Latest Trends in Planet Discovery

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1 Introduction

"the Universe is infinite. Moreover, there is an infinite number of worlds, some like this world, others unlike it." -Epicurus (341-270 B.C.)

1.1 History

The modern search for exoplanets, planets outside of our solar system, began in the mid-nineteenth century. Using successive images of the binary star system 70 Opiuchi, scientists raised the possibility that a dark companion (a planet?) was orbiting one of these stars. In 1963 a Jupiter mass planet was suggested to orbit around Barnard's star. These results were later discredited, but not before generating much momentum for the science of exoplanets.

The first set of good news came in 1992 when Alexander Wolszczan and Dale Frail made a surprise discovery in the Virgo cluster: the pulsar PSR 1257+12 was shown to have at least two planetary companions (in 2007 a third one was found)[7]. The discovery was the first confirmation of an extrasolar planet. It was also a surprise, no one thought that planets would orbit these remnants of supernova explosions!

In 1995 Michel Mayor and Didier Queloz made the first announcement of a planet orbiting a solar type star [12]. Using data from a spectrograph (a device that splits incoming light into a frequency spectrum) at the Observatory de Haute-Provence, the team was able to locate a Jupiter mass planet orbiting very close to the star 51 Pegasi. The planet is so close to its parent star that it completes one orbit in only 4.2 days, and estimated surface temperatures reach $1200°C$ [12]!

As of the date of this writing, scientists have discovered more than 500 new planets outside the Solar system (you can keep track with a desktop widget, available at http://planetquest.jpl.nasa.gov/widget.cfm) with the majority of these new findings made in the last five years. Numerous laboratories around the world have launched planet finding missions, and NASA and ESA have many such programs running. Both agencies and major universities have promoted the field and allocated significant funds to the development of ground- and space-based initiatives.

1.2 Significance

Considering the multi-billion dollar scope of funding requested for the field by the space agencies and the universities alike, one cannot but wonder about the significance of discovering celestial bodies rotating around distant stars. The galvanizing answer for many years has been - finding extraterrestrial life. The quest for extra-solar life, let alone intelligent life, has not only been used by popular science journals to captivate the reader but, importantly, also constituted a major part of budget discussion papers at both NASA [2] and the European Space Agency, ESA [17].

Despite the publicity, the first Earth-like planet is yet to be confirmed. A few groups are laying claim to the prize. One contender is the planet Gliese 581g announced by the Lick-Carnegie Exoplanet Survey in September 2010. The mass of this planet is about 4.3 times the earths and it is located in the middle of the star's habitable zone (more on that later)[3]. The NASA-sponsored Kepler Mission launched in 2009 (we will discuss the mission in more detail later), might have hit the jackpot with 68 Earth-size planet candidates so far and 5 of these candidates in the habitable zone [14].

Finding life may be the end game, however, the bulk of the meaningful scientific work is inevitably more prosaic. It constitutes a broad attempt to make an advancement in understanding the structure of star systems that have orbiting planets with possible inferences for our solar system.

Looking closer, we find that Exoplanet science is a discovery-rich field, and at present we are only in the process of articulating the right questions that future research will be designed to answer:

- What fraction of the stars have planet systems formed or forming around them?
- What kinds of stars may have terrestrial planets in the habitable zone (broadly - planets that receive just enough energy from the star to support liquid surface water)?
- What is the distribution of masses of these bodies?
- Are these systems anything like our Solar system such that we can dig deeper into the understanding of our own environment?
- If we come across a truly Earth-like planet, will we be able to detect bio-signatures and would those bio-signatures be similar to ours (methane in the atmosphere of Titan, for example, is a product of processes not related to life)

In order to tackle these and innumerable other issues, what scientists need is more data, and what we are seeing now is the field morphing from the discovery of individual planets to that of statistical analysis and classification. Importantly, the data gathered to-date (approximately two thousand proposed and 500+ confirmed planets) shows that planetary systems we are finding at other stars have very little resemblance to our solar neighborhood [7]:

- Many of the large planets discovered have orbital periods of only a few days (Hot Jupiters).

- Large planets are found both near and far from the star. Scientists are looking into mechanisms of planet migration closer to the star, and also wonder what stops this migration - as so many short periods planets have been found;
- Multitude of planets rotate at an angle to the star rotation, some have polar rotational patterns, and yet others rotate counter to the direction of the star rotation.
- Many of the discovered planets have highly elliptical orbits.

Importantly, scientists are finding a colorful array of individual planets with rich chemical traces that could potentially be confirmed as biosignatures.

Many of these findings suggest a review of hitherto established theories of star system formation that argue that planets, having formed within a primarily gaseous proto-planetary disk should, having condensed, be within a close range of the rotational plane of the star's equator orbiting in the same direction alongside it.

1.3 Laboratories and Missions

And so the excitement of being able to empirically confirm other worlds, improvements in measuring hardware and subsequent reduction in required funding led to a number of planet finding missions going into action. These initiatives still require substantial funding that varies depending on the method of discovery so the main backers tend to be either government owned organizations or large universities.

One notable setup is the facility in La Silla, Chile, operated by the European Southern Observatory (ESO) supported by 14 European countries. It is equipped with a 3.6-meter telescope that uses the High Accuracy Radial Velocity Planet Searcher (better known as HARPS) spectrograph. The equipment was designed in 2000, installed and commissioned in mid-2003, and became fully operational and available for use on October 1, 2003 [4]. The instrument's design allows for high accuracy in measuring radial velocity, on the order of 1 m/s. This level of precision allows for the detection of medium-sized planets with sizes between 5-6 times smaller than Jupiter if the planet rotates around the Sun-like star (a class-G star), all the way down to planets close in size to Earth and in star-proximate orbits around the so-called M-dwarf stars.

In April of 2009 the Lick-Carnegie Exoplanet Survey announced the discovery of the lightest exoplanet found at that time, planet *e* in the system Gliese 581. The team used one of the Keck telescopes of the Keck Observatory in Hawaii. The input of this newly discovered celestial body into the radial velocity model for Gliese 581 allowed the researchers to fine tune the orbital parameters of another planet in the same system, planet *d*, placing it in the outskirts of the habitable zone of the star [3]. An artist's representation of the habitable zone is depicted in Figure 1.

