Exoplanets:

Discoveries and Prospects

Eklavya Sarkar

Class 403

CEC André-Chavanne

CEC ANDRE-CHAVANNE
TRAVAIL DE MATURITE – TRAVAIL DE RECHERCHE

EXOPLANETS: DISCOVERIES AND PROSPECTS

EKLAVYA SARKAR
403
18 January 2013

ACKNOWLEDGMENT

This research project would not have been possible without the support, encouragement and help of the many people who chose to accompany me in exploring a new world. First and foremost, I would like to extend my deep gratitude to Pranjal Trivedi, Assistant Professor of Physics, University of Delhi, for his remarkable guidance, exemplary encouragement and stimulating ideas, all of which contributed tremendously to my thesis. I also thank the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, India for the use of their facilities, especially the library, during July 2012. I have furthermore to thank Mr. Daniel Kessler for accepting to supervise my project and giving valuable suggestions throughout the course of writing this paper. Lastly, I would like to express my profound appreciation to my sister and parents for their time, support and constructive ideas. A special thanks to Professor Didier Queloz, the co-discoverer of the first exoplanet, for taking out the time to meet and providing me with the cutting-edge information on this topic.

Table of Contents

Glossary 8

Prologue

I: The Quest of Mankind 10

II: The Evolution of Mindsets 11

Review

III: The Formation and Evolution of Planetary Systems 13

IV: The Dynamics of Planetary Motion 15

V: A Short History of Exoplanetology 20

VI: The Methods of Detection 22

Analysis

VII: Interpretation of Data 30

VIII: Habitability 40

Conclusion 46

Appendix

A: Bibliography 47

B: Figures and Graphs 49

Glossary

- **Absorption line:** A vertical dark line in an otherwise continuous spectrum that indicates missing light at specific or characteristic wavelength(s).

- **Astronomical Unit (AU):** Unit of length defined as 149,597,870,700 meters, which is the mean distance between the Earth and the Sun.

- **Extrasolar Planet or Exoplanet:** A planet which orbits another star, outside our own solar system.

- **Frost line:** Distance in a solar system from the central star where it is cool enough for water to exist in solid ice form.

- **Habitable zone:** A region around a star where the temperature of a planet (with a sufficient mass and atmospheric pressure) is suitable for life as we know it

- **Hot Jupiters:** Extrasolar planets whose characteristics are similar to Jupiter's, but with high surface temperatures because of the close orbit to their parent star.

- **Hydro-nuclear fusions:** The process of converting hydrogen into helium at the core of a main sequence star, with a goal of generating energy.

- **Interstellar cloud:** The generic name given to a region in interstellar space which has had an accumulation of dust and gas.

- **Jupiter-Analogs**: Extrasolar planets whose characteristics are similar to Jupiter's, including traits such as surface temperature.

- **Jupiter Masses:** A unit of mass equal to the total mass of Jupiter $\approx 1.8986 * 10^{27}\ [kg]$.

- **Main sequence star:** Stars of average size that undergo hydro-nuclear fusion and whose luminosities correspond predictably to their surface temperatures.

- **Molecular cloud:** A type of interstellar cloud whose density and size permits the formation of molecules, most commonly molecular hydrogen.

- **Nebula:** An interstellar cloud of dust, hydrogen, helium and other ionized gases that permit the formation of stars and other orbiting bodies.

- **Orbital Eccentricity:** A parameter that determines the amount by which its orbit around another body deviates from a perfect circle. Circular orbits have zero eccentricity, whereas eccentric orbits with eccentricities between 0 and 1 are elliptical in shape.

- **Orbital Period:** The time taken by an astronomical body to complete a full revolution around its star.

- **Parent star:** The central star around which a planet orbits.

- **Planetary system:** A set of gravitationally bodies bound in orbit around a central star.
- **Planetesimals:** Bodies of a few kilometres in size that exist in a protoplanetary disk and are formed through the accretion and collision of dust and rock particles. Go on to form planets.
- **Protoplanet:** Large planetary embryos that exist in a protoplanetary disk and are formed because of the collisions of planetesimals.
- **Protoplanetary disk:** A large rotating circumstellar disk of dense gas and dust surrounding a young newly formed star.
- **Protostar:** an early stage of a star, formed in a protoplanetary disk.
- **Semi-major Axis:** Half of largest separation between two points on the ellipse.
- **Super Earths:** Extrasolar planets with a mass slightly higher than Earth's, but substantially less than gaseous planets.
- **Supernova:** An explosion of a star which causes a huge but brief increase in its brightness.

PROLOGUE

I: The Quest of Mankind

What sets us apart from the stones and the stars is our insatiable desire to understand our kinship with both.

- Geoffrey W. Marcy
(University of California, Berkeley)

It is in man's nature to search, explore and discover. Throughout history, man's curiosity has always been pivotal in discovering new territories. This curiosity unites people together as folk with a common goal. The risks and rewards that come hand in hand with the curiosity of discovering the unknown is perhaps what makes the urge of exploration irresistible. There have been many examples of this throughout the history of mankind. What made the man-ape, an early ancestor of today's homo sapiens who lived a million years ago, leave his home and shelter and go out to explore unknown lands? Why did Christopher Columbus and Amerigo Vespucci leave Europe and dare to cross the vast oceans risking their lives in the process? What prompted Neil Armstrong and Buzz Aldrin to undertake one of the most ambitious journeys ever?

Today, it is the dream of many to see man set foot on a new planet. But is it simply a desire to explore and discover uncharted territories or is there a deeper motive lying hidden beneath the natural curiosity? Man has evolved multi-fold since his ape-like ancestor. The questions he asks himself today are no longer simply out of desire, necessity or curiosity. But there is one question to which man seeks an answer above all else. One that has been pondered over and over again since man has had the power of thought, but never answered, like an eternal thirst that cannot be quenched: Are we alone?

Since the dawn of mankind, we have looked up to the night sky filled with clusters of stars and pondered over many questions. What are those hundreds of tiny twinkling lights in the sky? What is our place in the universe? Are there others like us? To date these questions remain unanswered. The reason for this is simple: man cannot tell if any other living being lives elsewhere in the universe until he has made contact with it in some form. And till now, that has not been the case. But it is this hope that drives researchers' quest for extrasolar planets. It is perhaps the same urge that other famous explorers felt in their time that now drives scientists to build powerful machines like the *Kepler* telescope and undertake projects like SETI[1]. To look for new worlds potentially capable of harbouring intelligent life is arguably one of the most intriguing endeavours of modern science. But ultimately it may be that what we learn most from a potential discovery is the nature and origin of life here on Earth itself. And that would be a wonderful thing.

[1] *Search for Extraterrestrial Intelligence*

II: The Evolution of Mindsets

The definition of reality is ambiguous, because of its subjectivity. What man considers as "real" is defined by his knowledge and perception of the elements around him. Hence, knowledge is the determining factor of what people choose to believe and consider as the truth. That is why people and whole societies tend to live within their own convictions and only accept change when something unexpected is thoroughly and irrefutably proven as true. It is only then that people reconsider their understanding of the world and change mindsets.

In the early ages, most people, including notable philosophers such as Aristotle, believed that the Earth was stationary and at the centre of the universe, and everything else - the planets and stars visible with the naked eye at that time - revolved around it. This geocentric model seemingly had logical evidence. If the Earth was moving, wouldn't we feel the movement? And wouldn't we be flung off into space? This model was also the one put in place by the widely-influential Catholic Church, one of their fundamental beliefs being that man is special. He is a special person, created by a divine being and lives in a special place: at the centre of the universe. It was only when Galileo published his works that seemingly proved the contrary, that people slowly changed their minds.

Galileo Galilei was born on the 15th February 1564, three days before the death of another man who would later come to be regarded as the one who defined the Renaissance: Michelangelo. The Earth is estimated to have had around 500 million inhabitants[2] and was still thought to be immobile and at the centre of the universe. During the winter of 1609-1610, just a month or so before Galileo's 46th birthday, he discovered the moons of Jupiter that stunned the public and began the process of his long war with the Church.

Galileo, with his homemade telescope, discovered through his observations four points of light that appeared to form a straight line near Jupiter. He observed them regularly over the course of a few months and made sketches showing the relative positions of Jupiter and the orbs surrounding it.

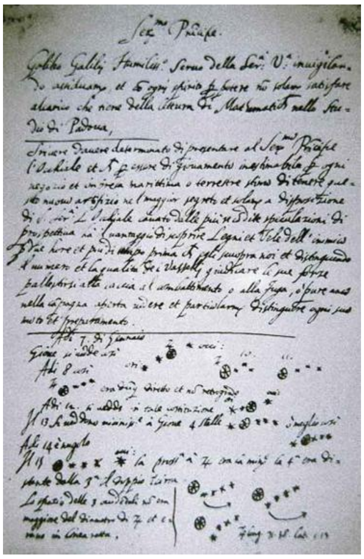


Figure 1: Galileo's first noted observations of Jupiter's moon

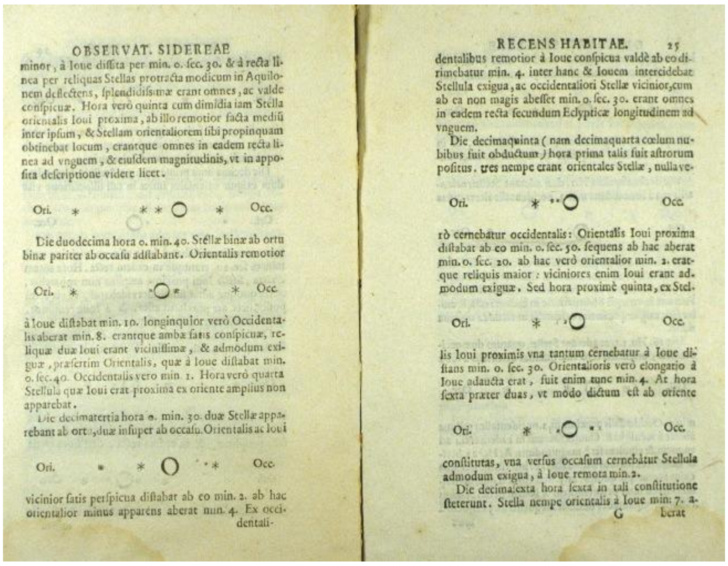


Figure 2: Pages from Galileo's published *Sidereus Nuncius*, illustrating Jupiter and its moons

[2] *United States Census Bureau*, http://www.census.gov/population/international/data/worldpop/table_history.php [as of January 2013]

Although he initially believed that the points of light were stars, he quickly ruled that out after noticing a startling feature. What stood out in his observations was the fact that the positions of the celestial orbs kept changing on subsequent nights. In fact, at times, one of them would even disappear completely. This would have been inexplicable had these really been stars, since they are fixed in the sky, and their only apparent movement is due to the Earth's rotation on its own axis.

Galileo quickly arrived at the conclusion which is, to date, accepted as the truth. He concluded that the celestial orbs surrounding Jupiter were not stars, but actually bodies that were orbiting the planet itself. These bodies would later be called the Galilean moons in his honour.

Although Galileo was the one who received much acclaim for his discoveries, the hypothesis of the heliocentric model, where the Earth revolves around the Sun, had already been proposed philosophically by Aristarchus of Samos, an ancient Greek astronomer, but who had not received any support at the time. It had been further developed by Nicolas Copernicus in 1543, in his book *De Revolutionibus*. Although all of Aristarchus's writings had disappeared by Copernicus's time, the former's ideas had survived because Aristotle had taken the time to refute them. Copernicus took the idea from its philosophical roots, removed the speculation and instead elaborated it in full geometric detail. Unlike Galileo, Copernicus was spared the harassment and accusation of heresy by the Catholic Church, as he spoke only in hypothetical terms and had no proof, therefore ran no risks.

Galileo's discovery of Jupiter's moons was a huge blow to the accepted geocentric model of the universe, because it meant that heavenly bodies could also orbit around something other than the Earth, which implied that the Earth was not so special after all as claimed by Catholicism. Galileo’s observations of Jupiter's natural satellites created a revolution in astronomy, as it did not conform to the principles held worldwide which were set in place by Aristotle. With proof that bodies revolved around Jupiter, it added scientific substance to the idea that the Earth could also revolve around the Sun. The world that people thought was immobile finally started moving in their minds.

Along the way Galileo struck another blow to Aristotle's concepts, this time about the Earth's moon. Through his telescope he observed that the moon was not a perfectly smooth and polished surface of crystalline perfection, as it was then believed. Instead, it had a rocky, rough and uneven surface covered with craters, prominences, valleys and chasms. With one look through his telescope, Galileo saw the opposite of the philosophical and theological teachings that had been in place for nearly two millennia. In a few weeks his observations, published in the same book that described Jupiter's satellites, undid twenty centuries of certainty and startled people enough to change mindsets.

Both of Galileo's discoveries were revolutionary, and inspired many younger generations of astronomers. The discovery of exoplanets is just as big a leap forward, although perhaps in much more subtle ways and certainly with less sensationalism. The scientists in this field are making progress in a similar way that led to Galileo's breakthroughs. They had striven to prove an ancient concept, and are now expanding on that idea with methods that are truly pushing the boundaries of scientific measurements and doing so with astonishing accuracy that could perhaps lead to the one of the biggest breakthroughs in astronomy: detecting a planet capable of harbouring life. We don't know how long it will take. Maybe tomorrow, or maybe not in our lifetimes. But regardless, it is a certainity that a foundation is being created and built that will change the way the universe is perceived, because this time, not only will we better understand our world and its place in the universe, but also its place in relation to another world.

III: The Formation and Evolution of Planetary Systems

Our solar system (comprising the Sun and its planets including Earth) is estimated to have begun forming around 4.5 billion years ago, with the gravitational collapse of a massive molecular cloud. Scientists believe that a collapsed fragment of this cloud formed what is now our solar system. This fragment consisted of Helium and, more importantly, Hydrogen, which is the most abundant element in the universe[3]. These two elements constituted 98% of the mass of this cloud, also known as a nebula. Because of the conservation of angular momentum, the nebula spun faster as it collapses, making most of the mass collect at the centre, which became increasingly hot as it condensed. About a hundred thousand years later, due to the competing forces of gravity, gas pressure, magnetic fields and the rotating motion, the nebula flattened out to a huge, spinning protoplanetary disc. The Sun, at that point still a protostar, formed at the hot and dense centre of the disc, and went through numerous hydro-nuclear fusions before entering its prime phase of life, known as the Main Sequence.

Despite the Sun's formation, a certain quantity of leftover gas and dust remained floating in the protoplanetary disc. The amount was sufficient to form the planets via the process of accretion. With a bit of luck and the help of turbulent motions in the gas, the remaining cosmic dust grains floating around the Sun eventually collided and coalesced, forming clumps which gradually became larger and larger. As the size of these bodies increased, so did their mass, making their gravitational pull stronger, and therefore attracting further bodies. These stuck together until a situation was reached whereby the bodies coalesced into one large object in *each* orbital region. Once these objects are more than a few kilometres in size, they are called planetesimals. However, most of these planetesimals would break apart during violent collisions, and only a few of the strongest would be to able resist and survive such encounters and form into a protoplanet, and later attain the full planetary stage, a process strangely reminiscent of the sperm race.

