached from planetary systems. PSO J318.5-22 and Cha 110913 are two such free-floating planets without any parent stars.

Very recently a rocky planet in the habitable zone of our nearest star Proxima Centaury has been discovered. Proxima Centauri is the third star orbiting the binary stellar system Alpha Centauri A and Alpha Centauri B.

3. What Makes a Planet Habitable?

With the discovery of a large number of exoplanets and exoplanetary systems, the focus has naturally been shifted towards searching for that special kind of planets which may have appropriate physical conditions to harbor life. Till date we know only one such planet and that is our Earth. Therefore, the search for another planet similar to the Earth has received tremendous interest and importance. In fact the main goal of Kepler was to find such planets. But where are those planets? Where is another Earth that may be habitable.

The first and foremost condition for a planet to be habitable is the presence of water in liquid state. Therefore the surface temperature of the planet should be such that water can exist in liquid state. The circumstellar region at which the temperature should be between the freezing and the boiling points of water is known as the 'Habitable Zone' of a star. The distance of the habitable zone of a star depends on the effective temperature of the star. The second condition of planetary habitability is that it should have a rocky surface in order to retain the liquid water. However, the appropriate distance from the star with a specific effective temperature does not guarantee the ambient temperature of the planet to be appropriate for the existence of liquid water in its surface. Two other factors are important namely, the albedo and the greenhouse effect.

Albedo: All planets have a certain amount of reflectivity. The fraction of starlight that is reflected by the planetary surface or atmosphere is called the planetary albedo[5].

[5]The Earth reflects about 30% of the sunlight because the albedo of the Earth is 0.3. The albedo of Mars is 0.2. On the other hand, the albedo of Venus is as high as 0.75.

The surface temperature or the equilibrium temperature $T_{\rm p}$ of a planet is given by

$$T_{\rm p} = T_{\rm s}(1 - A)^{1/4}(R_{\rm s}/2d)^{1/2},$$

where $T_{\rm s}$ is the effective temperature or the surface temperature of the star, $R_{\rm s}$ is the radius of the star, d is the orbital distance of the planet and A is the albedo of the planet. If $A = 0$, then for $0 < T_{\rm p} < 100^{\rm o}\,{\rm C}$ (the freezing and boiling points of water is $0^{\rm o}$ and $100^{\rm o}\,{\rm C}$), $0.57 < d < 1.1$ AU for the Sun, whose $T_{\rm s} = 5505^{\rm o}{\rm C}$. This means that the habitable zone of the Sun is extended from 0.57 to 1.1 AU. Accordingly, both Venus and the Earth orbit within the habitable zone of the Sun while Mars is marginally within the zone due to its highly elliptical orbit. However, if we substitute the values of A for Earth and Venus, then the surface temperature of the Earth and Venus become $-18^{\rm o}{\rm C}$ and $-41^{\rm o}{\rm C}$ respectively, which is much below the freezing point of water. The average surface temperature of Mars would in that case be $-59^{\rm o}{\rm C}$ as the mean distance of Mars from the Sun is 1.51 AU.

Greenhouse Effect: The ambient temperature of any planet also depends on the chemical composition and physical properties of its atmosphere. For example, in case of the Earth, 30% of the sunlight gets reflected back to the space by the atmosphere and the remaining 70% penetrates it which heats up the ground and the oceans. Subsequently, the hot ground and oceans re-radiate the energy in infrared wavelength. This infrared radiation gets scattered multiple times by the molecules of water vapor, carbon dioxide, nitrogen and other gases in the atmosphere and cannot escape to the space. Consequently, the planetary environment becomes warm. This phenomenon is called the greenhouse effect.

The amount of energy trapped depends on the optical depth of the atmosphere which is the inverse of the mean free path of the photon before it is completely lost. If T_{g} is the atmospheric temperature of the planet due to the greenhouse effect then

$$T_{\mathrm{g}}^4 = T_{\mathrm{p}}^4(1 + 0.75\tau_{\mathrm{g}}),$$

where the mean optical depth τ_{g} for the Earth, Venus and Mars are 0.83, 60.0 and 0.2 respectively. Venus has a thick atmosphere and hence a high optical depth. As a result, a strong greenhouse effect causes its temperature to rise from -41°C to as high as 480°C. On the other hand, a thin atmosphere of Mars causes only 10°C increase in the temperature. Due to the greenhouse effect, the average atmospheric temperature of the Earth becomes 15°C and consequently only the Earth has the appropriate ambient temperature to keep water in liquid state. In essence not all planets in the habitable zone of a star are habitable. The planet needs to have an ambient temperature determined by an atmosphere with appropriate physical conditions, and has to be rocky as well. Typically, any planet that is less than about 1.6 times the size of the Earth and less than six times heavier than the Earth is believed to be rocky. At present, technological limitations do not allow us to obtain medium resolution spectra of any planet to determine the albedo and physical properties. However, transit spectra of many planets are available and they provide us a fair understanding of the planetary atmosphere.