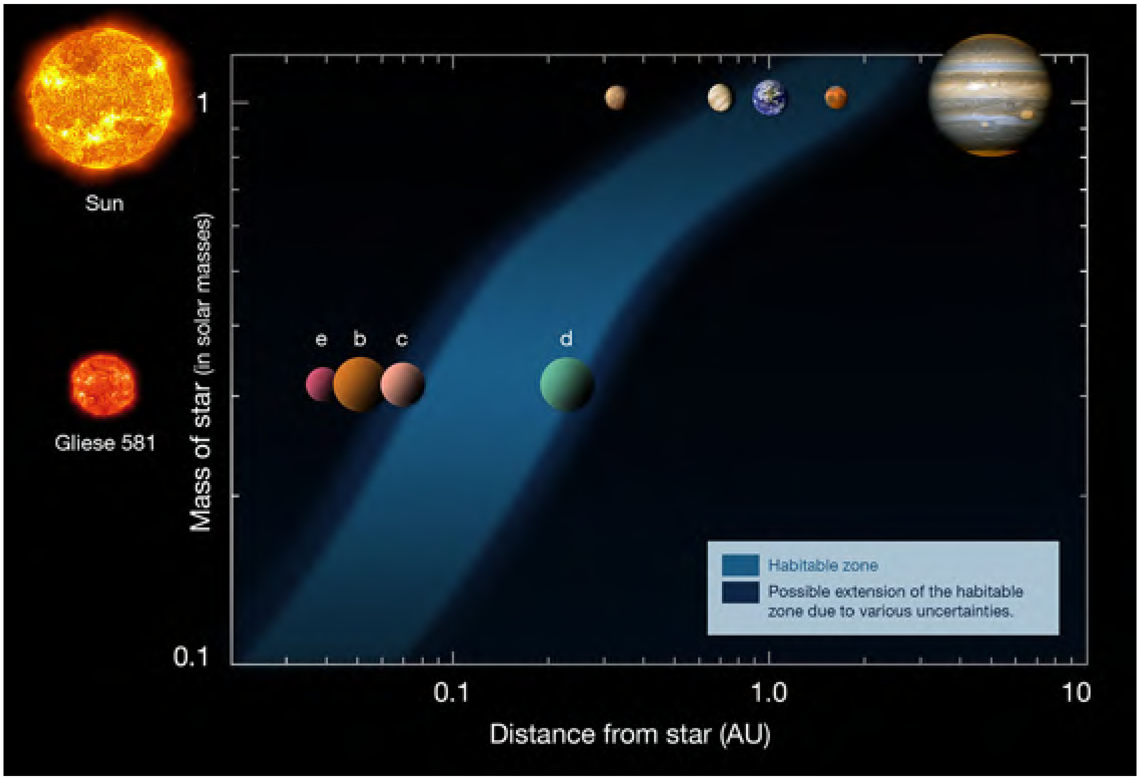

Figure 1: The habitable zone of the star Gliese 581 (artist's representation). Image courtesy of the ESO, based on a diagram by Frank Selsis, University of Bordeaux [1].

The facilities to support this fledgling but already establishing itself in the mainstream field of science are diverse and the technologies they use vary in many respects: from the fundamental physics laws in use to modes of accessibility to scientists to, not least importantly, cost of discovery. We take a closer look at the method that has so far proven to be the most prolific contributor to the database of known exoplanets: radial velocity.

2 Discovering Exoplanets with Radial Velocity

2.1 The First Discovery

For an observer on Earth, the Sun appears stationary. In reality, however, both star and planet are orbiting around the system's common center of mass (CM). While the center of mass is very close to the center of the star, it is not exactly at the center. Therefore the star wobbles around the center of mass with the same period as the planet. The more massive the planet, and the closer the orbit, the larger the amplitude of the wobble.

This motion of the star can be measured from the Doppler shift of the star's spectral lines. A planet shows up as a periodic change in the overall velocity of the star with respect to the observer. This change in velocity is very small, however, and very stable and precise measurements are needed to make a reliable detection. For example, the semi-amplitude of the wobble induced by Jupiter on the Sun is 12.5 m/s, or 28 miles per hour–that is assuming that the observer is looking head-on at the orbit.

Despite the difficulties, many planets have been discovered to-date using the radial velocity technique. Most of the data sets for these measurements are publicly available. In what follows, we use a downloadable console, the *systemic Console*, available on the oklo.org website. The *systemic Console* is an all-in-one software package (distributed freely) developed by the team of scientist Stefano Meschiari, Aaron S. Wolf, Eugenio Rivera, Gregory Laughlin, Steve Vogt, and Paul Butler [13]. The *systemic Console* contains full radial velocity data sets for the majority of the stars studied so far, as well as powerful data manipulations tools to aid in planet discovery. The data and plots in what follows are obtained using the data and functions on this console.

The first discovery of an exoplanet orbiting a solar-type star was made by Mayor and Qualoz in 1995. Using the ELODIE spectrograph, they were able to detect an object of minimum mass $0.5M_{Jupiter}$ orbiting the star 51 Pegasi. Figure 2 shows the up to date radial velocity data sets for this star.

We observe that the velocity of the star's excess positive motion (conventionally, when the star moves away from us) its excess negative motion (towards us) exhibit periodicity - an influence typically associated with the gravitational pull of a large rotating body (for example, a planet). It is difficult to make any other meaningful statements in this mishmash of data yet.

Encouraged by the observed periodicity, we plot the periodogram for the star (see Figure 3).

The largest spike is at 4.23 days. It is a good indication that the spike is caused by the motion of a planet. In Figure 4 we see the date set for 51 Pegasi and a superimposed graph of the radial velocity of the star with one planet orbiting it. We set the period of this planet to be 4.23 days, and run a few numerical simulations to optimize for the other orbital parameters: mass, mean anomaly, and eccentricity. This generates what looks like a good fit for the data.