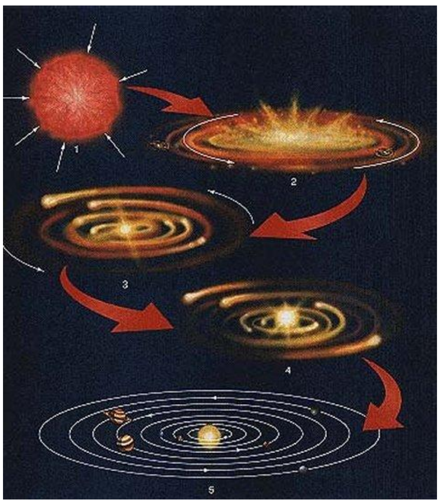


Figure 1: The Formation of a Planetary System

[3] http://en.wikipedia.org/wiki/Hydrogen#Natural_occurrence, section 3.0 “Natural Occurrence”

No two material objects made by nature are the same. We know that no planets in our own solar system are identical. Each planet has different physical properties and characteristics, which makes each one of them unique in this vast universe. We can, however, group the planets in our solar system into two distinct categories: the terrestrial planets, which, like Earth, are largely composed of rock, and the gas giants, which, similar to Jupiter, are mostly made of gaseous material and are significantly larger than their rocky counterparts.

Because of the heat in the inner region of the solar system, molecules such as water and methane were not able to condense, leaving behind only the metallic elements that have a high melting point, such as iron, nickel and aluminium. It is these compounds that became the foundation of terrestrial planets, like Mercury, Venus, Earth and Mars. Due to the rarity of these compounds, these terrestrial planets could not grow large.

The formation of the gas giants is a more complex process, and remains partially unclear. Gas giants develop further out, in the colder regions of solar systems, where fundamental compounds such as ice are found frozen solid. It is believed that the early formation of the gas giants is roughly similar to that of terrestrial planets, the only difference being that these planets have access to ice instead of rock, the former being four times more massive. This substantially enhances the mass and size of the planetesimals, making these types of planets much bigger. Once the cores of the planetesimals are around 5 to 10 times Earth's mass, they have enough gravitational force to begin gathering and accreting gas from the protoplanetary disc. Finally, with enough gas and ice, these protoplanets slowly settle into their orbits.

Generally, the difference between the inner and outer planets ought to exist everywhere, since none of what was explained above refers uniquely to the Sun and our own solar system. In every system, within a certain distance, ice should melt due to the heat of the protostar, resulting in small rocky planets, but beyond this distance, it should be cold enough for ice to exist in a solid state resulting in massive gas planets. Therefore, a dividing line, known as the *frost line*, between the two types of planets is determined by temperature, which is the determining factor for the melting, and therefore, the existence of ice. The dividing line would be at a different distance for each planetary system, as it would depend on the temperature, and hence, the luminosity or the amount of energy emitted by the star.

With this understanding of planetary systems, one can make a prediction, or rather, an educated guess, on how the planetary systems of other stars ought to look: small rocky planets on the inside and large gaseous planets on the outside, just like our very own solar system. Right?

IV: The Dynamics of Planetary Motion

Exoplanets are planets that orbit around stars other than our Sun. They are essentially planets that exist in planetary systems other than our own solar system. To understand how extrasolar planets behave, we first need to understand how our own planets work. Two important laws of planetary motion are of particular relevance to the exploration of exoplanets. These are Newton's Law of Universal Gravitation and Kepler's Third Law of Planetary Motion, which are described briefly below.

Newton's Law of Universal Gravitation:

As a planet orbits around its parent star, its motion causes the parent star to move in its own small orbit in response to the planet's gravity. Mutual gravitation attraction implies the planet also exerts the same attractive gravitational force on the star. This force is expressed as:

$$F = \frac{G * M_s * m_p}{r^2}$$

Where:

- F is a vector whose direction is always along the line joining the centre of mass of M_s and m_p. Expressed in Newtons $[N]$.
- G is the Universal Constant of Gravitation $\cong 6.67 * 10^{-11}$ $[N]$
- M_s is the mass of the star $[kg]$
- m_p is the mass of the planet $[kg]$
- r is the distance between the star and the planet $[m]$

We also know that $M_s > m_p$. Both bodies exert this equal force on each other. However, the acceleration on each one is different. Using Newton's second law of motion, we can derive the acceleration:

$$F = m * a$$

$$\leftrightarrow a = \frac{F}{m}$$

$$\leftrightarrow a = \frac{G * M_s * m_p}{r^2} \div \frac{m}{1}$$

$$\leftrightarrow a = \frac{G * M_s * m_p}{r^2} * \frac{1}{m}$$

Depending on which body's acceleration we trying to find, the two masses cancel out to become:

Either $a = \frac{G * M_s}{r^2}$, which is the acceleration on m_p due to M_s

or $a = \frac{G * m_p}{r^2}$, which is the acceleration on M_s due to m_p

Although the gravitational constant G and the planet-star distance r remain the same for both bodies, the difference between the two accelerations is huge because of the difference between M_s and m_p . This is very important for one of the methods of detection, explained later.

Kepler's Third Law of Planetary Motion:

Kepler's Third Law relates the orbital period (*P*) i.e. the time a planet takes to complete a full orbit around its star, and the semi-major axis (*a*), which is the distance from the star to its orbiting planet. Since the orbits of planets are not perfectly circular, the distances are not called radii, but semi-major axis and they are measured in Astronomical Units (AU), which is the Earth-Sun distance. Kepler's law implies that the square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit. In simpler words, using this equation, one can determine a planet's distance from its star, as long as we know how long it takes to go around it.

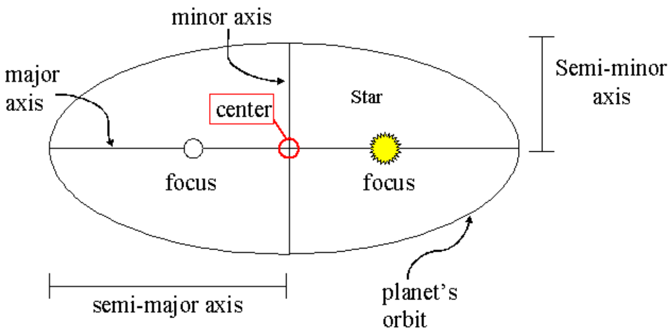


Figure 2: The Semi-Major Axis of any Planetary System

This law can be simply expressed as:

$$P^2 = constant * a^3$$

$$\leftrightarrow \frac{P^2}{a^3} = constant$$

The ratio of the period squared to semi-major axis cubed gives a value which is constant for different planets around the same star. It is a constant for any smaller object orbiting the same massive central object, like the planets orbiting the Sun in our solar system: [4]

Planets	P [years]	*a* [AU]	P^2	a^3	Constant
Mercury	0.241	0.39	0.06	0.06	0.98
Venus	0.615	0.72	0.38	0.37	1.01
Earth	1	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51	1.01
Jupiter	11.9	5.20	141.61	140.61	1.01
Saturn	29.5	9.54	870.25	868.25	1.00
Uranus	84	19.19	7056.00	7066.83	1.00
Neptune	165	30.06	27225.00	27162.32	1.00

[4] Data taken from http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html and http://en.wikipedia.org/wiki/Planet#Planetary_attributes section 4.1 « Planetary Attributes ».

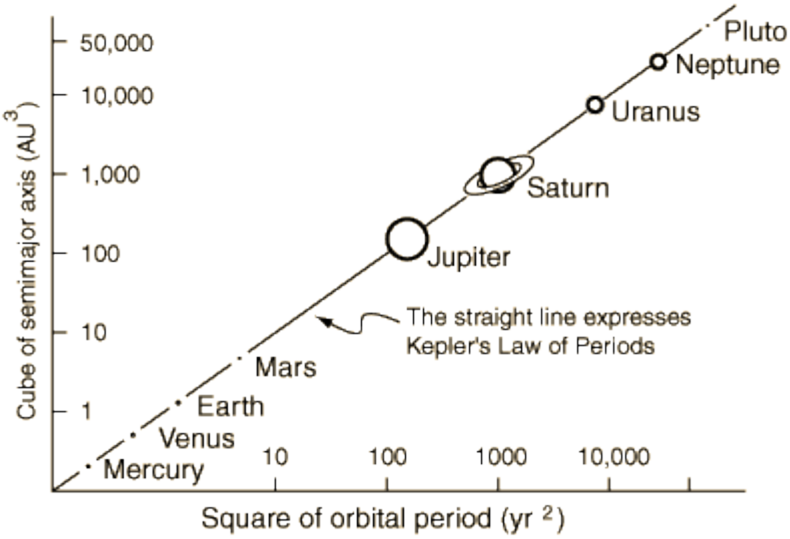


Figure 3: Kepler's Third Law as applied to planets in the solar system

However, the constant would not be the same for planets across different planetary systems:

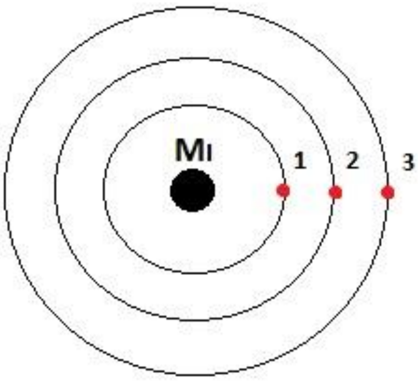


Figure 4

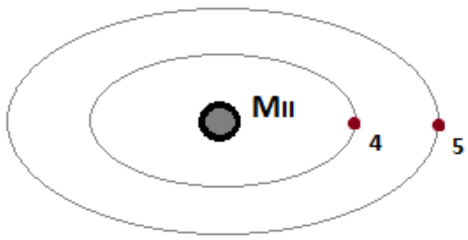


Figure 5

$$\frac{p_1{}^2}{a_1{}^3} = \frac{p_2{}^2}{a_2{}^3} = \frac{p_3{}^2}{a_3{}^3} \neq \frac{p_4{}^2}{a_4{}^3} = \frac{p_5{}^2}{a_5{}^3}$$

Using Newton's Law of Universal Gravitation and Newton's Laws of Motion one can derive Kepler's Third law. Let us use the following simplified model to help our understanding:

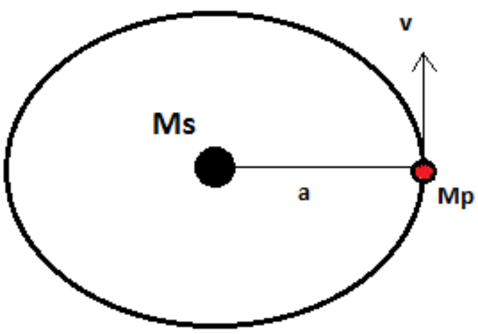


Figure 6

Newton's law of universal gravitation implies that the star and planet are attracted by each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Simply put:

$$F = \frac{G * M_s * m_p}{a^2}$$

The planet is attracted to the star due the gravitational force which is also equal to the centripetal force, as shown in this close-up of the planet:

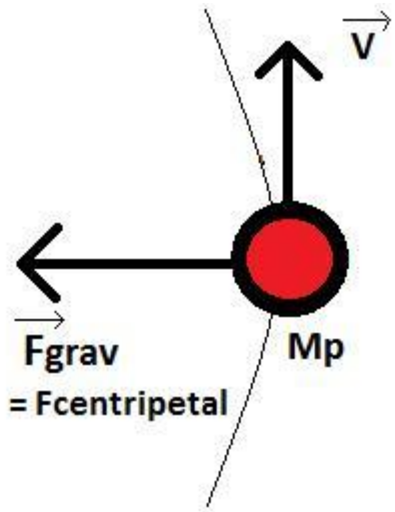


Figure 7

Newton's second law states that this force is calculated by the equation:

$$F = mass * acceleration$$

For circular motions, the acceleration is equal to the squared speed divided by the star-planet distance (r), which is the semi-major axis (*a*):

$$acc = \frac{v^2}{r} = \frac{v^2}{a}$$

The speed (*v*) is calculated by the division of distance (approximately the perimeter of a circle) over time (the orbital period):

$$v = \frac{distance}{time} = \frac{2 * \pi * r}{p} = \frac{2 * \pi * a}{p}$$

Therefore, with the following equation, we can successfully derive Kepler's 3rd law:

$$Fgrav = Fcentripetal$$

$$\leftrightarrow \frac{G * M_s * m_p}{a^2} = m * acc$$

$$\leftrightarrow \frac{G * M_s * m_p}{a^2} = m_p * \frac{v^2}{r}$$

$$\leftrightarrow \frac{G * M_s * m_p}{a^2} = \frac{m_p * v^2}{a}$$

$$\leftrightarrow \frac{G * M_s}{a} = v^2$$

$$\leftrightarrow \frac{G * M_s}{a} = (\frac{2 * \pi * a}{P})^2$$

$$\leftrightarrow \frac{G * M_s}{a} = \frac{4 * \pi^2 * a^2}{P^2}$$

$$\leftrightarrow \frac{a^3}{P^2} = \frac{G * M_s}{4 * \pi^2}$$

$$\leftrightarrow \frac{a^3}{P^2} = constant$$

Where:

- a is semi-major axis of the orbit $[m]$
- *acc* is the acceleration $[m/s^2]$
- *p* is the Orbital Period $[s]$
- *G* is the Universal Constant of gravitation $\cong 6.67 * 10^{-11}$ $[N]$
- M_s is Mass of the star $[kg]$
- m_p is Mass of the planet $[kg]$

Both these laws are important because, as we note later, they apply as much to the planets in our solar system as to extrasolar planets. These laws provide the basis for the detection and measurement of some properties of extrasolar planets, which is why their full comprehension is essential.

V: A Short History of Exoplanetology

There are infinite worlds both like and unlike this world of ours. We must believe that in all worlds there are living creatures and planets and other things we see in this world.

- Epicurus
(341-270 BCE; 2300 years ago)

There cannot be more worlds than one.

- Aristotle
(384-322 BCE)

Mankind has long since speculated about planetary systems other than our own. Philosophers hypothesized centuries ago that our solar system was not unique; that there were in fact countless more that existed in the seemingly limitless ocean of stars. The possibility of life existing on a planet orbiting another star was not just a plausible theory but it also had the advantage of the odds on its side. The fact that there are hundreds of billions of galaxies in the observable universe, with each galaxy containing some hundred billion stars;[5] it seems almost ridiculous to suggest that Earth might be the only planet in the whole universe capable of supporting life.