Volcanoes and earthquakes reprocesses the minerals in the Earth and maintain the silicon-carbon ration in the atmosphere. Therefore, these natural phenomena helps in maintaining the ambient temperature of the Earth.

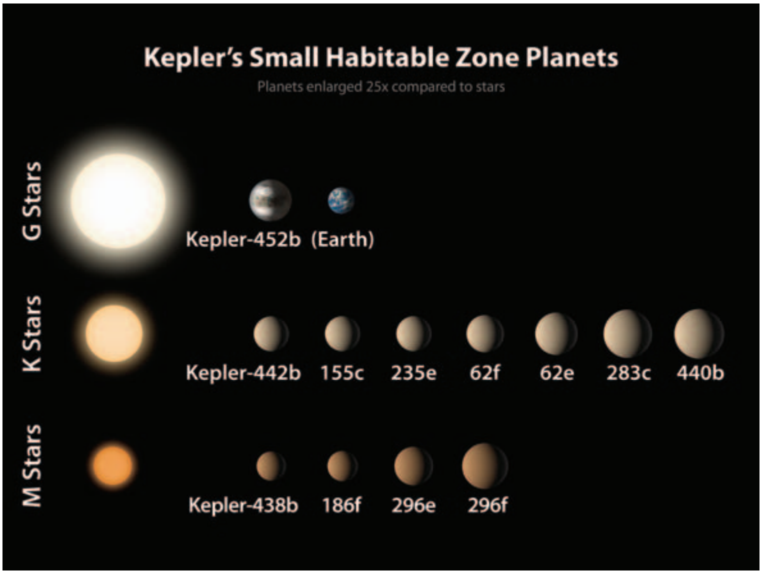

Figure 4. Artist's impression of a few rocky planets in the habitable zones of their parent stars. All these planets are discovered by Kepler.

(Credit: NASA Ames/JPL-CalTech/R.Hurt)

4. Why Search for Another Earth?

The environment on Earth has enabled life to evolve and survive for a long period. So, another prototype of this planet may also have at least nascent life, if not evolved life. The eternal question of mankind "are we alone?" or "is life a common phenomenon in the vast arena of the cosmos?", can only be addressed if we find a few planets very similar to the Earth.

The search for planets in the habitable zone of stars has led to the discovery of a large number of warm planets with different sizes and mass. For example, Kepler 22b is a mini-Neptune which is about 2.5 times larger than the Earth and hence not a rocky planet, but it orbits in the habitable zone of the star. Similarly, Kepler 90h, the seventh and the outermost planet in the planetary system of Kepler 90 should have a surface temperature of about 20°C and so water can exist in liquid state. But this planet is as large as Jupiter and so it is a gas giant and not a rocky planet. But a habitable planet must be rocky in order to sustain liquid water on its surface. The Kepler Telescope has discovered as many as 21 planets that are believed to be rocky and also orbiting in the habitable zone of their parent stars (*Figure* 4). Many of these stars are the coolest and the lightest stars, known as M-dwarfs.

A rocky moon of a giant gaseous planet in the habitable zone of its parent star may also harbour life.

A good number of rocky planets orbit in the habitable zone of M-dwarfs. Since M-dwarfs are the coolest stars, their habitable zone is very close to them. On the other hand, M-dwarfs are very active stars. They emit strong extreme UV rays and X-rays and often eject strong flares. Since the habitable zone is very near to the star, the planets in the habitable zone are exposed to strong radiation which may cause evaporation of lighter elements such as hydrogen and even oxygen. Considering energy-limited hydrodynamical mass[6] loss with an escape rate that causes oxygen to escape along with hydrogen, the present author derived an upper limit on the ratio between the extreme UV luminosity L_{EUV} and the optical (bolometric) luminosity L_{B} that constrains the habitability of a planet. Accordingly, if $L_{\mathrm{EUV}}/L_{\mathrm{B}} > 1.3 \times 10^{-4}$ then the planet will lose most of its water and hence become uninhabitable.

[6] X-ray and UV ray irradiation increases the kinetic energy of the atmospheric particles, e.g., the atoms and the molecules. When the kinetic energy of a particle becomes comparable to its gravitational potential energy, the particle escapes the planetary atmosphere. The bulk flow of matter due to this is governed by the laws of hydrodynamics.

The origin, evolution and most importantly the survival of life on the Earth has been possible due to a formidable combination of several favorable astronomical and geological conditions. Volcanic and plate tectonic activities, presence of a magnetic field, presence of a large moon, and many other natural phenomena helped in keeping the atmosphere of the Earth habitable for a long period of time so that nascent life could evolve into complex and developed organisms.