For this fit we calculate the chi-square statistic reflecting how well the function fits the data and initially the fit is far from satisfactory. The shape of the graphical representation of the function that can be further adjusted to fit the velocity data more precisely. Varying mass (4.23 times the mass of Jupiter in this case), mean anomaly (266.80 degrees - the suggested position of the planet in orbit relative to its periastron, the point in the orbit where the planet is closest to the star), eccentricity

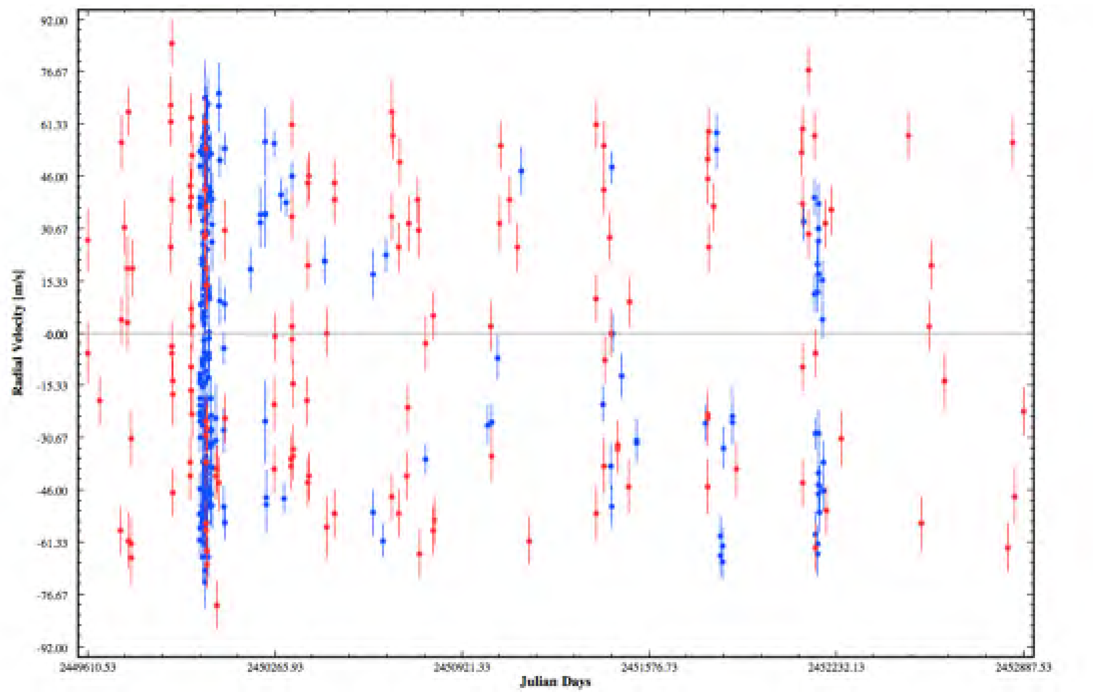

Figure 2: Radial velocity data sets for the star 51 Pegasi. This is the 51Peg_BO6L data set on the *systemic Console*. It includes nine years of measurements on the ELODIE spectrograph (red)[15] and seven years of observation at the Lick Observatory (blue)[6].

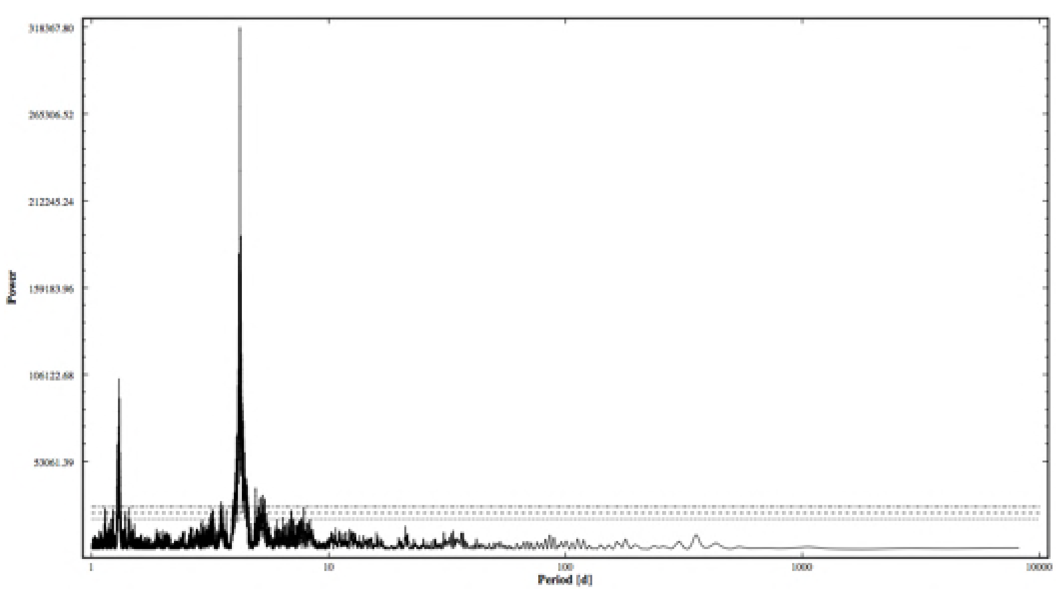

Figure 3: Periodogram for the star 51 Pegasi using the 51Peg_BO6L data set from the *systemic Console*.