However, the lack of scientific evidence to back this visionary viewpoint meant that the thinking over the past two thousand years ranged over all extremes. On the one hand, some, like Epicurus, believed in the existence of worlds in the universe other than ours and in their capacity to harbour life. On the other hand, many, such as Aristotle, faithfully held the view that the Earth was unique in the universe and that other similar worlds could not exist. Christianity and other faiths would also claim the hand of God in the creation of Earth and all living beings.

Hence, the search for extrasolar planets became a subject of intense scientific investigation. Due to the lack of evidence, it was unknown how common they were, how similar they were to the planets of the Solar System, or how typical was the make-up of our own Solar System in comparison with planetary systems around other stars. The question of habitability was also an important one. If there were any other planets, did they also have the necessary surface conditions to support some form of life? There were many questions but few answers. The main obstacle lay in the inability to directly observe these unknown bodies.

The Hubble Space Telescope has perhaps spoiled us all - we have now come to expect to frequently see images of distant galaxies and nebulae. Taking an image of an extrasolar planet therefore should not be any more difficult than taking an image of a distant galaxy. However, the problem arises due to the fact that the host star completely outshines its small, and rather faint, planet. In most cases the planets are too close to their respective stars to be directly imaged, especially from Earth's surface, given the disturbing effect of our atmosphere.

It was only in 1995 that the first definitive detection of an extrasolar planet was reported by Michel Mayor and Didier Queloz of the University of Geneva. Although a few other detections had

[5] http://en.wikipedia.org/wiki/Galaxy

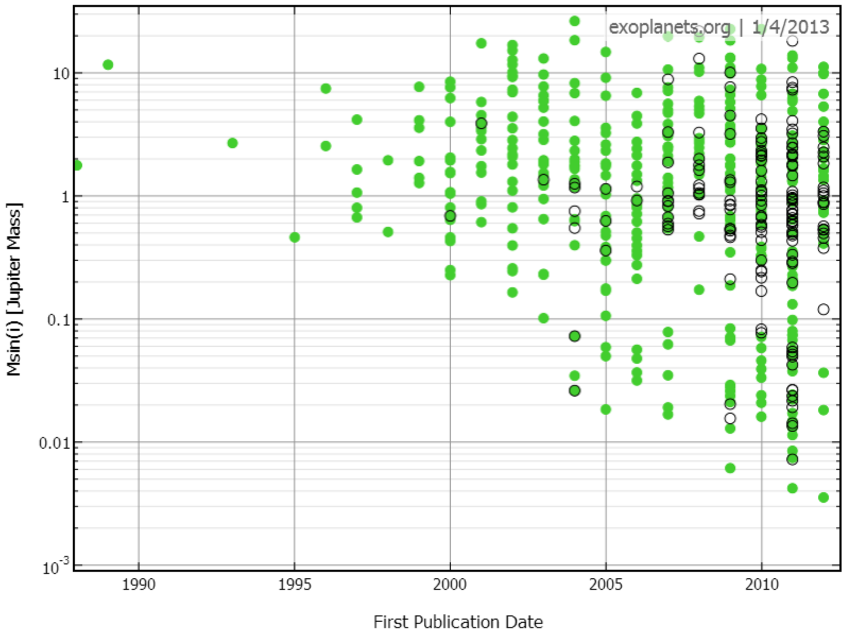
been made some years earlier by radio astronomers Aleksander Wolszczan and Dale Frail, they had not been found around an ordinary star but around a pulsar - the superdense remnant of a massive star that had exploded as a supernova. Mayor and Queloz's announcement of the exoplanet *51 Pegasi b* in October 1995 in Geneva was essentially considered to be the first unambiguous exoplanet detection. Over the years, there have been several other discoveries that could be regarded as milestones, such as the detection of multiple planet systems and the first detection of planetary atmosphere.

Since 1995, there has been astonishing progress in this field. New discoveries and significant developments continue to be announced roughly on a monthly basis, an unprecedented level of advancement in any field of science. As of 1st January 2013, a grand total of 854 exoplanets had been identified with the use of several different methods of detection.[6] The search for exoplanets has rapidly become a respectable domain of scientific research and a field of astronomy capable of standing on its own. The advance in this domain has not only been accompanied by the publication of several thousand scientific papers but has also seen improvements in optical astronomical instrumentation which led to the launch of the *Kepler* telescope and new techniques of detection.

[6] Jean Schneider, *The Extrasolar Planets Encyclopaedia*, http://exoplanet.eu/catalog/ [as of 4th January 2013]

VI: The Methods of Detection

Over the past two decades several different techniques have been employed to detect exoplanets. As mentioned earlier, the light emitted by a parent star always washes out the little light reflected by its planet(s). Hence, scientists had to come up with alternative and indirect methods to detect exoplanets, since observing them directly is almost impossible. This chapter gives an overview of the most established methods that have yielded success and also the logic and science behind them, while discussing the advantages and disadvantages of each method.



Graph 1: Discovery of exoplanets by year using Radial Velocity Method (Green) and Transit Method (Black)

The Radial Velocity Method

Also called the RV method, it has been the most successful technique used to date. Michel Mayor and Didier Queloz found the first acknowledged exoplanet using this method in 1995. It has since been used to locate 498 extrasolar planets to date.[7]

As seen in Graph 1, scientists have been able to detect a large variety of planets over the years. The mass of exoplanets are expressed in relation to the mass of Jupiter, as *Jupiter Mass.* However, mass measurements of the planets are uncertain up to a factor of $sin(i)$, where i is the angle of inclination of the planets that orbit around its star. Hence mass is plotted as $M * sin(i)$, and not just M. Over the years, the technology has improved in sensitivity and accuracy and scientists have now found many planets with Jupiter masses lower than 0.1, a feat not achieved till around 2004.

This technique is most effective for detecting massive planets that orbit close to their parent stars. It is worth noting that this method only provides a lower limit on the planet's mass, which is its biggest disadvantage. A planet's true mass can only be determined when a combination of this technique and the Transit Method, described later, are used together.

[7] Jean Schneider, *The Extrasolar Planets Encyclopaedia*, http://exoplanet.eu/catalog/?f="radial"+IN+detection+OR+"astrometry"+IN+detection [as of 4th January 2013]

The RV method is based on the natural system of gravity and orbits, defined by *Newton's law of Universal Gravitation*.[8]

As mentioned previously, a planet's gravitational force makes its parent star wobble in its own small orbit. Although the force that the star and planet exert on each other is the same, the difference between their accelerations is huge because of the difference between the mass of the star and planet, which is equal to at least 10^3. Since the acceleration of the planet is based on the mass of the star, which is very high, the planet moves a lot. Conversely, the star's acceleration is small, as it is based on the planet's mass, which is relatively small. This feeble acceleration is what causes the star to "wobble" in its small orbit.

This "wobble" causes small perturbations in the observable properties of the star, such as its angular position on the sky with regard to the Earth. A more important change is the *variation* in the *speed* with which the star moves towards or away from Earth, where it is being observed. To better understand the RV method, we first need a basic understanding of the Doppler effect and general spectroscopy, as both are used in combination to detect exoplanets.

The Doppler Effect

Let us take the example of the sirens of a firetruck to understand this concept. Let us imagine an immobile firetruck that has its sirens on. This stationary source produces sound waves λ at a constant frequency f which move outward at the constant speed of sound $c \approx 340\ [m/s]$. Since the sound waves propagate away from the source in *all* directions, they would appear as circles if they were visible, and all observers will hear the *same* frequency, which is, in this case, the actual frequency of the source. In other words, the observed frequency f is equal to the emitted frequency f_0.

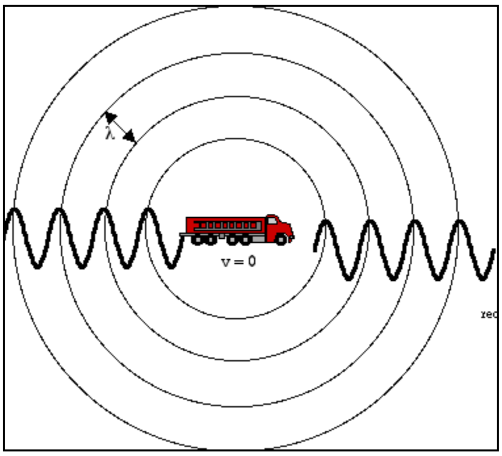


Figure 8: A stationary firetruck emitting sound waves at a constant frequency

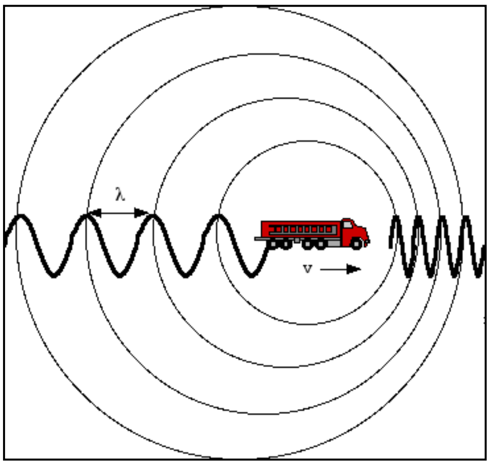


Figure 4: A moving firetruck emitting sound waves at a constant frequency

However, if the firetruck starts moving in a direction, the sound waves become uneven due to the difference of wave lengths. The sound waves emitted by the sirens are at the *same frequency in both cases*. However, since the source is now moving, the centre of each new wave is slightly displaced in the direction of the firetruck (as shown in the figure on the right). As a result, the sound waves start to collect on the front of the firetruck, and spread apart behind it. This phenomenon is called the Doppler effect. As the wavelength of the sound waves is different, the observed frequency

[8] See *Newton's Law of Universal Gravitation* in Chapter III : « Dynamics of Planetary Motion ».

is affected as well. Therefore, an observer in front of the source will hear the sirens at a higher frequency, while another observer behind it will hear is at a lower frequency. The change of observed frequency is what causes the audible change of pitch of the sirens. The observed frequency f can be calculated using the following formula:

$$f = \left(\frac{c + v_{observer}}{c + v_{source}}\right) * f_0$$

Where:

- c is the velocity of the waves in the medium, in our case air, which is approximately equal to 340 $[m/s]$.
- $v_{observer}$ is the velocity of the observer, expressed in $[m/s]$. It will be positive if the observer is moving towards the source, and negative if moving away from it.
- v_{source} is the velocity of the source, also expressed in $[m/s]$. Similarly, it will be positive if the source is moving away from the receiver, and negative if moving towards it.
- f_0 is the frequency emitted by the source, expressed in $[Hz]$.

In order for this effect to be observed, the relative motion must be along the line joining the observer and the source of the waves, i.e. either towards or away from the observer. The motion that is directed along this line is called the *Radial Motion*, and the velocity of this motion is called the *Radial Velocity*. If the observer, in relation to the wave source, is neither approaching nor receding, there is no effect. The Doppler effect is a phenomenon that affects the wavelength and frequency of any form of wave motion such as sound waves, water waves, light waves, and indeed all electromagnetic waves.

Now let us make our analogy more relevant to astronomy. Instead of a firetruck emitting sound waves, let us imagine a star emitting light waves. We, the humans on planet Earth, are the observers, and the star is the source of the light waves. If this star is without an exoplanet, it would have no apparent radial velocity, as it would be stationary. However, as mentioned previously, when a planet is orbiting a star, the latter also moves in its very small orbit in response to the former's gravitational force. Or rather, both of them orbit their common centre of mass, which happens to be *within* the star itself, causing it to wobble slightly. Therefore, *if* we can observe this "wobble", *then* we can conclude that an actual exoplanet is likely orbiting it. This "wobble" is actually the variations in the radial velocity of the star. Astronomers can detect these variations by applying spectroscopy to the Doppler effect.

Spectroscopy

Now let us imagine that our abovementioned star *does* have an exoplanet orbiting it, causing variations in its radial velocity, which are "seen" by us, the observers. Just like the firetruck, when the star appears to be moving *towards* us, the wavelengths it is emitting will be smaller i.e. more compressed and bunched up, and therefore of higher observed frequency. Conversely, when it moves *away* from us, the wavelengths will be larger i.e. more stretched and spread out, and the observed frequency lower. However, light waves behave slightly differently from sound waves: instead of a change in their audible *pitch*, light waves change in their *spectral colour*. In other words, the frequency, wavelength and spectral colour of light waves are all inter-related.

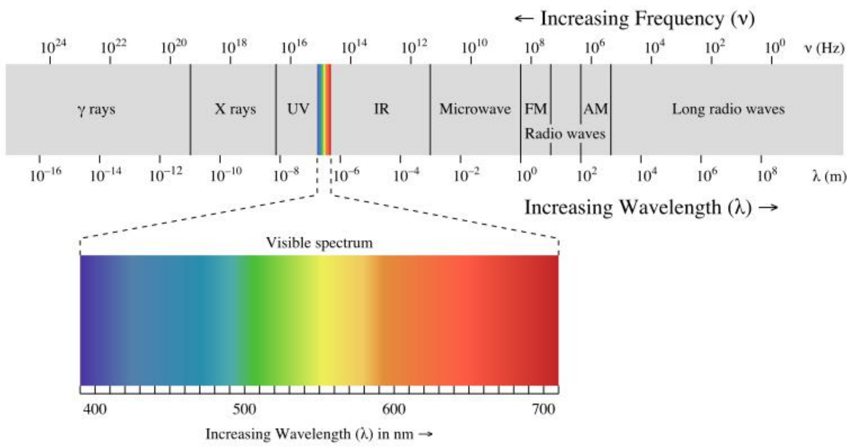


Figure 9: The Electromagnetic Spectrum, with the visible light section highlighted

The wavelengths corresponding to the visible spectrum are as following:

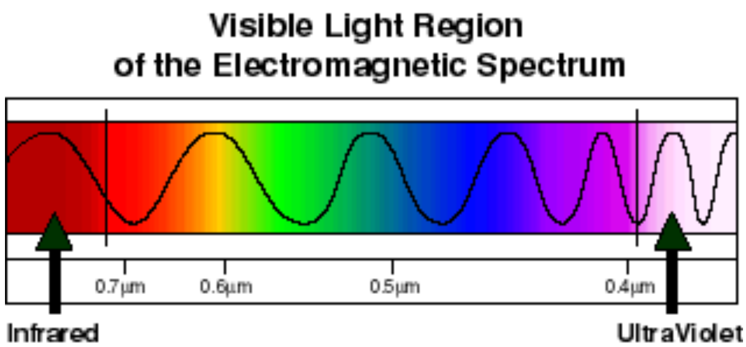


Figure 10: Variation in wavelength and frequency by colour

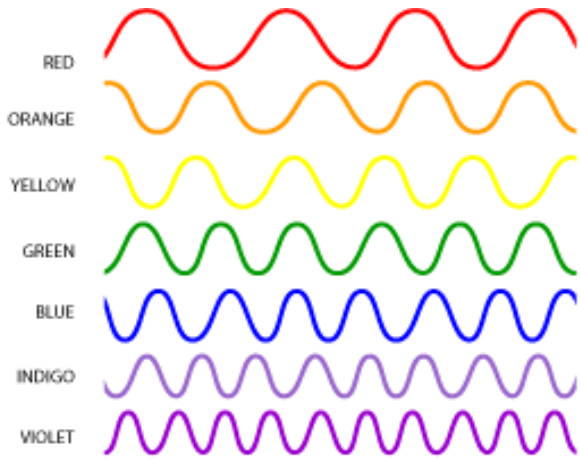


Figure 11: Wavelengths according to colour

When the light waves have small wavelengths and a high frequency, the light waves are *blueshifted*, meaning they have a blue spectrum colour. When the light waves have large wavelengths and low frequency, they are *redshifted*, meaning they have acquired a red spectrum colour.