The present technology can only enable us to detect the rocky planets in the habitable zones. Next generation space telescopes such as James Webb Space Telescope and a few large ground-based telescopes such as the European- Extremely Large Telescope, the Giant Magellan Telescope and the Thirty Meter Telescope should provide information on the atmospheric composition and hence the ambient environment of these planets. However, it will not be possible to determine if the other necessary conditions are met in a habitable planet. Therefore, the presence of life in those planets can be confirmed only through the detection of biosignature.

The magnetic field of the Earth prevents the energetic charged particles carried by the solar wind from entering into the atmosphere of the planet and thus protect the atmosphere and life in it.

Search for Biosignature

Unicellular nascent life appeared on the Earth about 3.5 billion years ago, about one billion years after the planet was born. The atmospheric composition at that time was drastically different

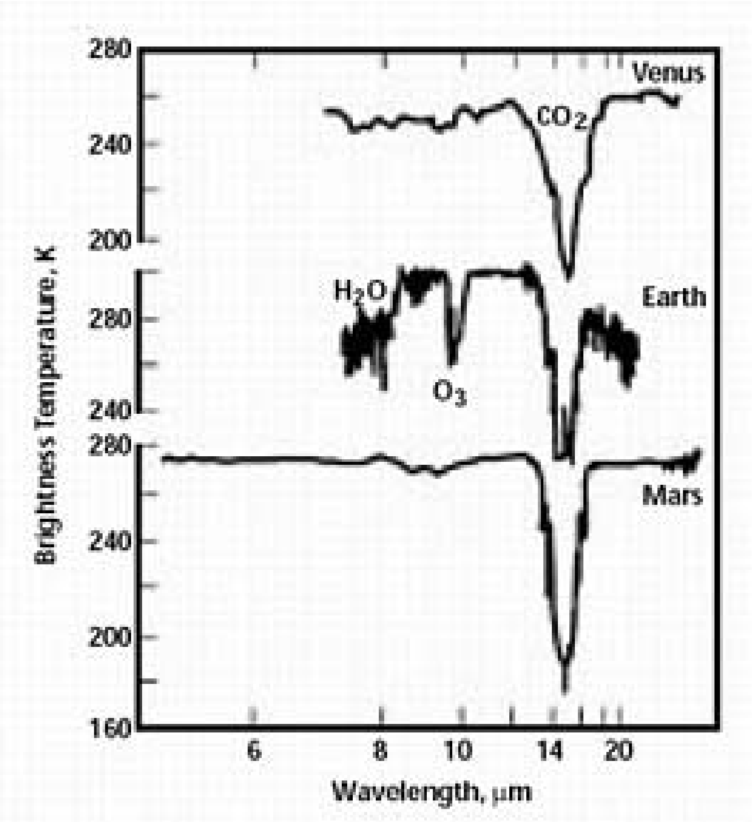

Figure 5. Infrared spectra of Venus, Earth and Mars. Only the spectrum of the Earth shows the absorption feature of ozone at 9.6 micron band.
(Credit: NASA)

than what it is today; there was no free oxygen. The oldest unicellular life such as purple and green bacteria survived by anoxygenic photosynthesis. Two billion years after the Earth was born, oxygen-producing prokaryotic bacteria, cyanobacteria, made the atmosphere oxygen rich. So, free oxygen molecules were produced by the appearance of life on the Earth. These oxygen molecules (O_2) were photodissociated by the solar UV rays at the upper atmosphere producing atomic oxygen (O). A molecule of oxygen then combined with an oxygen atom to form a molecule of ozone (O_3) in the upper atmosphere. This ozone layer[7] which protects life from intense gamma rays, X-rays and UV rays of the Sun, was discovered in 1913. Since the ozone layer in the upper atmosphere of the Earth is produced by living organisms, it serves as an important biosignature of life. No other planet in the solar system shows the presence of ozone in its atmosphere (*Figure* 5). Therefore, once the next generation of telescopes are available, search for ozone in those rocky planets orbiting within

[7] See Shashi K Pathak and Nigel J Mason, Our Shrinking Ozone Layer, *Resonance*, Vol.7, No.12, pp.71–80, 2002.

the habitable zone of their stars will begin. Detection of ozone in the spectra of any habitable planet will confirm the presence of life. Until then, the Earth will remain the only known habitatable planet in the vast arena of the cosmos.

Suggested Reading

[1] **Sujan Sengupta, *Worlds beyond our own: The search for habitable planets*, Springer, 2015.**

[2] **F J Pont, *Alien Sky: Planetary atmosphere from earth to exoplanet*, Springer, 2014.**

[3] ***Exoplanets: Worlds without end*, Scientific American Editors, Scientific American, 2015.**

[4] **Tahir Yaqoob, *Exoplanets and alien solar systems*, New Earth Lab, 2011.**

[5] **Therese Encrenaz, *Planets: ours and others : from Earth to exoplanets*, World Scientific, 2013.**

[6] **M Perryman, *The Exoplanet Handbook,* Cambridge University Press, 2014.**

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