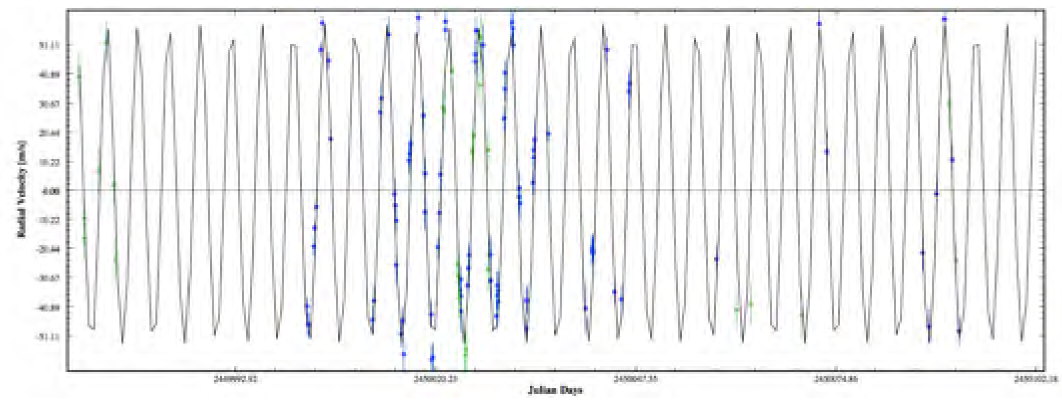

Figure 4: Best fit curve to the radial velocity data for 51 Pegasi. Best fit was obtained using the Keplerian integrator on the *systemic Console*

of the orbit (0.16 - a mathematical parameter of an ellipse indicating the value by which it is elongated relative to a circle) and other variables we get the chi-square statistic to single digits.

The current reported parameters for this planet can be obtained for the Exoplanet Orbit Database ([18]). They are: Minimum Mass $M\sin(i) = 0.46M_{Jupiter}$ (we will discuss in the next chapter why only the Minimum Mass is calculable using the RV technique), semimajor axis $a = 0.0521$ AU, orbital period $T = 4.23$ days, mean anomaly $\omega = 58°$, and orbital eccentricity $e = 0.01$.

2.2 Multi-planet Systems

The coveted find for scientists are systems with multiple planets which allow astrophysicists to invoke possible parallels with our solar system. While looking for planets in the so-called habitable zone of the star (i.e. an orbit that has just the right proximity to the star to receive enough heat to sustain surface liquid water - more on that later) is not the primary scientific mission of such discoveries, confirmed Earth-like, terrestrial planets make for a bulk of newspaper stories and popular science journal articles. The *Sytemic* software allows for the possibility to model systems with multiple planets.

A good example is the star *Upsilon Andromedae* that has the first multi-planet system to be discovered [16]. The newest (the one spanning the longest time) for this star is the *upsand* data set in the *systemic Console*, obtained by Fischer et. al [9]. Working through the data sets and trying to correlate the RV data for the star with the composition of possible planet masses, orbits, positions relative to each other, etc. yields a complex system of five planets with a possible orbital representation given in Figure 5.

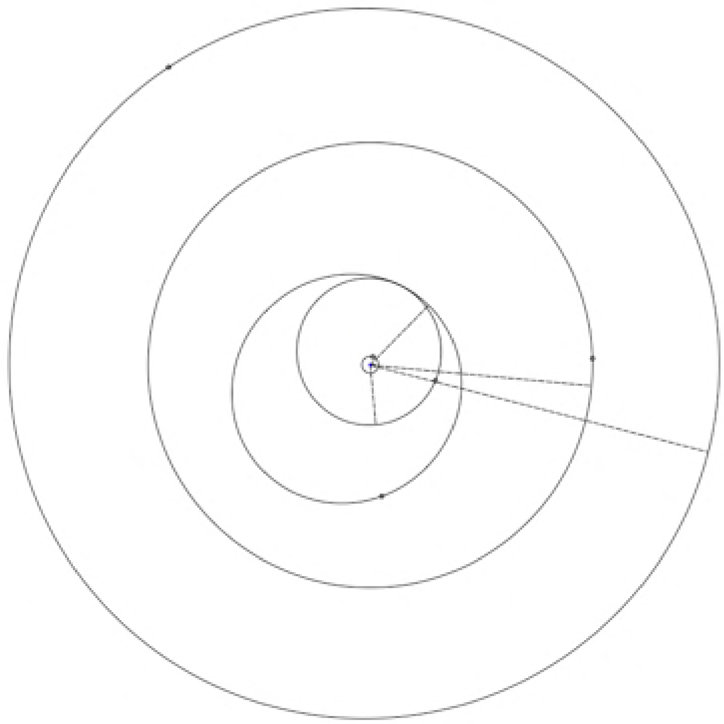

Figure 5: A possible orbital representation of the planetary system surrounding the star Upsilon Andromedea

3 Physics Behind the RV Method

The radial velocity technique exploits the wobble of the star around the center of mass of the planet-sun system. In what follows we consider systems with only one planet, or at least ignore the interactions between planets.

Johannes Kepler (1571-1630) was the first to combine physics and mathematics in the study of planets and their orbits. Working with the great astronomer Tycho Brahe, Kepler was able to deduce three laws of planetary motion.

1. Planets revolve around the sun in elliptical orbits with the sun at one of the two foci.

2. A line joining a planet and the sun sweeps out equal areas during equal intervals of time.

3. The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.

Kepler's observations are illustrated in Figure 6. This diagram describes the relative motion of the planet with respect to the sun. In reality, both planet and sun are zooming through space, going along with the expansion of the universe, and spiraling around the galactic core, far from stationary. Kepler's third law shows that the closer the planet is to the sun, the shorter the period (and more pronounced the wobble). This explains part of the bias towards discovery of planets close to the star: less time is needed to observe a complete period.