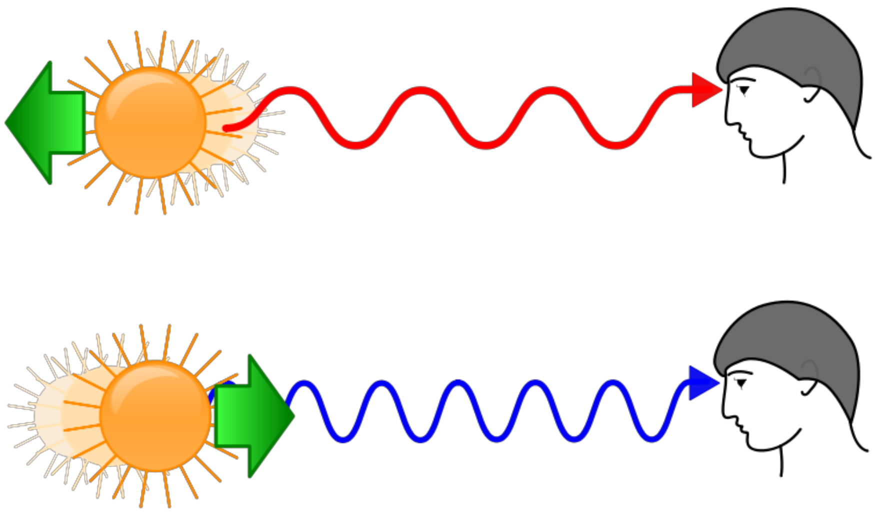


Figure 12: Change of Spectrum Colour due to the direction of the Radial Motion of the Star

Because of the Doppler effect, we know that when light waves are redshifted, they are moving *away* from us in radial motion, because of their increase in wavelength (and therefore decrease in frequency). In the same vein, when the light waves are blueshifted, we know that they are moving *towards* us, because of the decreasing wavelength and increase in frequency.

So when we observe the spectrum colour of the light waves emitted by our chosen star, we see that they continuously change from red to blue. This periodic spectrographic shifting occurs because the star is continuously moving on its small orbit, and thus periodically reducing and increasing its distance to us, the observers.

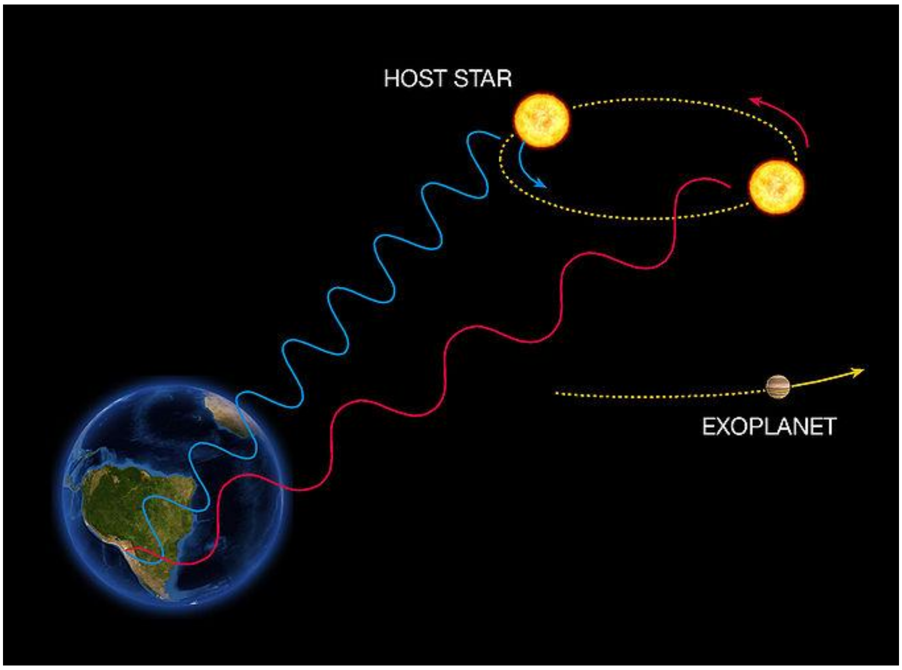


Figure 13: "Wobble" of star causing a Periodic Spectral Colour Change. The motion of the star has been exaggerated to illustrate the point.

To sum up, by using high precision spectroscopy instruments, we can effectively detect a periodic spectrographic shift in the spectral colours of the host star, implying a periodic change of wavelength in its visible light waves, in turn indicating an apparent radial motion, which can only be caused by the gravitational force of an exoplanet as it compels the star to move around the combined centre of mass of both the bodies, thereby confirming its existence.

Transit Method

Another method that has produced results in detecting exoplanets is the transit method, which is mostly known due to the space based missions such as *CoRoT* [9] and *Kepler*. The basics of this technique are simple: if a planet passes in front of the star it is orbiting, the intensity of the light that is being received on Earth will see a small drop.

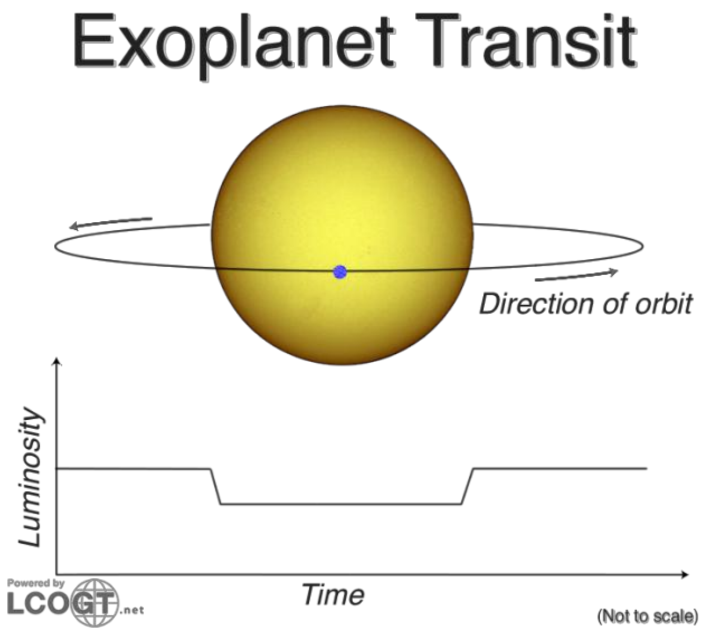


Figure 14: The Observable Drop of Light during a Transit

By observing the variations in the brightness of the star's light caused by the transits of the planets, one is able to detect exoplanets. Although the drop in luminosity depends on the relative size of the star and planet, the typical amount is estimated to be between 0.01% and 1.7%.[10] The duration of the transit also depends on the planet's distance from the star and the star's size.

This technique has one obvious flaw: it is only applicable when the planet's orbital plane is aligned with our line of sight, so that we can witness the planet blocking some of the star's light.

[9] *Convection Rotation et Transits planétaires*, a space mission led by the European Space Agency and the French Space Agency with a goal of search for exoplanets.
[10] http://en.wikipedia.org/wiki/Transit_method#Transit_method

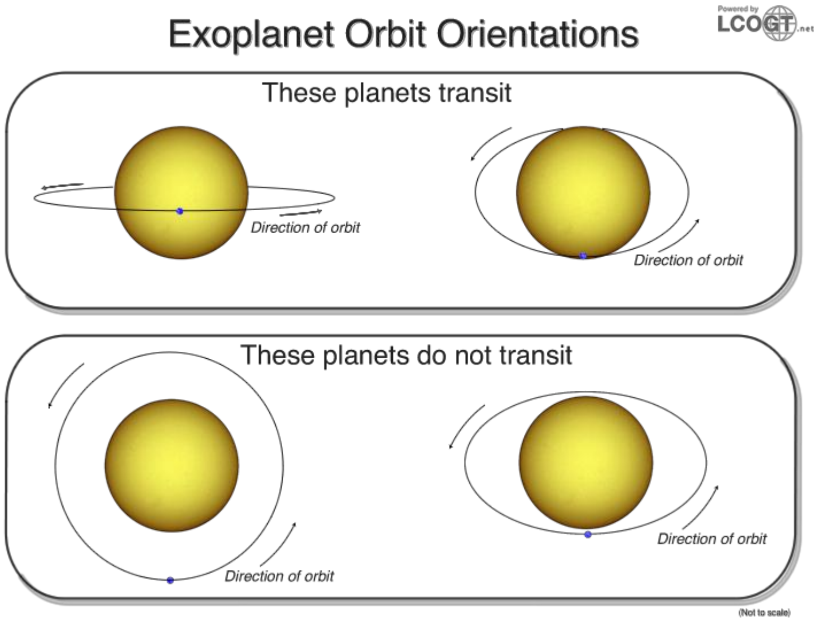


Figure 15: Varying Orbital Inclinations determine the Observation of a Planetary Transit from Earth

A planet orbiting a sun-sized star at Earth-Sun distance (1 AU) will have a probability of 0.47%[9] of producing a transit to an observable alignment. One could therefore deem this method as potentially impractical and unproductive. However, by scanning for stars in large areas of the sky which contain several thousands of them, one can, in principle, find extrasolar planets at a pace which could potentially exceed that of the Radial Velocity Method. It is in this hope that many missions have been launched, notably the *Kepler* mission. As of December 2012, 291 planets [11] have been found using this method and over 2000 candidate exoplanets found by *Kepler* are awaiting confirmation.

Another disadvantage with the transit method is the length of time necessary to confirm the authenticity of planet candidates. Indeed, observation of a single transit is not enough to be fully accepted as a planet due to the high rate of false detections. Hence, it can take many years for a candidate to be confirmed as an extrasolar planet, as one has to wait for it to orbit several times. This method is also more biased towards detecting large planets with small orbits, designated as Hot Jupiters, as they transit more frequently and are therefore easier to detect.[12]

On the other hand, one of the advantages of the transit method is that the dip in light provides an estimate of the planet size. But by far, the biggest advantage is that we can determine the atmospheric composition of the exoplanet which is vital in ascertaining its potential for habitability. When the planet is transiting the star, the starlight goes through the planet's atmosphere before reaching the Earth, giving us the opportunity to detect whether elements such as oxygen are present in it.

The dip in the emitted light of a star is more when the planet transiting it has an atmosphere, as the elements present in it absorb *some* of the light waves in addition to those that were already blocked by the body of the planet. The atmosphere of the planet essentially acts like a filter to the light waves of the star, blocking some and letting go of some, depending on the atmospheric elements.

[11] http://exoplanet.eu/catalog/?f= "transit"+IN+detection
[12] See *Probability Distribution of Periods*, in chapter VII: Interpretation of Data

The elements present in the atmosphere block the wavelengths that correspond to them, which result in the appearance of black lines in the spectrum, and are called *Absorption lines*.

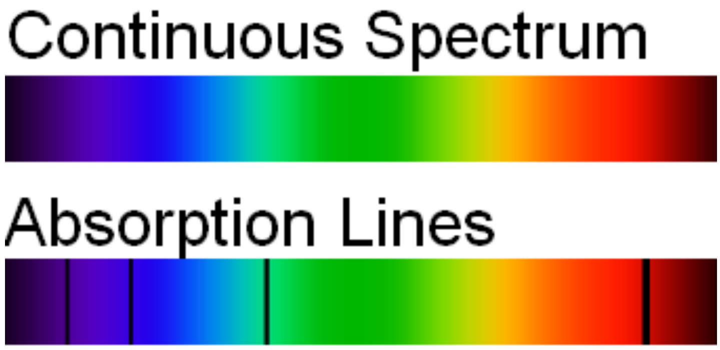


Figure 16: An example of Absorption Lines

Each element is associated with a specific set of wavelengths that it blocks because of its chemical properties. So when we find absorption lines in the light spectrum of a star that has a planet transiting it, we know that the planet in question has an atmosphere. By analysing the absorption lines, we can determine the chemical composition of the atmosphere by looking at the element(s) corresponding to the wavelengths. If the absorption lines of the stellar spectrum correspond exactly to the absorption spectrum of an element, then it indicates its presence.

Figure 17: Absorption Lines in the Spectrum of a star matching those of Hydrogen, confirming its presence

For example, by finding absorption lines in the spectrum of a star that match those of oxygen, we could determine whether the exoplanet orbiting it could potentially be habitable or not.

ANALYSIS

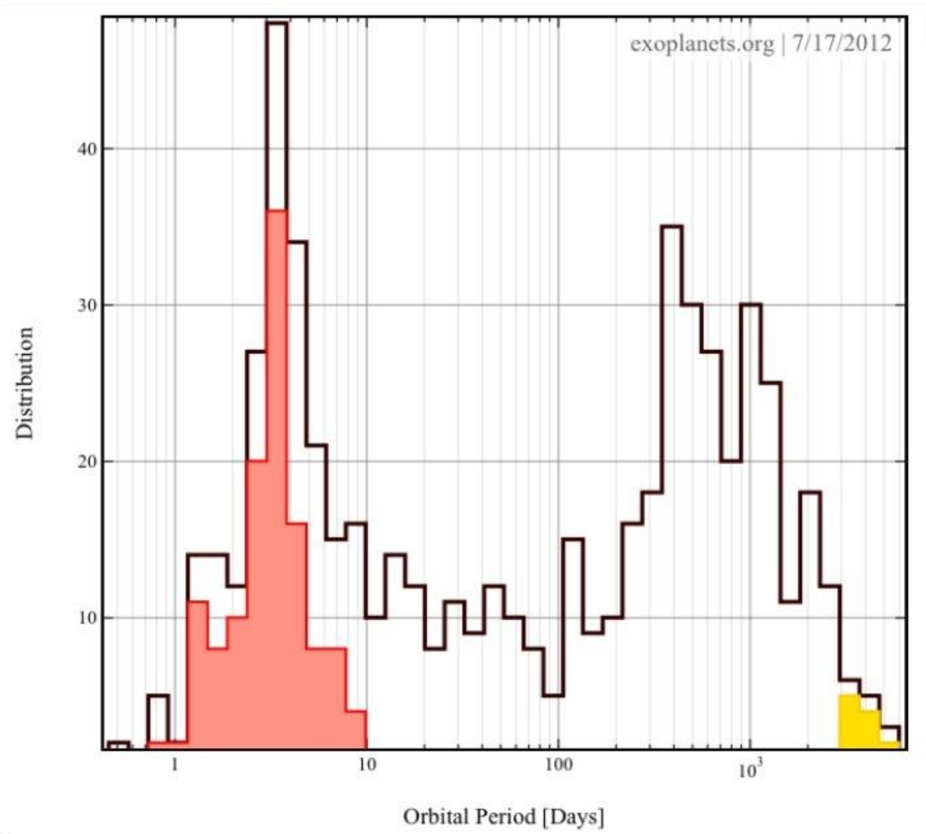
Now that we've seen and understood the historical background, the scientific value of the research, and the implications of the discoveries, we will look at the actual data found and compiled by space missions, so that we can relate them to actual physics. By plotting graphs of the data, we can visually see the correlations with theories or laws of physics established several centuries ago by renowned physicists such as Newton and Kepler.