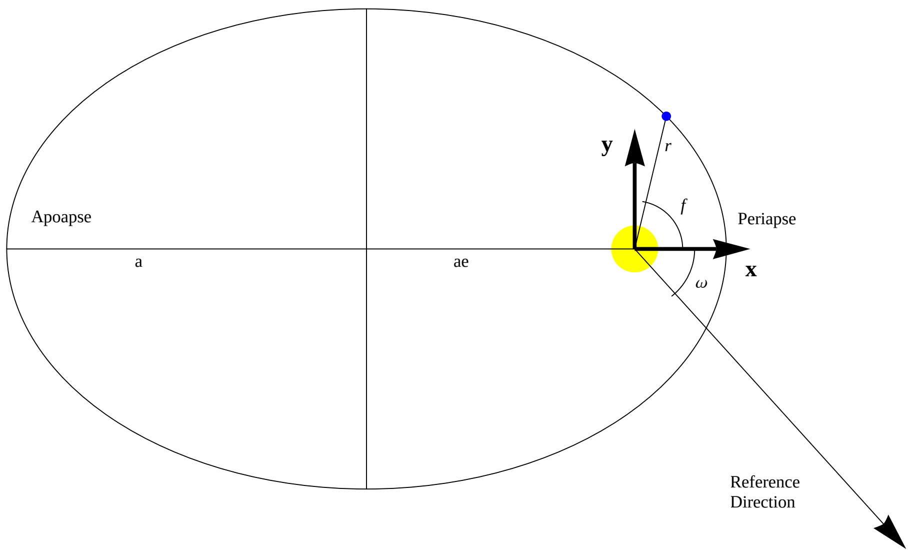

Figure 6: A diagram illustrating a planet moving in an ellipse with the sun at the focus.

Kepler's laws, illustrated in Figure 6, describe the motion of the radius r, or distance of the planet to the star. It shows that this radius follows an ellipse. Using Newton's laws of gravitation, we find that the equation for the ellipse is

$$r(f) = \frac{a(1-e^2)}{1+e\cos(f)}$$

where ω is the longitude of periapse, the angle from a chosen reference direction to the line joining the star with the periapse of the planet's orbit. The angle f measures how far the planet has moved from periapse.

Moving away from this sun-centered reference, we can start to analyze the motion of the planet and star around their common center of mass CM. This situation is depicted in Figure 7. From considerations of symmetry, we know that this center of mass lies on the line joining the center of the star to the center of the planet. Because of this, both star and planet move in ellipses, with the same eccentricity but 180° out of phase, around the CM.

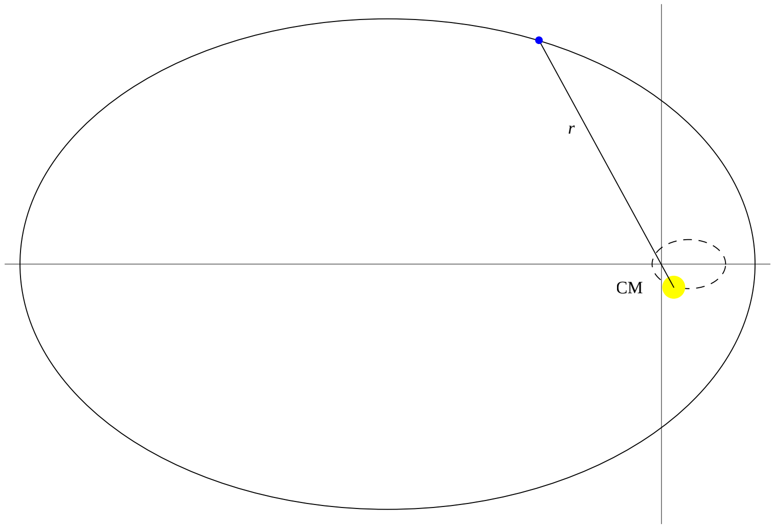

Figure 7: Both the star and the planet orbit in an ellipse around their common center of mass.

It is this motion of the star around the CM that causes the wobble that scientists on Earth detect as a shift in radial velocity.

What does this wobble of the star look like from the Earth? Right off the bat, we can make a few observations. First, if the plane of orbit is perpendicular to our line of sight, then the wobble will not show as a doppler shift (it would, however, show up in astrometric measurements). On the other hand, the greatest radial velocity shift will be observed if the orbit is head-on.

What about all the possibilities in between? How does the angle of inclination effect the observed radial velocity curve? In order to find out we calculate the projection of the star's velocity vector onto the line of sight. The set-up is shown in Figure 8.

After some calculations, we find that the observed radial velocity v_r is given by

$$v_r = V_Z + K(\cos(\omega + f) + e\cos(\omega))$$

where K is the radial velocity semi-amplitude reflecting the true motion of the star independent of the observer and is given by

$$K = \frac{m_p}{m_s + m_p} \frac{2\pi a \sin(i)}{T\sqrt{1 - e^2}}$$

The term V_Z is the proper motion of the center of mass, the motion of the entire system, star and planet, relative to the observer. It is a signal that needs to be subtracted from the data before starting any planet search. Luckily it can be treated as a constant. For an interpretation of the angles i, ω, and f, refer to Figure 8. Here T is the period, a the semimajor axis, and m_p and m_s refer to the mass of the planet and star respectively.

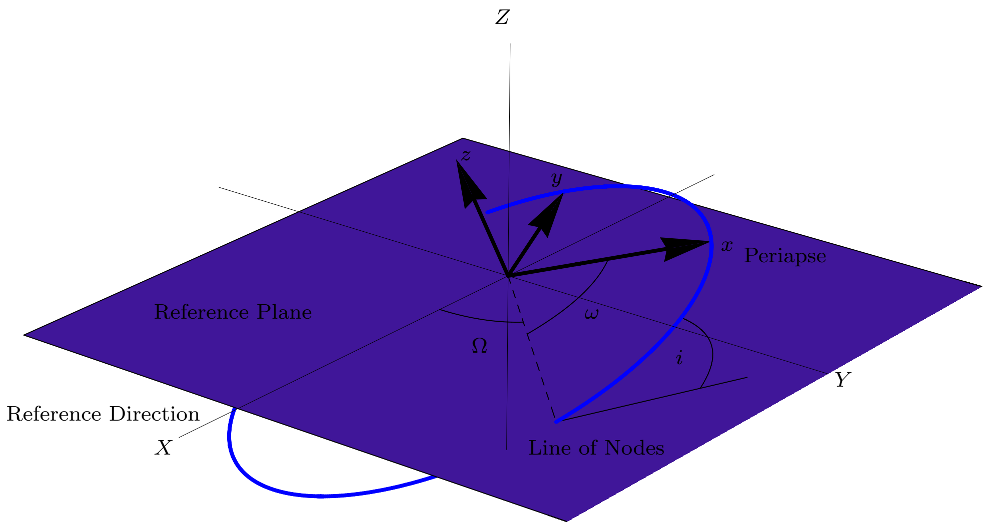

Figure 8: An illustration of the motion of the star around the CM of the system and the projection of its velocity onto the line of sight.