VII: Interpretation of Data

To fully understand the science behind the field of exoplanets, one must look at the actual research data which is often made public. Several teams have compiled all the information into large databases available for public viewing through the Internet, such as the NASA Exoplanet Archive or the Extrasolar Planets Encyclopaedia. The most useful tool in these websites is the graph plotter, which allows one to visually explore, comprehend and analyze the data in several different ways.

In the following pages we will analyse a set of interesting graphs generated using the data from www.exoplanets.org, a site maintained by the California Planet Survey consortium which displays the list of confirmed exoplanets (i.e. no candidates), along with their characteristics.

Probability Distribution of Orbital Periods:



Graph 2: The Number of Exoplanets found for each value of Orbital Period

The above graph shows the number of exoplanets detected in relation to their orbital periods i.e. the number of days they take to complete a full orbit around their parent star.

At a quick glance, there are a few features that stand out in this graph. First of all, there are two big peaks, one between 3 and 4 orbital period days which is narrow but long, and the other, short but wide, which peaks at approximately 400 orbital period days. The other noticeable feature is the deep dip between the two peaks.

Now if we were to put the orbital periods of our solar system's planets, five out of the eight planets would fit in the second peak. Yet, we seem to find as many exoplanets within the parameters of the first peak. Furthermore, it seems that no planets have been detected that have more than 5000 days as their orbital period, which is just a bit more than Jupiter's orbital period. Even though many of the planets detected don't seem to have Jupiter's orbital period, a large number of them do have Jupiter's mass.

The graph shows two coloured sections. The smaller, yellow section represents the *Jupiter-Analogs* i.e. the exoplanets that are like our own Jupiter in terms of mass and orbital period. The bigger, red section represents the *Hot Jupiters*, which are also similar to Jupiter in terms of mass, but they have a much smaller orbital period, meaning they orbit very close to their parent star, hence receiving a lot of light and heat, making them, as their name suggests, hot. As the (second) graph shows, the orbits of these Hot Jupiters are smaller than that of Mercury, the planet closest to its host star in our own solar system. There are 125 Hot Jupiters shown in the graph, but only 11 Jupiter-Analogs. And therein lays the biggest surprise in the search for exoplanets.

Researchers have found many such intriguing patterns which have confounded expectations. What makes the findings of Hot Jupiters unusual to us, is that before we started discovering many planets, the general consensus was that the smaller sized planets would orbit closer to the star and perhaps the massive ones remained on the outskirts of the planetary systems. However, many of the newfound planets orbit their stars at relatively tiny distances, less than one-sixth of the distance from sun to Mercury, the innermost planet in our solar system. No one anticipated that Jupiter-like planets could exist so close to their stars. With this new data, what we thought was basic knowledge of solar systems is now no longer up-to-date. We must now also re-evaluate our place in the universe: how common is our solar-system type? Is it unique? Are we a rare type or are we typical? How much do we really know and understand?

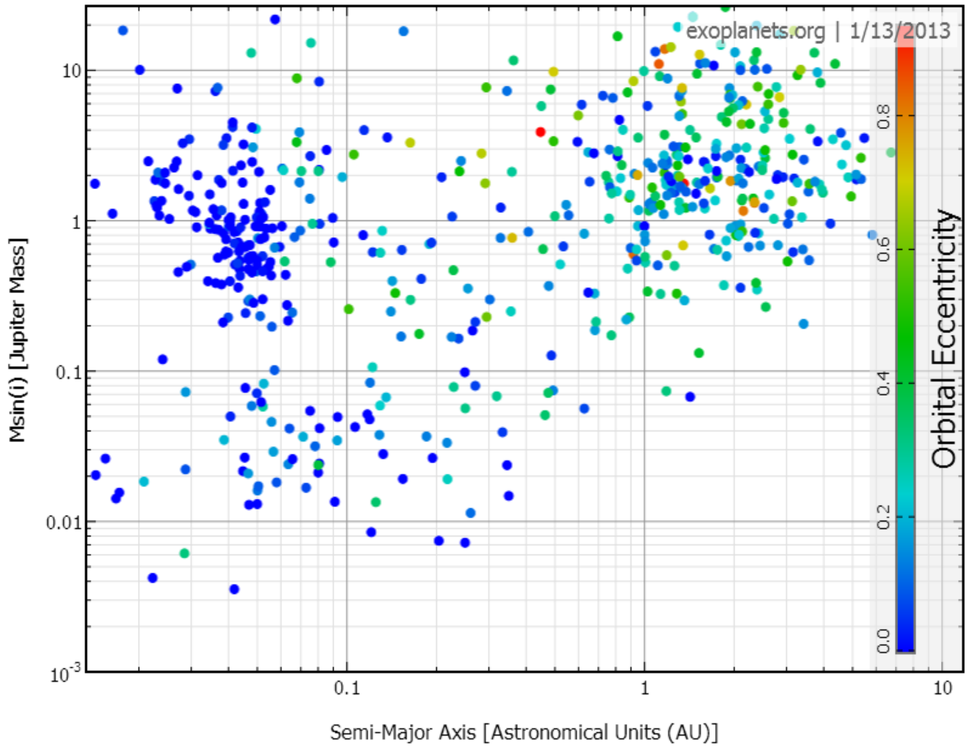
Currently, exoplanets are detected by using their parent stars as a tool. In other words, we are discovering new extrasolar planetary systems, and already have enough to come up with the following statistic: at least 50% of the exoplanets discovered so far are *not* like our solar system in terms of the planetary positioning. This implies that our kind of solar system makes up *at best* only half of the all the planetary systems in the universe. Essentially, when we look at the stars, we see that only one out of every two stars have terrestrial planets. This suggests that systems like ours are *not* the majority in the universe! Even the terrestrial planets that have been found are several times more massive than Earth, and thus called "Super Earths".

One of the theories put forward to explain the mystery of Hot Jupiters is the Theory of Migration, which says that the planets migrated inwards with time, and we are therefore seeing them at a later stage of formation. Indeed, these massive planets must have started out a hundred times further away and with time migrated inwards to reach their present distances from their stars.

This of course begs the question as to how and, more importantly, why would they migrate, assuming they did? Were their original orbits unstable? What generated the energy to give momentum to these massive bodies? Perhaps the truth will never be clear to us, but the Theory of Planetary Migration does provide us with some explanation for occurrence of Hot Jupiters.

Minimum-Mass in relation to Semi-Major Axis:

The following graph is a good illustration of Hot-Jupiters:



Graph 3

The X-Axis of this graph represents the semi-major axis, which is the distance from the star to its orbiting planet. The Y-Axis represents the mass of the exoplanets, which is measured in relation to Jupiter's mass to make the scale more relevant to the issue of Hot Jupiters.

Finally, a colour scale is added, as shown on the right side of the graph, to represent the Orbital Eccentricity of each planet. The Orbital Eccentricity is the amount by which the planet's orbit deviates from a proper circle. At zero, the orbit of a planet is perfectly circular, represented in blue. As the eccentricity increases, the orbit becomes more parabolic, seen in red in Graph 3 above.

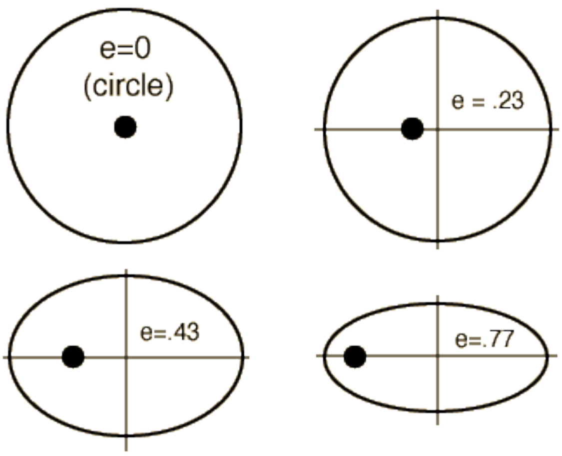
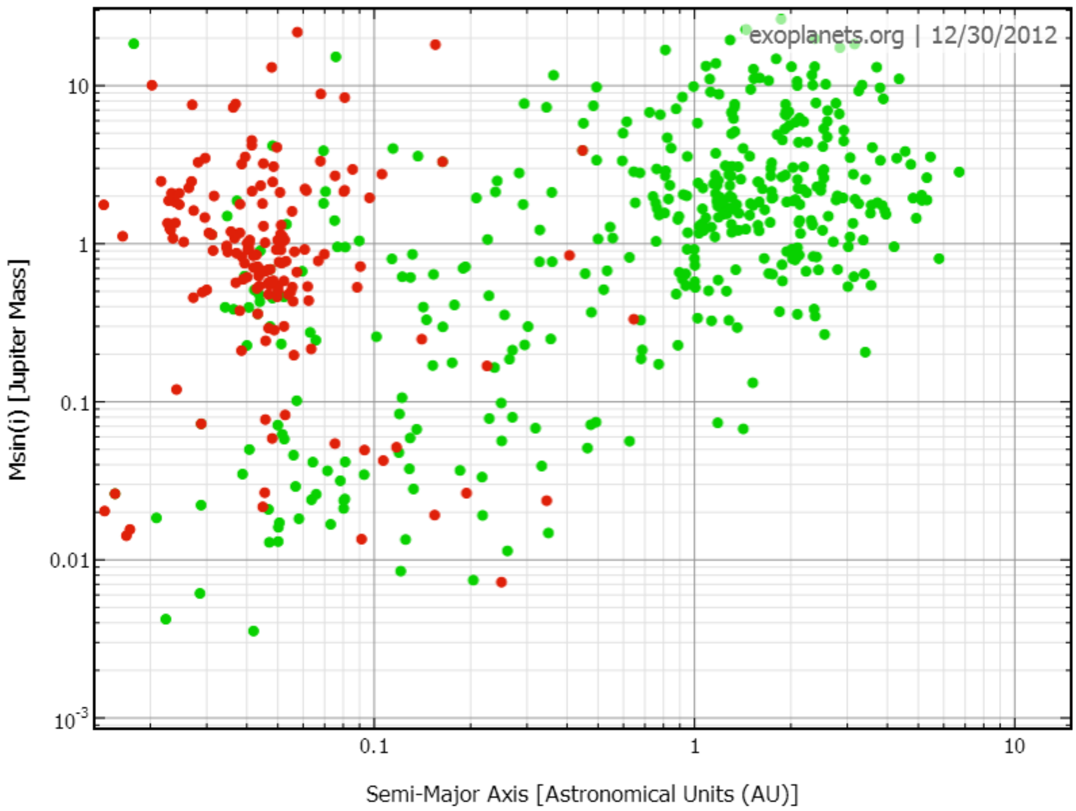


Figure 20: Variations in Orbital Eccentricities

In Graph 3, one can clearly see two main concentrated clusters of planets. As mentioned before, the majority have the same mass as Jupiter. The top left hand side clump consists of planets that are hotter, since they are much closer to their star. These are the typical Hot Jupiters, and most were detected using the **Transit Method**. We can also see that almost all of these planets are represented in blue, meaning their orbital eccentricity is close to zero, implying a circular orbit.

However, the other clump of planets is in a much colder region, being much further away from its star. The semi-major axis is approximately 1 AU. Unlike the previous cluster, this clump has a mixed orbital eccentricity: they range from 0 to 0.8, meaning they tend to have a more eccentric orbit. These seem to be the typical gas giants, also called Jupiter-Analogs, and are mostly detected by the **Radial Velocity** method, as illustrated in Graph 4 below.



Graph 4: Planets detected by Transit Method (Red) and Radial Velocity (Green)

The difference in eccentricities between the two clumps is striking. Most planets in the left clump have perfectly circular orbits, while those in the right clump are more varied and tend to be eccentric. It is the difference in the semi-major axis between the two clumps that causes this dissimilitude. The planets of the left clump have a smaller semi-major axis, meaning they are closer to their star, and thus *tidally locked* by its huge gravitational pull. A tidally locked astronomical body takes just as long to rotate around its own axis as it does to revolve around its partner. This causes one side to constantly face the partner body. A prime example illustrating this phenomenon is the Moon, which is tidally locked to the Earth, as it is always showing us the same hemisphere. However, the planets on the right hand side clump are not tidally locked, because they are too far away from their stars and therefore receive a weaker gravitational pull. At 1 AU, they mirror the Earth: they have the necessary angular momentum to continuously orbit their parent stars, but are not tidally locked by it.

Graph 3 also raises an interesting question: could two planets from the two different clumps exist in the same planetary system? In other words, could a planetary system possibly contain both a Hot Jupiter and a Jupiter Analog? So far, only *one* has been found, and it is considered a rare configuration.

However, to properly answer this question we need to improve our knowledge of the formation of Hot Jupiters. Recall that these types of planets have been mostly found using the Transit method. When a planet passes in front of its star, we can effectively measure its orbital inclination angle. When we look at the statistics, we see that most of the Hot Jupiters do *not* have an orbit perpendicular to the axe of rotation of the star, which is strange because it is unlike any planet in our solar system. For the planets to be orbiting their stars at an inclined plane, it is believed that some violent event or mechanism took place. So, the Hot Jupiters were probably formed by some unknown dramatic and dynamic phenomenon that "broke up" whole systems of these planets. This also implies that the theory of migration does not explain everything about the formation of Hot Jupiters, as they themselves cannot be the catalysts of the violent mechanisms. Therefore the probability of only one planet turning into a Hot Jupiter, while another planet in the same system remains untouched, is very low and would be considered odd. Most of the confirmed Hot Jupiters are isolated, meaning they are *the* single planet orbiting their stars. They live a lonely life indeed.

But perhaps the most noticeable feature in this graph is the presence of gaps. The fact that we don't seem to be finding any planets in the lower right corner and in the lower range, between 10^{-3} to 0.01 Jupiter Mass, which is where the rocky terrestrial planets should be, is surprising. If we put in the data of our own planets, Venus and Earth would find themselves in the lonely and isolated bottom of the chart. None of our planets would be placed in the left hand-side clump.

Furthermore, there is also a large gap *between* the two clumps. Is this how the actual universe is? Are Earth-like planets really so rare, or is what we are seeing actually a selection effect, biased by our methods of detection?