Observe that the radial velocity, minus the constant V_Z, is periodic. Just as we would expect from the description of the stars motion around its CM. Looking at the form of the equation for the semiamplitude K, we all see that the best we can hope for with the radial velocity technique is for an estimate of the minimum mass $m_p \sin(i)$ of the planet! That follows naturally from the fact that the orbital plane of a distant planet might be at an angle to our plane of sight (which itself is perpendicular to our line of sight), and because there is no possibility of using the RV technique to determine what this angle is.

The mass of the star can be determined using other methods, for example, from measurements of its luminosity.

The semi-amplitude K is half of the amplitude of the motion on the star around the CM. It is illustrated, for a case of low eccentricity, in Figure 9. The semiamplitude is also given by $K = (v_{r,max} - v_{r,min})/2$.

3.1 Practical Implications

What does the RV formula entail in practical terms? What kind of precision would one need in order to detect a hypothetical planet? In order to find out, lets for a second reverse the position and assume that a distant observer in a remote galaxy is trying to discover Earth revolving around the Sun.

Imagine Mr. Spock, an astronomer on *Gliese 581d*, a planet in the star system approximately 20 light years away from the Sun, is taking measurements of the Suns

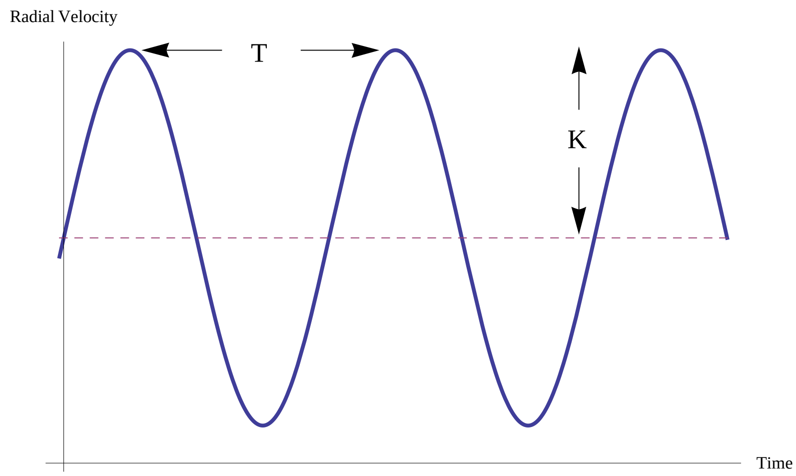

Figure 9: An illustration of the period T and semi-amplitude K for the motion of a star with one orbiting planet in a nearly circular orbit.

radial velocity. Consider a simplified case in which only one planet is assumed to orbit the Sun (say the Earth). What is the radial velocity semi-amplitude that Mr. Spock will record? Is this signal within limits of our current technology?

We would need to assume a hypothetical value for the angle of inclination, lets take $i = \pi/6$ so that the plane perpendicular to Spock's line of sights is inclined at an angle of 30° to the plane of Earth's orbit. From our knowledge of the Earth's mass, its period of rotation around the sun, the eccentricity of the orbit, and the mass of the sun, we find that our Sun's"wobble" due to the gravitational pull of the Earth is a miniature 4.5 cm/s! The most high-precision spectrograph today, the HARPS spectrograph, has an accuracy in the order of a few meters per second, and its successor ESPRESSO will have an instrumental precision of around 10 cm/s. Not enough to detect Earth. Never mind stellar sources of error, such as the convective currents on the sun, which further complicate detection.

We can plot what the radial velocity measurements, without noise, would look like and graph the radial velocity as a function of the angle. We set the angle to be zero at a chosen reference direction (this shifts the graph left or right, but does not change the shape, see Figure 8 for the general setup). We let $V_Z = 0$, i.e. assume that it has been subtracted from the data. WIth the parameters above we get the results in Figure 10.

If we change the observation angle such that the Earths orbit is directly in the line of sight, the sine curve for the RV will increase in its amplitude and look as in the second graph (Figure 11).

This is easy to explain, as the wobble would be more pronounced if it occurs back and forth vis-a-vis the observer without going sideways.

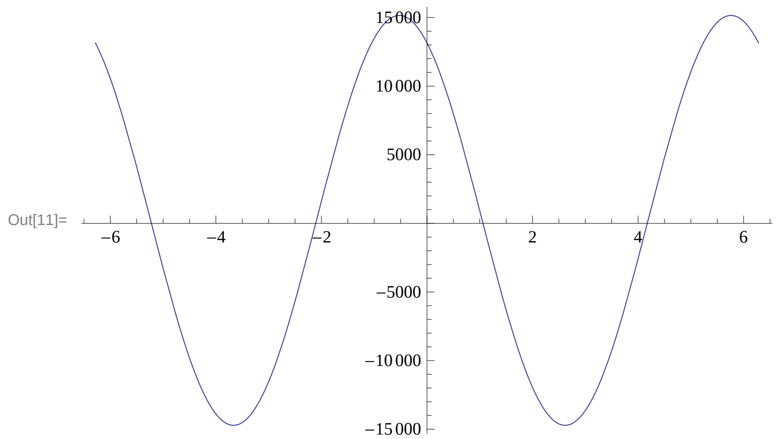

Figure 10: The plot of what a hypothetical radial velocity curve would look like for one Earth-like planet orbiting the sun. The plane of observation is assumed to be at an inclination of 30° to the plane of the orbit (see Figure 8 for the setup). Because the Earth follows a nearly circular path, the plot of radial velocity with respect to time would differ very little from this.

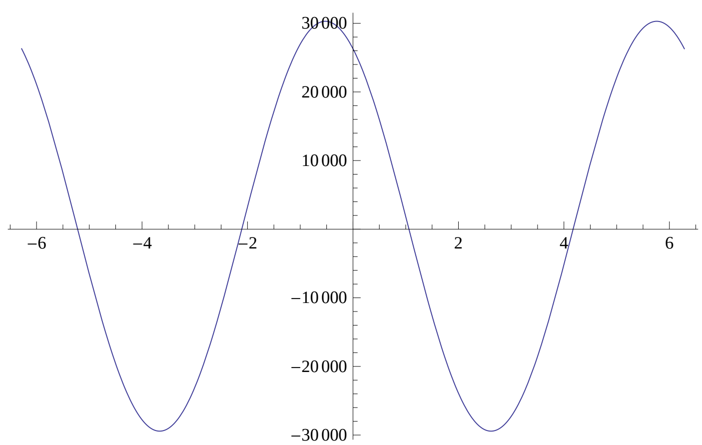

Figure 11: The plot of radial velocity if the angle of inclination is 90°

Even the larger planets in our solar system would be hard to detect, in part because they are located so far from the Sun. Jupiter, for example, leaves a radial velocity trace with semiamplitude about 6 m/s, assuming that the angle of inclination $i = 30°$. This, however, is within the limits of current technology. Of course, Mr. Spock would have to continue taking measurements for about 12 years before observing one complete period!

In general, the spectrographs in use today allow us to detect planets that are relatively large, comparable in size to Jupiter. Or smaller planets orbiting very close to their suns. This explains why the RV method has a strong bias towards discovering "hot Jupiters". Other planet detection methods suffer from different biases and have different strengths. The results of the past fifteen years of planet search are summed up in Figure 12. It illustrates how different detection methods have optimal regions of planetary mass and semimajor axis. We also see that regardless of the method of detection - detecting and mapping small earth-like planets is difficult.

This brings us back to the original exciting idea of finding extra-terrestrial life. As the ultimate prize in planet discovery is the detection of potentially habitable Earth-like planets, how does one use the radial velocity technique for this purpose? Earth-like planets, or terrestrial planets, are composed of silicate rocks and metals and are substantially different from gas giants which might not have solid surfaces (although they may have solid cores) and are composed of hydrogen, helium and water [2]. Terrestrial planets have lower masses and therefore are more difficult to detect in orbits around large stars as the wobble-caused spectral shift is too insignificant for us to detect with todays equipment.

One idea was to look at planets around smaller and cooler stars, known as M-dwarfs. To put things in prospective, astronomers broadly classify stars into groups designated by letters O, B, A, F, G, K, and M, based on the stars' spectral characteristics, where the O-star is the hottest and the letter sequence denotes successively cooler stars down to M-class. Our Sun, for example is the G-class star with surface temperature around 6,000 Kelvins. The M-stars, by comparison, have surface temperatures of approximately 3,500 Kelvins, are less than 0.45 times the mass of the Sun, less than 0.7 times the Suns radius, and are less than half of the Suns luminosity. Incidentally, class M stars happen to to be the most populous type constituting about 75% of all stars in the solar neighborhood [10].

3.2 Planets Orbiting M-Dwarfs

One reason scientists are interested in smaller planets is the possibility of life. The notion of "potential for life" is in debate, although the standard is to analyze a potential life-carrier planet (or possibly another celestial body, such as a satellite of a giant Jupiter-like planet) on the basis of its ability to have surface water in liquid form. Liquid water in turn is conducive to the planet's ability to sustain an atmosphere, as well as a defined range of surface temperature and pressure. As a minimum, atmosphere is important in its ability to mitigate the effects of dangerous radiation that emanates from the star. Surface temperature is closely related to the