In truth, the reason why we are not detecting planets in the lower right corner is not because of a selection effect, but because we are at the *threshold* of our current detection capacities. Let us consider a small mass on the graph, say 0.03 Jupiter mass. For this given mass, we can see that we are being able to detect exoplanets relatively easily at a short distance. However, when we increase the distance i.e. the semi-major axis, the planets become much harder to detect. In fact, for our chosen mass, we seem to be finding no planets at all after 0.4 AU. This is due to the weakening of the amplitude signal the Radial Velocity method requires to detect planets. The weakening occurs because the required signal is directly dependent on the orbital period of the exoplanet.

The following equation[13] of the RV method relates, for any exoplanet, its amplitude and orbital period (and therefore the semi-major axis, as both are directly related):[14]

$$m_p * \sin(i) \approx 3.5 * 10^{-2} * \frac{k}{p^{1/3}}$$
$$\leftrightarrow \frac{m_p * \sin(i)}{3.5 * 10^{-2}} \approx \frac{k}{p^{1/3}}$$

[13] CASSEN, P., GUILLOT, T., QUIRREBACH, A., *Extrasolar Planets*, section 4.0 "Radial-Velocity Surveys", p.62-75

[14] See *Kepler's Third Law of planetary motion*, under the chapter "Dynamics of Planetary Motion".

$$\leftrightarrow Constant = \frac{k}{p^{1/3}}$$

$$\leftrightarrow Constant = k * p^{-1/3}$$

Where:

- $m_p * \sin(i)$ is the fixed minimum mass of the exoplanet, expressed in units of Jupiter Masses $[M_{Jupiter}]$.
- i is the angle of inclination of the orbit of the planet with respect to the plane tangent to the celestial sphere
- k is the amplitude of the signal, expressed in meters per seconds $[m/s]$.
- p is the orbital period of the exoplanet, measured in years $[years]$.

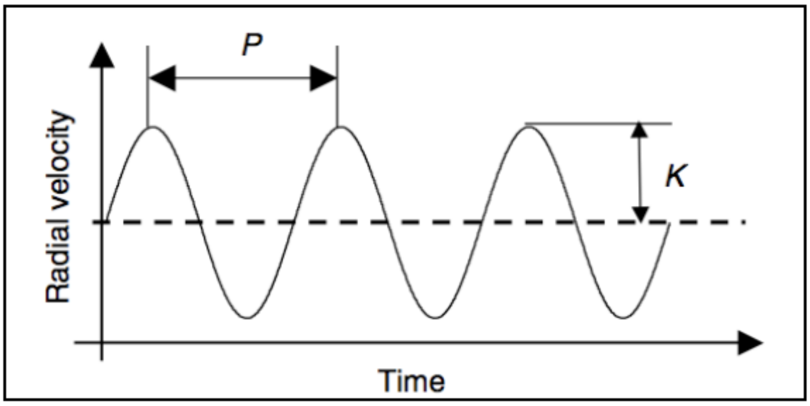
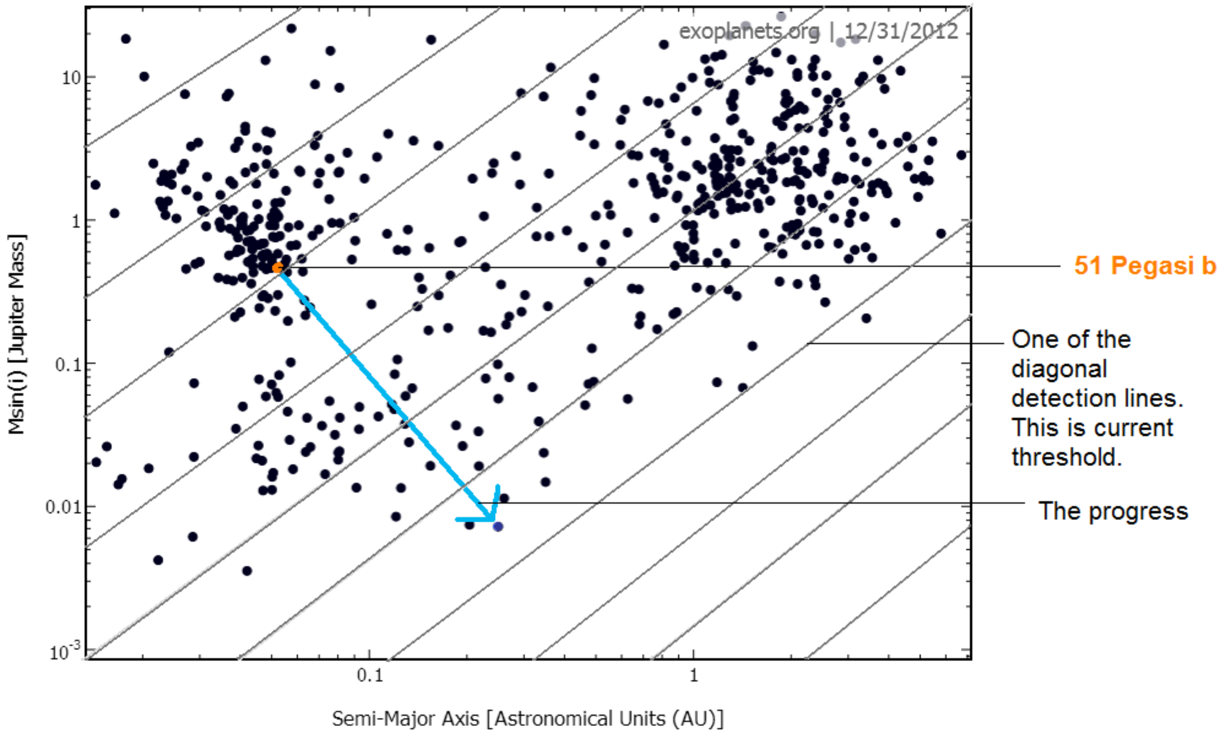


Figure 18: The relation between the orbital period p and the amplitude k, in a graphical form

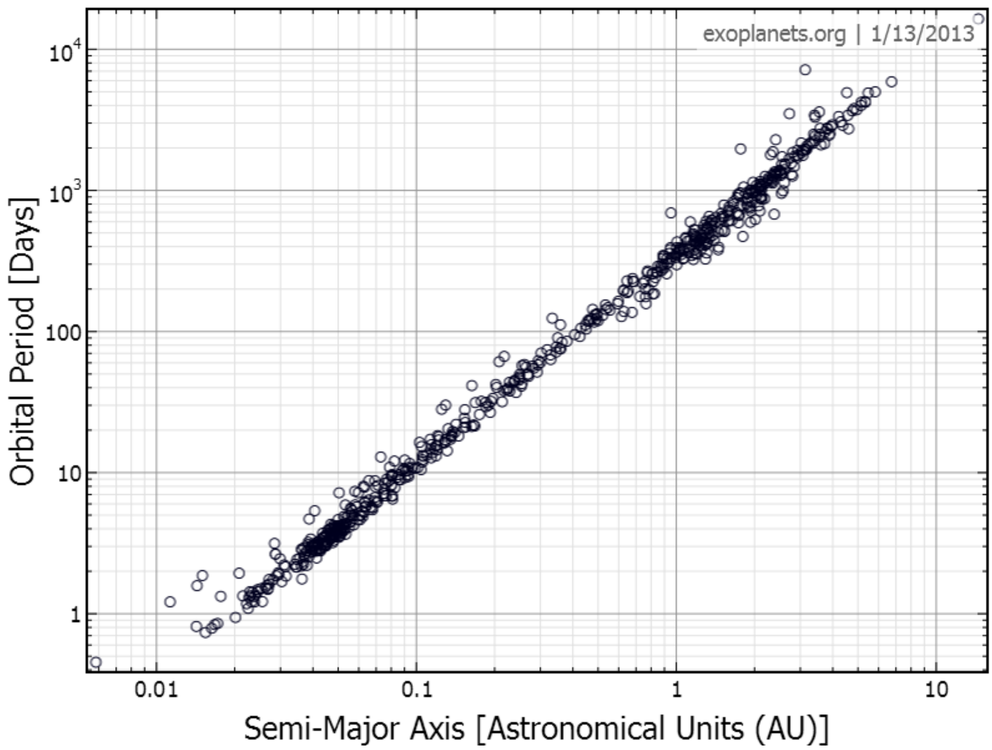
Since the mass and the inclination of the exoplanet are fixed, we can simplify the original equation and see that the product of the amplitude and the orbital period equals a constant. This implies an inversely proportional relationship between the two variables. We can see that as the orbital period p increases, the amplitude k decreases. Conversely, as the orbital period decreases, the amplitude increases. The radial velocity method is unable to detect planets with a high value of semi-major axis (i.e. a large orbital period), because the amplitude of the signal becomes very low. Thus, with reference to Graph 3, we cannot detect any planets in the region from which signals of low amplitude are emitted. This is why many planets have been detected in the top left corner, but none in the lower right corner.

To be able to detect planets in the lower right corner area of the graph, we have to improve the sensitivity of our instruments of measure, so that the amplitude of the signal can be detected more accurately. We have already made significant progress since the detection of **51 Pegasi b**, and will continue to do so. The progress is depicted on Graph 5 which also shows the detection lines. The detection lines correspond to the amplitude k of the signal. We see that we are effectively moving diagonally from the top left corner to the lower right corner. The upper left diagonal detection lines have larger amplitudes, while the lower ones have smaller ones, the smallest being approximately 1 meter per second.



Graph 5: The lines in this graph have been manually added to better illustrate the point. They are not accurate.

Semi-Major Axis in relation to Orbital Period:



Graph 6

Graph 6 clearly shows a striking relationship between the semi-major axis and the orbital period of exoplanets. Unlike the previous graphs, we can see that there is a tight correlation between the time taken by the planet to go once around its orbit, and the distance from its star. We have simply changed the parameter of the Y-Axis, and we get an entirely different view. This time if we put in our own planets, they would fit in perfectly.

This graph is perhaps a special one, as it proves the universal application of one of physics' fundamental laws: *Kepler's Third Law of Planetary Motion*,[15] put in place long before the discovery of an exoplanet. It is important for the search of exoplanets as it can effectively be used to calculate the distance between an exoplanet and its star, and determine if it resides within the habitable zone[16].

According to this Law, the ratio between the cube of the semi-major axis a^3 and the square of the orbital period p^2 is constant i.e.:

$$\frac{a^3}{p^2} = constant$$

However, in Graph 6 based on values drawn from exoplanets, we note that that the line represents the same ratio. If In the logarithmic scale of the above graph, we choose two points on the x axis ($a_1;\ a_2$) and the corresponding points on the y axis ($p_1;\ p_2$), then:

$$\leftrightarrow \frac{{a_1}^3}{{p_1}^2} = \frac{{a_2}^3}{{p_2}^2}$$

$$\leftrightarrow \left(\frac{a_2}{a_1}\right)^3 = \left(\frac{p_2}{p_1}\right)^2$$

If $a_1 = 0.1\ and\ a_2 = 1, then\ p_1 = 10\ and\ p_2 \approx 320$. Therefore:

$$\leftrightarrow \left(\frac{1}{0.1}\right)^3 = \left(\frac{320}{10}\right)^2$$

$$\leftrightarrow 1000 = 1024$$

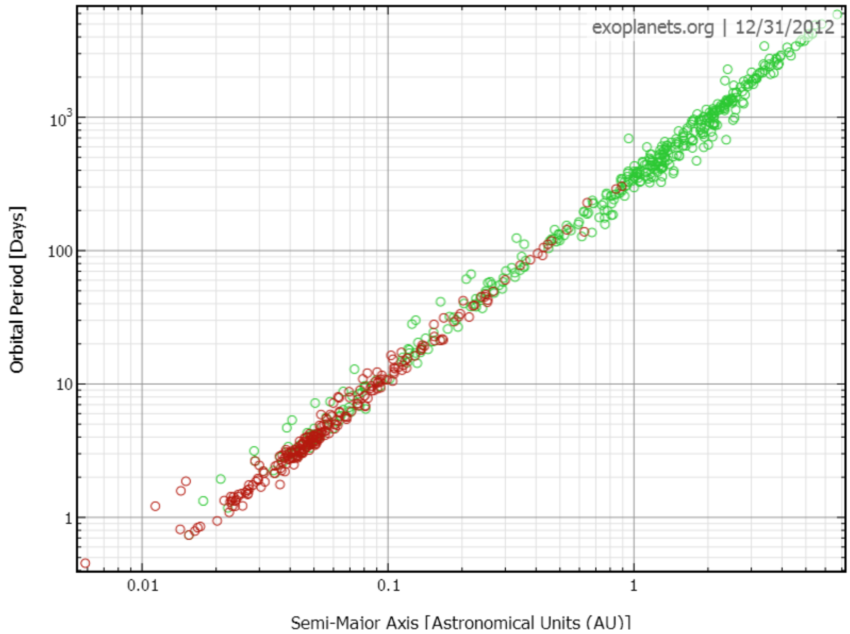
$$\leftrightarrow 1000 \approx 1000$$

This proves that for any given point on the line i.e. for the values of any planet, the ratio of the two parameters is constant. This is consistent with Kepler's Third law. The law that Kepler derived by observing the planets of our solar system holds true for the extrasolar planets that are being discovered now, some three or four hundred years later. We can see that the slope of the line in Figure 5 and Graph 6 are the same. This certifies that gravity functions the same across planetary systems. Kepler's law illustrates that all planets across different systems and diverse environments obey gravity in *exactly the same way*.

We can also observe that the line is straight for most of the data, except for the lower left corner, where the data appears to be more scattered. The planets in this region are the same as those in the left hand side clump in the Graph 3. We can see that there are more planets *above* the orbital period of 1 day, than below it. This begs the question as to why the scatter is only one-sided. One possible

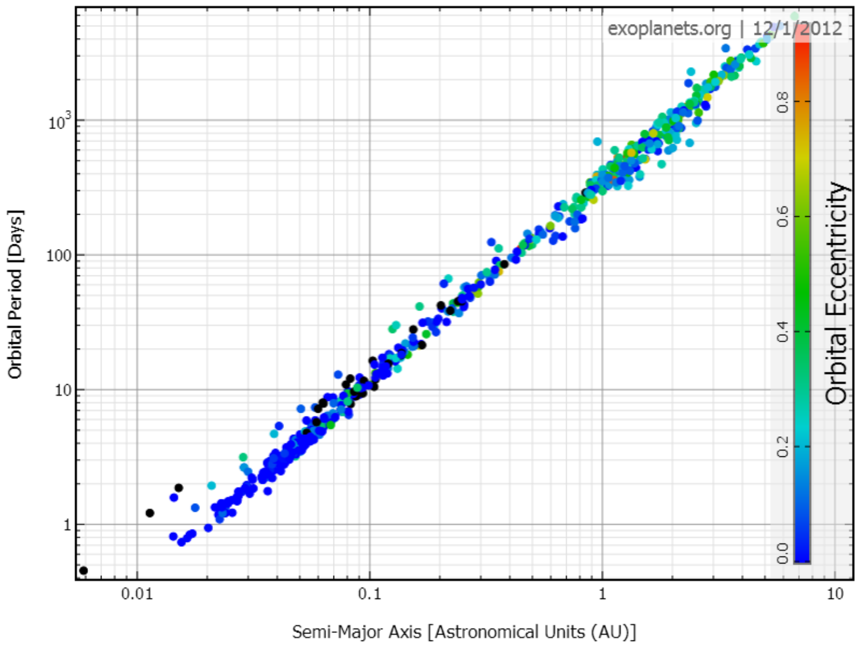
[15] See *Kepler's Third Law* in chapter « Dynamics of Planetary Motion »
[16] See chapter VII « Habitability »

explanation is that our current scientific technology is not advanced enough to correctly measure planets that orbit in less than a day. By checking the data of the 11 planets that are in the lower left column, we see that seven of these planets were detected using the **Transit method**, and the other four through the **Radial Velocity** method.



Graph 7: Planets detected by Transit Method (Red) and Radial Velocity (Green)

Another question is why the scatter is only present in the area where the semi-major axis is small. Why is there no scatter in the top right corner instead? The reason is the closeness of the planets to their stars. At small distances, the planets are subject to a stronger gravitational force by the host star, making their orbits more circular. As shown in Graph 8, the blue colour indicates a low orbital eccentricity, meaning a more circular orbit.



Graph 8

They effectively become like the moon is to the earth: they get tidally locked and rotate in a circular motion. The orbits become more elliptical as the eccentricity increases. At low orbital eccentricity, it is harder to determine the Semi-major axis correctly. The blue points therefore have a larger margin of error than the other points. Hence we can assume that these planets are either not *exactly* following Kepler's law due to their low eccentricity and extreme closeness to their star, or else they are indeed following the law but we've made marginal errors in our measurement of the orbital period.

To conclude, we can see that plotting the data on graphs helps to not only visually represent all the discovered exoplanets, but also serves to categorize and differentiate between them. By interpreting the graphs, we can question the reasons for different phenomena, such as Hot Jupiters, and attempt to explain them by elaborating theories such as that of Planetary Migration. On the other hand, we can also note how all exoplanets are similar in terms of obeying the same laws of gravity and motion, leading us to conclude that certain rules of physics apply to every element in the universe.

Furthermore, by interpreting these graphs we also realise the current limitations of the astronomical instrumentation, and attempt to improve on these in order to detect a wider range of exoplanets. By trying to further refine the technology, we can focus on reaching the goal of finding habitable terrestrial planets in the unexplored regions of these graphs.

VIII: Habitability

"Two possibilities exist: either we are alone in the Universe or we are not. Both are equally terrifying."

-Arthur C. Clarke

Although the search for other planets is partly motivated by our efforts to understand their formation and to improve the understanding of our own solar system, the ultimate goal is to find extraterrestrial life. Now that we've seen and analysed the actual data compiled by space missions and connected them to actual physics laws, we arrive at the final act of our play: habitability. So far we have only talked about the detection and location of confirmed exoplanets, but we don't know much about their ability to nurture life i.e. their habitability.

For a planet to harbour any form of life, it must satisfy certain specific parameters that would make it habitable. Life only exists under certain conditions that are essential to creating the necessary sustainable environment for life to grow and evolve. There is presently no reason to believe that planets satisfying these conditions do not exist in large numbers. Although till now we have not been able to find such planets, it is likely to be only a matter of time.

One should keep in mind that the assessment of the suitability of a planet for supporting life is largely based on Earth's characteristics, because it is the one planet in the universe that we know for certain is habitable. Therefore, we can only look for life *as we know it*. It may well be that life exists under different conditions, but we can only speculate about its existence. This final chapter will cover the major factors required for life (as we know it*)* to exist on exoplanets such as, distance, mass and atmosphere.

Drake's Equation

Before we start defining the different conditionalities for life, let us first take a look at two notable figures in astronomy and their thoughts on the odds of life existing elsewhere.

Carl Sagan was a famous American astronomer, best known for his research and thoughts on the possibilities of extraterrestrial life. Like many astronomers, he believed that our galaxy is teeming with life, and a large number of extraterrestrial civilisations should theoretically exist. However, due to the lack of evidence of such civilisations, he gave credence to the theory that these tended to *self-destruct* once they became sufficiently technologically advanced.

Didier Queloz, co-discoverer of the first extrasolar planet, agrees with Sagan's belief that life exists elsewhere in the universe, but emphasizes that a chain of consecutive events are needed for life to emerge, and therefore 'luck' is a critical factor. Therefore, the galaxy may not quite be as teeming.

Sagan and Queloz both strongly believe in the existence of extraterrestrial life, simply due to the odds. Another notable astrophysicist, Frank Drake, came up with a mathematical equation that could, in theory, estimate the number of detectable extraterrestrial civilisations in the Milky Way Galaxy. It states that:

$$N = R^* * f_p * n_e * f_l * f_i * f_c * L$$

Where:[17]

- N is the number of civilizations in our galaxy with which communication might be possible (by detecting their electromagnetic emissions).
- R^* is the average rate of star formation per year in our galaxy, expressed in $[stars/years]$.
- $f_p$is the fraction of those stars with planetary systems.
- $n_e$is the number of planets, per solar system, that can potentially sustain life.
- f_l is the fraction of suitable planets on which life actually appears.
- f_i is the fraction of life bearing planets on which intelligent life emerges.
- f_c is the fraction of civilizations that develop a technology that releases detectable signs of their existence into space.
- L is the length of time for which such civilizations release detectable signals into space, expressed in $[years]$.

Drake's equation is different from any of the previous equations related to the detection of exoplanets, because of the high number of unknown variables it contains. Because of these current uncertainties, there is no definitive "right" or "wrong" answer, but only an estimate. As we learn and understand more of our place in the universe, some of the unknowns slowly become clearer, and the end result more accurate.

Scientists acknowledge that there are very large uncertainties in Drake's equation, and often tend to make very crude estimates to make progress. With our current state of knowledge, we know that the first three terms of the equations are closer to 10 than 1, and that all the f factors are *less* than 1. However, L remains the biggest unknown. By making some assumptions, we can simplify the equation to arrive at perhaps a more useful version of the Drake Equation:

$$N = R^* * f_p * n_e * f_l * f_i * f_c * L$$
$$\leftrightarrow N \approx 10 * 10 * 10 * 0.1 * 0.1 * 0.1 * L$$
$$\leftrightarrow N \approx L$$

This would mean that the number of civilisations with whom we can possibly make contact is approximately equal to their longevity, which is the same conclusion Drake and his colleagues arrived at in 1961. This also implies that unless L is very large, N will be small. If SETI succeeds in detecting a signal emitted by an alien civilisation, it would mean that L on average must be large, as we wouldn't have otherwise discovered the signal by only looking at a small proportion of the stars in the Milky Way. Because of the finite speed at which the detected alien signal would travel, it would be telling us about their past by the time they reach us, as they are many light years away. But because the alien civilisation's L must be large for us to detect such a signal, this could tell us if our own future is a long one. Another question that emerges is that even if we do find signs of life, how and what would we communicate with them?

The Recipe for Life

When we look at the Earth from space, we see that almost 75% of it is covered by water, which is a vital natural resource for all living organisms. A plant uses water to derive some of its nutrients from minerals in the soil. These minerals have to be dissolved in water in order to be

[17] Enumeration based on http://en.wikipedia.org/wiki/Drake's_Equation#The_equation and http://www.seti.org/drakeequation

absorbed by the plant. The vast oceans and other bodies of water provide shelter for various species of sea life. Earth's atmosphere is regulated by clouds which are made of water molecules. And of course, all animals need to drink water regularly in order to stay alive. Life on Earth is built around water.

Therefore for a planet to harbour life as we know it, it must contain water. Unlike popular belief, water is *not* a rare commodity in the universe. On the contrary, it exists in abundance everywhere in the universe. Water has been detected in interstellar clouds within our galaxy, the Milky Way, and in other galaxies as well.[18] One only has to look at the chemical properties of water to understand its banality. A water molecule is composed of two hydrogen atom covalently bonded to a single oxygen atom.

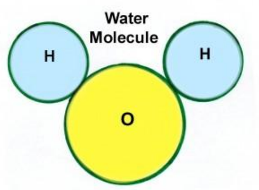


Figure 22: The Atomic Structure of a Water Molecule

Hydrogen is the most abundant element in the entire universe, created during the 'big bang'. Oxygen is the third most abundant element, created by the nuclear fusion of stars. Together these two form water. All planets in the solar system, with the exception of Uranus and Neptune, have a small quantity of water vapour in their atmosphere, ranging from 0.0004% (Jupiter) to 3.4% (Mercury). One of Saturn's moons, Enceladus, has a composition of 91% of water vapour and is considered to be one of the most potentially habitable spots in the solar system.[19]

However, for life to develop, water is required not as vapour or ice, but as a *liquid*, which is much rarer, as it is dependent on the surface temperature, which in turn is reliant on atmospheric pressure, which is determined by the surface gravity of the planet. All these requirements can only simultaneously be found in the habitable zone. Furthermore, liquid can only exist on a surface, meaning gaseous planets cannot sustain water.

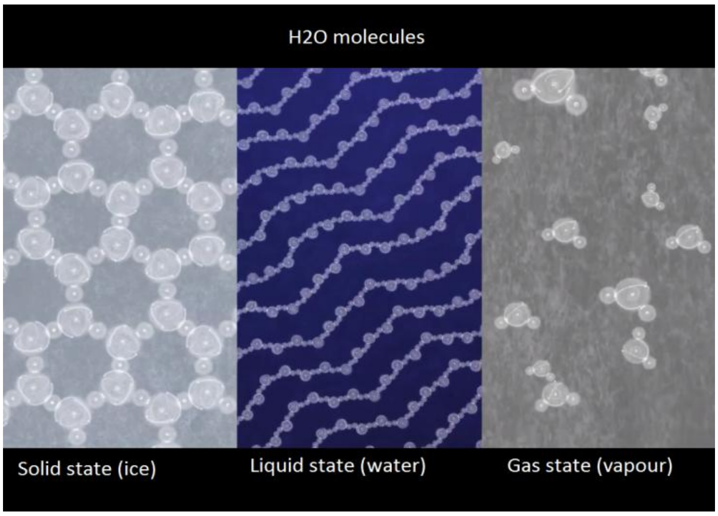


Figure 23: Different states of water

[18] http://www.nasa.gov/topics/universe/features/universe20110722.html
[19] Data taken from http://en.wikipedia.org/wiki/Water#In_the_universe section 3.1 « In the Universe »

In essence, the major factors required for harbouring life on any planet seem to depend on its mass, atmosphere, and distance from its parent star. These are elaborated below.

i) Distance

A planet must have a solid, rocky surface and be at a perfect distance from its star to maintain liquid water on its surface. Too far out, the planet will be too cold to sustain liquid water on its surface, as the surface temperature will fall below its freezing point, causing the oceans to turn to ice. Too close in, the planet would have a temperature that would exceed the boiling point of water and the oceans would turn to vapour. Thus the perfect region for water to be able to exist as liquid is the belt between these two extremes, which is called the habitable zone.

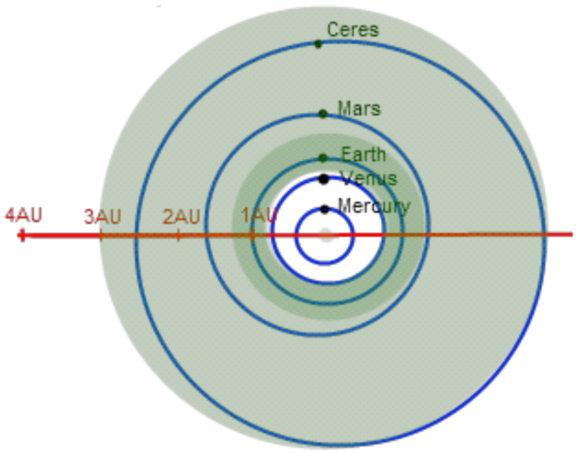


Figure 24: The Habitable Zone (in green) of our solar system

This region is also known as the Goldilocks Zone, originating from the well known story of *Goldilocks and the Three Bears*, in which the Goldilocks chooses the soup which is neither too hot, nor too cold. Similarly for a planet following this principle, it should exist neither too close, nor too far from its star, but at the right distance.

Each planetary system's habitable zone would start at a different distance from its star, as it depends on the mass of the central star. The more massive the star, the more heat it would emit, pushing further away the inner edge of the habitable region, as shown in the figure below.

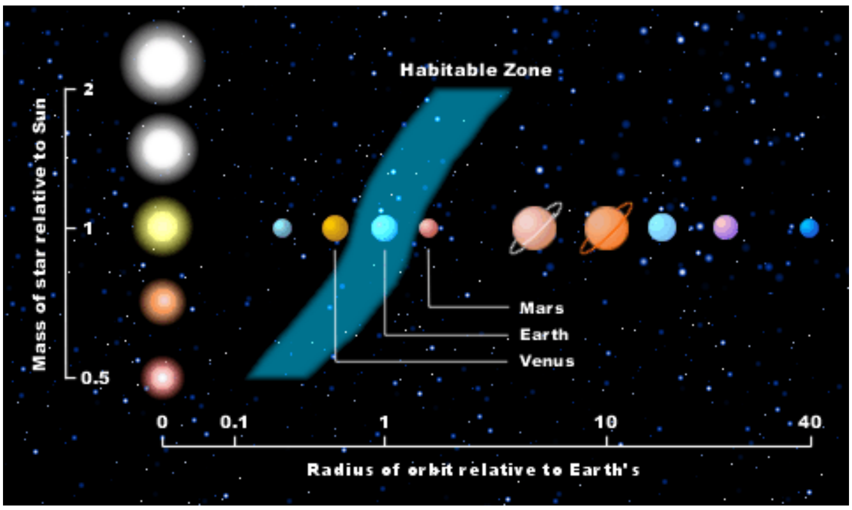


Figure 25: The Habitable Region (Blue) depending on the Star's Mass

So when we search for exoplanets, we look within the habitable zone, as those are the best bets to find Earth-like planets. Currently it is unknown whether the few planets that have been found in the habitable zone are terrestrial or gaseous. The planets that have been authenticated as terrestrial are *not* located in the Goldilocks Zone.[20] Moreover, simply finding planets in the habitable zone does not guarantee life, as there are several other critical factors that play an important role.

ii) Mass

For a planet located in the habitable zone, the planet's gravity must be strong enough to hold an atmosphere, which serves as a buffer, helping maintain a steady surface temperature. The surface gravity of the planet can be calculated using the following formula:

$$g = \frac{G * M}{r^2}$$

Where:

- G is the Gravitational Constant $\cong 6.67 * 10^{-11}$ $[N]$
- $M$is the mass of the planet $[kg]$
- r is the radius of the planet $[m]$

As we can see, the gravity is dependent on the mass and radius of the planet. This is critical. For example, if the Earth was smaller, let's say around the size of Mars, the force of gravity would be considerably weaker, as both the mass and the radius would be smaller, and therefore it would not be able to keep the water molecules from flying off into space, resulting in a very thin atmosphere. This would reduce the effectiveness of the atmospheric buffer, allowing extreme temperatures to exist, and thus prevent the accumulation of water. This is why liquid water cannot exist on Mars, although it is located at the edge of the habitable zone. The small mass barely allows water to exist in a solid state at the polar ice caps. This is why knowing the mass of an exoplanet is essential in order to assess the status of its habitability.

iii) Atmosphere

This is perhaps the most important element in judging the capability of a planet to sustain life. Without the pressure of an atmosphere, liquid water cannot survive. Let's take the Moon as an example: it does not possess an atmosphere, not even a thin one like Mars. So if we spill some water on moon, it would either boil away as vapour, or freeze solid to make ice. So in order to harbour life, a planet must have an atmosphere, and one that is thick enough for the planet to maintain a constant temperature, and to exert pressure for water to remain as liquid as well.

However, the *thickness* of the atmosphere isn't the only vital component of the habitability puzzle. Its actual *composition* has to be correct as well. Let us take Venus as an example. Venus is the closest planet to Earth in terms of its physical characteristics: it is also located in the habitable zone, has a surface gravity of 8.9 $[m/s^2]$, which is 90% of Earth's gravity, has 82% of Earth's mass, and 86% of its volume, and the density is nearly identical.[21] An alien astronomer observing our solar system would consider Venus as a good bet for life to exist.

[20] Didier QUELOZ, Professor of physics and astrophysics, *Interview on the habitability of exoplanets*. Conducted by Eklavya SARKAR on 05/12/2012 at the Observatory, Geneva

[21] http://www.universetoday.com/36711/earths-twin/

Figure 26: Size comparison of Venus and Earth, drawn to scale

However, Venus is *not* habitable for life as we know it, because it is way too hot. Its atmosphere is the densest of the terrestrial planets in the solar system, and exerts 92 times Earth's pressure on its surface. Its atmosphere is almost entirely composed of carbon dioxide and other greenhouse gases, and is completely devoid of any molecular oxygen. As a result, the mean surface temperature of Venus is around 464°C, which is the highest in the solar system, and way above the boiling point of water.[22] Unlike Earth, it also lacks a magnetic field, which keeps the solar wind from sweeping away the free Hydrogen, an essential ingredient for water, into interplanetary space. Venus's surface is therefore dry as a bone and covered by deserts. Even though Venus mirrors Earth in many aspects, it is definitively not habitable.

So finding exoplanets with the same mass, distance and atmosphere as Earth is only the beginning. As with Venus, these factors are not necessarily enough for life to develop. We must take a closer look at the *makeup* of the atmosphere, and determine whether the vital elements, such as hydrogen, oxygen, but also nitrogen and carbon, are present in the correct *quantity* and *percentage*. These lay the *basis* for the foundation and development of life as we know it. The actual list of ingredients for life is far bigger, and can be detailed endlessly. The correct planetary orbit and rotation, the right geochemistry and the geological mechanisms can all change a planet's status from being habitable to not habitable. The factors are boundless.

However, the series of successive phenomena required for life to appear relies on one factor that cannot be controlled or categorized: chance. To our current understanding, it is chance that makes a small body collide with another to form planetesimals that later develop into the terrestrial planets. It is perhaps through the sheer chance of a comet colliding with Earth that water was imported to this planet. In fact, "luck" may be another necessary ingredient for the creation of life itself.

And what about life as we *don't* know it? What if it requires a liquid other than water to emerge and flourish? Maybe it is us who are the different creatures, living in an unusual and extreme environment. Or perhaps Earth is only one of many *kinds* of habitable worlds. We can speculate endlessly, but the only way to find out for sure is to go out and explore.

[22] Data taken from http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html

Conclusion

In this paper, I present a distillation of an extensive literature review on exoplanets and explain the methods of detection linking them to fundamental laws of physics. I used publicly available research data on exoplanets, and under the guidance of an astronomy expert, generated a series of graphs using combinations of relevant parameters. I interrogated the graphs and correlated them to the basic laws of physics, such as Kepler's Third Law of Planetary Motion and Newton's Law of Universal Gravitation. With the graphs as a basis, I interviewed renowned astrophysicist, Professor Didier Queloz, to gain further insight into the current discoveries and scientific thinking on issues such as the recurrent findings of Hot Jupiters. Finally, I identified and explained some of the factors that influence the emergence of life, including non-rational factors such as chance. Based on this review and analysis, I am able to explain *why* we search for exoplanets and how meaningful this quest actually is.

We have come a long way since the discovery of the first exoplanet in 1995. The field has grown into a vast scientific domain that goes beyond pure physics and has slowly been delving into realms of astrobiology and chemistry. We have seen that the rate of discovery of exoplanets has been steadily increasing, and planets seem common around their stars in our galaxy. A few have been detected in the habitable zone, but unfortunately don't seem terrestrial. In fact, the planetary systems discovered do not resemble our own solar system, as many of them contain Hot Jupiters and Super Earths, neither of which exist in our system. This could be due to a selection effect of our limited methods of detection, or possibly the way the universe is.

Through the detection of exoplanets, we have learnt about the nature of Earth itself and the different life forms it has sustained since nearly four billion years. We have gained a critical understanding of our unique place in the vast cosmos and the actual scientific evidence to prove that we seem to be in an isolated corner of a graph, different from all our other cosmic neighbours. By looking *out*, we have not only expanded both our physical and conceptual borders, but also understood the uniqueness of what has happened *here*, on Planet Earth. One has, in the process, better ingrained the value of *our own* life. We are indeed *lucky* to be alive, and are *special* as many faiths have proclaimed since ages. No other scientific field has given us as much substance to answer the questions that have existed since the early philosophers started wondering. This is why we continue to look for exoplanets.

Despite not having discovered other life, the fact that we are actively asking ourselves questions and searching for answers by undertaking new scientific projects, shows that we are constantly trying to expand our knowledge. Arthur C. Clarke once stated that the two possibilities of us being either alone in the universe, or not, are both equally terrifying. I would say that both are equally awe-inspiring. Because even if we *are* alone, the fact that we think, ponder, dream and ask these questions might actually be one of the most important and useful elements in the universe. It shows that our quest for knowledge and understanding *never* gets dull. In fact the *more* we know, the *more* remarkable our cosmos seems to be, and more questions seem to open up.

It is these very unanswered questions that drive our curiosity to push the frontiers of current scientific thought and endeavour. So by opening up evermore questions, perhaps *nature itself* pushes mankind to constantly strive for answers. If extra-terrestrial beings *do* exist somewhere in this ocean of seeming emptiness, I thoroughly hope that we share the same thirst for knowledge, because it is the one element that has the power to bring us together. Meanwhile, we can only try to briefly capture the beauty of nature, as it takes its course on a cosmic scale.

Bibliography

Lectures:

- BAILYN, C. (2007) *Introduction to the Course*. BSc Astronomy: Frontiers and Controversies, Yale University [viewed online, July 2012]

- BAILYN, C. (2007) *Planetary Orbits*. BSc Astronomy: Frontiers and Controversies, Yale University [viewed online, July 2012]

- BAILYN, C. (2007) *Discovering Exoplanets: Hot Jupiters*. BSc Astronomy: Frontiers and Controversies, Yale University [viewed online, October 2012]

Interviews:

- QUELOZ, Didier, Professor of Physics and Astrophysics, Geneva University, *Interview on habitability of exoplanets* (60 minutes). Conducted by Eklavya SARKAR on 05/12/2012 at the Geneva Observatory, Switzerland

- TRIVEDI, Pranjal, Assistant Professor of Physics, University of Delhi, India, *Discussions on the interpretation of data and graphs.* Held between Pranjal TRIVEDI and Eklavya SARKAR during July 2012 at the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, India

Books:

- BOSS, A. (2009) *The Crowded Universe: The Search for Living Planets*. Basic Books. New York, United States of America. 978-0-465-00936-7

- CASSEN, P., GUILLOT, T., QUIRREBACH, A. (2006) *Extrasolar Planets*. Saas-Fee Advanced Course 31. Netherlands. Springer-Verlag Berlin Heidelberg. 3-540-29216-0

- MASON, J.W. (2008) *Exoplanets: Detection, Formation, Properties, Habitability*. Chichester, UK. Praxis Publishing Ltd. Springer. 978-3-540-74007-0

- LIVIO M., SAHU, K., VALENTI, J. (2008) *A Decade of Extrasolar Planets around Normal Stars*. Space Telescope Science Institute Symposium Series 19. New York, United States of America. Cambridge University Press. 978-0-521-89784-6

- PERRYMAN, M. (2011) *The Exoplanet Handbook*. New York, United States of America. Cambridge University Press. 978-0-521-76559-6

- RANKIN, W. (1993) *Newton for beginners.* Cavendish House, Cambridge Road, Barton, Cambridge. Icon Book Lts. 1-874166-07-2

- ROBINSON K. (2007) *Spectroscopy: The Key to the Stars, Reading the Lines in the Stellar Spectra*. Springer, 1st edition. 978-0-387-36786-6

- SCHARF, C.A. (2009) *Extrasolar Planets and Astrobiology*. Maple Vail Press. University Science Books. 978-1-891389-55-9

- STEVES, B.A., HENDRY, M. and CAMERON, A.C. (2011) *Extra-solar Planets: The Detection, Formation, Evolution and Dynamics of Planetary Systems*. Taylor & Francis. The Scottish Universities Summer School in Physics. 978-1-4200-8344-6

Websites [accessed between June 2012 and January 2013]**:**

- Allan H. Weis, Oracle Education Foundation, *Oracle ThinkQuest*, http://library.thinkquest.org/C003763/flash/extrasolar1.htm
- Chris Mihos, http://burro.astr.cwru.edu/Academics/Astr201/Light/light.html
- Dr. Jason Wright, et al., *The Exoplanet Orbit Database*, http://exoplanets.org
- Fraser Cain, *Universe Today*, http://universetoday.com
- Jean Schneider, *The Extrasolar Planets Encyclopaedia*, http://www.exoplanet.eu
- Kelly Stoetzel et al., *Ted-Ed.*, http://ed.ted.com/series#/out-of-this-world
- Michele Beleu, et al., *Planet Hunters,* http://www.planethunters.org
- Wayne Rosing, *Las Cumbres Observatory Global Telescope Network*, http://lcogt.net/spacebook/radial-velocity-method
- Wikipedia: *Carl Sagan*
  Doppler Spectroscopy
  Drake Equation
  Earth
  Extrasolar Planet
  Frank Drake
  Galileo Galilei
  Gas Giant
  Habitable Zone
  Hot Jupiters
  Hydrogen
  Isaac Newton
  Johannes Kepler
  Kepler (spacecraft)
  Kepler's Laws of Planetary Motion
  Methods of detecting Extrasolar Planets
  Nicolaus Copernicus
  Orbital Inclination
  Oxygen
  Planet
  Planetary Habitability
  Search for Extraterrestrial Intelligence
  Terrestrial Planet
  Venus
  Water

Figures and Graphs

Figures:

Cover image: Dirk Terrell, *Sunset on a Four-star World*, http://www.boulder.swri.edu/~terrell/ph1-3_1024.png

1. Wikipedia, *Galileo Galilei*, http://en.wikipedia.org/wiki/File:Galileo.script.arp.600pix.jpg.jpg
2. The University of Oklahoma, *Sidereus Nuncius*, http://digital.libraries.ou.edu/histsci/books/1466.pdf
3. The Electronic Universe, *Solar System Formation: Condensation Theory*, http://zebu.uoregon.edu/~imamura/121/lecture-5/lecture-5.html
4. The University of Alabama, *Orbital Motion of* Planets, http://bama.ua.edu/~may001/ay102/notes/Lab13key.html
5. Hyperphysics, *The Law of Periods*, http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html
6. Image created by self using *Microsoft Paint*
7. Image created by self using *Microsoft Paint*
8. Image created by self using *Microsoft Paint*
9. Image created by self using *Microsoft Paint*
10. NASA's Imagine the Universe, *Doppler Shift*, http://imagine.gsfc.nasa.gov/YBA/M31-velocity/Doppler-shift-2.html
11. NASA's Imagine the Universe, *Doppler Shift*, http://imagine.gsfc.nasa.gov/YBA/M31-velocity/Doppler-shift-2.html
12. Wikipedia, *Light*, http://en.wikipedia.org/wiki/File:EM_spectrum.svg
13. NASA, *Visible Light Waves*, http://science.hq.nasa.gov/kids/imagers/ems/visible.html
14. NASA, *Visible Light Waves*, http://science.hq.nasa.gov/kids/imagers/ems/visible.html
15. Wikipedia, *Redshift*, http://en.wikipedia.org/wiki/File:Redshift_blueshift.svg
16. Wikipedia, *Radial Velocity*, http://en.wikipedia.org/wiki/File:ESO_-_The_Radial_Velocity_Method_(by).jpg
17. Las Cumbres Observatory Global Telescope Network, *Transit Method*, http://lcogt.net/spacebook/transit-method
18. Las Cumbres Observatory Global Telescope Network, *Transit Method*, http://lcogt.net/spacebook/transit-method

19. South Oakleigh Secondary College Physics, *Bohr Model of the Atom*, http://socphysics.blogspot.ch/2010/08/bohr-model-of-atom.html

20. Explore Learning, *Star Spectra*, http://www.explorelearning.com/index.cfm?method=cResource.dspExpGuide&ResourceID=558

21. Hyperphysics, *Orbit Eccentricity*, http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html

22. Berkley Astronomy Department, *The Radial Velocity Equation*, http://astro.berkeley.edu/~kclubb/pdf/RV_Derivation.pdf

23. Drew Brophy, *Painting Story – MIOCEAN*, http://drewbrophy.com/tag/water-molecule/

24. Ted Education, *A needle in countless haystacks: Finding habitable worlds*, http://ed.ted.com/lessons/a-needle-in-countless-haystacks-finding-habitable-planets-ariel-anbar

25. Wikipedia, *Habitable Zone*, http://en.wikipedia.org/wiki/File:Estimated_extent_of_the_Solar_Systems_habitable_zone.png

26. Eberly College of Science: Department of Astronomy and Astrophysics, *The Habitable Zone*, https://www.e-education.psu.edu/astro801/content/l12_p4.html

27. The Sofia Globe, *NASA to use rare Venus transit as planet-hunting exercise*, http://sofiaglobe.com/2012/06/04/nasa-to-use-rare-venus-transit-as-planet-hunting-exercise/

Graphs:

All eight graphs generated by self relating different parameters of the publicly available data at www.exoplanets.org/plots