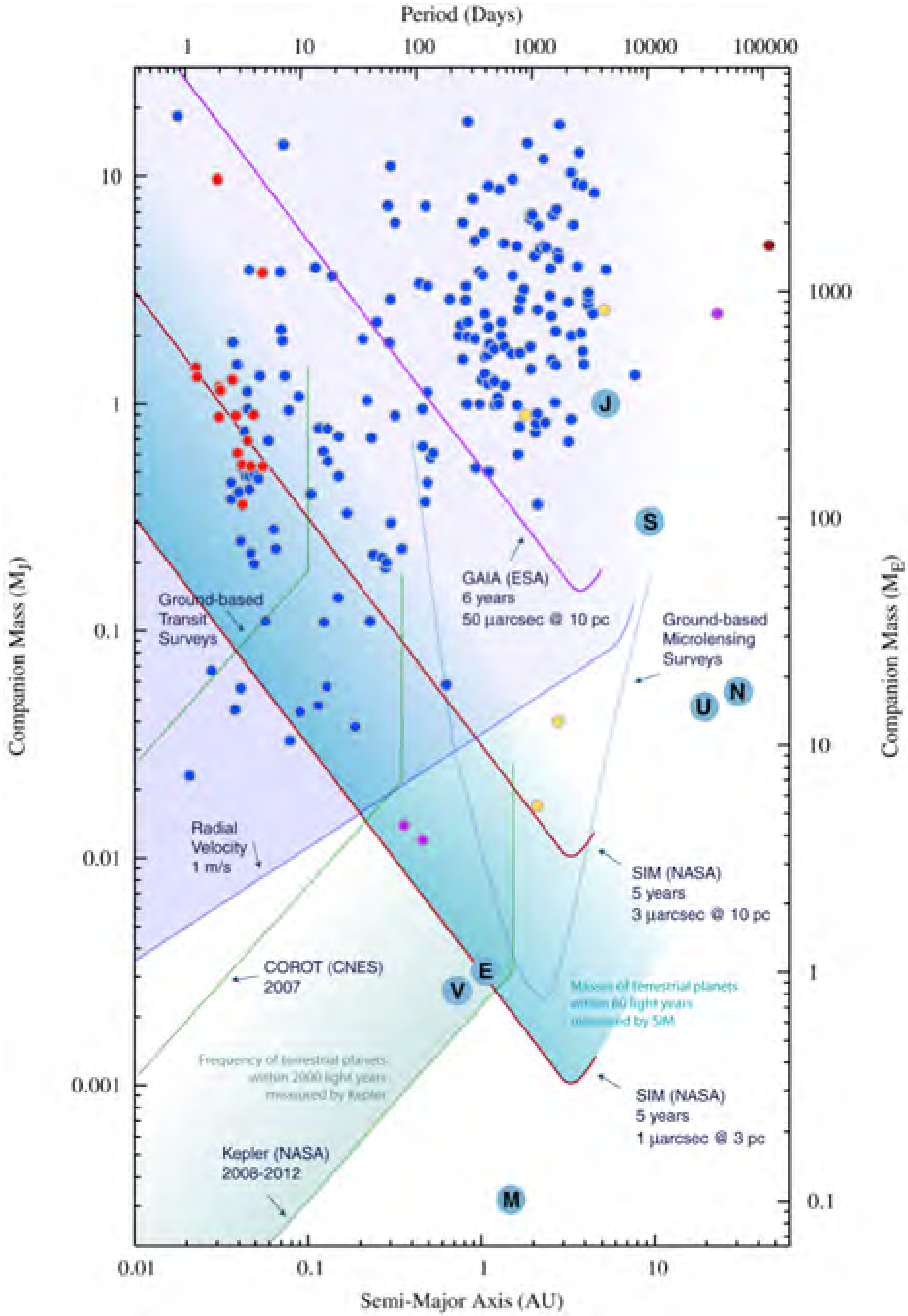

Figure 12: A summary of planets detected so far, and the equipment/technique responsible. Image from [2]

distance of the planet from the star. There is no commonly accepted standard at present as to what the precise conditions for sustaining life are and therefore looking for a planet with Earth-like characteristics is often considered a relevant starting point

[8].

Nonetheless, broad considerations of different possibilities lead scientists to define a so-called Habitable Zone (HZ) of orbital ranges for relevant stars, a zone in which it is possible for a planet to sustain life. The habitable zone is not a static parameter, as stars grow hotter and more luminous with age moving their respective habitable zones outward. This change raises the question of the orbital stability of the system. Also - in a planet-rich star system the sequence of formation of giant and terrestrial planets is critically relevant, because the migration of the large planets from outer towards inner bounds of the system have profound effects on the composition of the protoplanetary disk, abundance of the solid material available for the formation of smaller, high metallicity planets, as well as eccentricity of orbits due to gravitational interactions [8]. It is thought that the evolution of life requires very long periods of stable climate, and hence orbit.

In terms of observation, M-Dwarf stars are an exciting possibility for looking for "potential for life" planets, controversy or not. The habitable zones of these small stars lie very close to the star, meaning shorter periods of rotation for potential planets, and larger radial velocity traces. For example, Mandell and colleagues provide inner and outer boundaries of 0.10 AU and 0.19 AU for the habitable zones of larger M dwarfs, with masses about $0.4M_{SOL}$ [10].

What would the radial velocity signal look like for an Earth-like planet in this habitable zone? Let's go through a simple numerical example. Assuming a semimajor axis for an Earth-like planet of 0.1 AU (1.49 x 10 7 km), a star's mass of $0.4M_{SOL}$ we would get the orbital period of 18.27 days. Substituting this number in our formula for Radial Velocity we get a semi-major amplitude K for the star's RV of 23 cm, still too small to be detected by present-day technology but almost six times larger than the wobble caused by an Earth-like planet rotating around a star the size of our Sun. A *Super-Earth*, however, conventionally a planet with a mass up to ten times larger than that of Earth (but an order of magnitude smaller than Jupiter-like planets) would increase the wobble linearly relative to the mass of the planet. Thus, a planet with a mass of, say four Earths rotating around *Gliese 581*, would result in radial velocity of a star close to 1 m/s if regarded head-on - a measure that is coming within reach of present-day technology.

4 Conclusions and Future Directions

4.1 Challenges and Limitations of the RV Method

The radial velocity technique has proven incredibly efficient at detecting planets. As discussed, however, these planets tend to be large and hot, not something that can support life, and too biased to be an indicator of statistical properties of planets in the universe in general.

Some of the challenges to the radial velocity method are unavoidable. It does not matter how much we improve our instruments, certain sources of stellar and photon noise will remain. To minimize the error from stellar and photon noise, the general strategy is to average out observations over an appropriate time period. The most significant source of stellar noise is granulation and super-granulation (or "stellar jitter"). The granules are caused by convective motions (from inside the sun towards the surface) often having velocities of a few km/s in the vertical direction. The activity can be averaged out over successive measurements to result in an error of a few m/s. An acceptable fit for a planet would allow for some stellar jitter as added noise. Another source of noise is magnetic activity at the surface of the star, particularly strong in the early life of the star. This is the reason why radial velocity techniques are unlikely candidates for studying planet evolution in the early stages, when the protoplanetary disk is still present [16].

Instrumental effects can be reduced by better design. And scientists have made considerable progress. The HARPS spectrograph has an instrumental precision of a few m/s and its successor ESPRESSO will have a precision of about 10 cm/s. To put things in perspective (scientists have to work really hard to get the precision right), a precision of 1m/s in RV corresponds to shifts of only a few 10^{-5} angstroms (1 angstrom is 10^{-10} meters), or equivalently, to 1/3000 of the width of a spectral like, or 1/1000 of the width of a CCD pixel. In order to get at this precision, thousands of measurements in both the stellar and calibration spectra are needed. At present instrumental effects can cause an error of about 2-3 m/s even when other things are accounted for [16].

4.2 Kepler Mission and other Methods

Other methods of detection, while not always as prolific, can overcome some of the limitations of RV. Figure 13 illustrates the different techniques in use today. One method of note is the search for transits that measures the dimming of the light produced by the star at the time when the planet passes in front of it in its orbital path. Up until a few years ago, no planets had been detected using this technique, although it had been used to find orbital parameters, such as estimates of exact mass and the composition of the atmosphere, for planets already confirmed using other techniques. Because of the possibility to detect Earth-like planets, however, much advances have taken place in this field recently.

A major step forward was the launch of the Kepler mission in August 2009. Kepler Mission is NASAs first mission capable of finding Earth-size planets around other stars. It is designed to survey a portion of the Milky Way galaxy and to look for

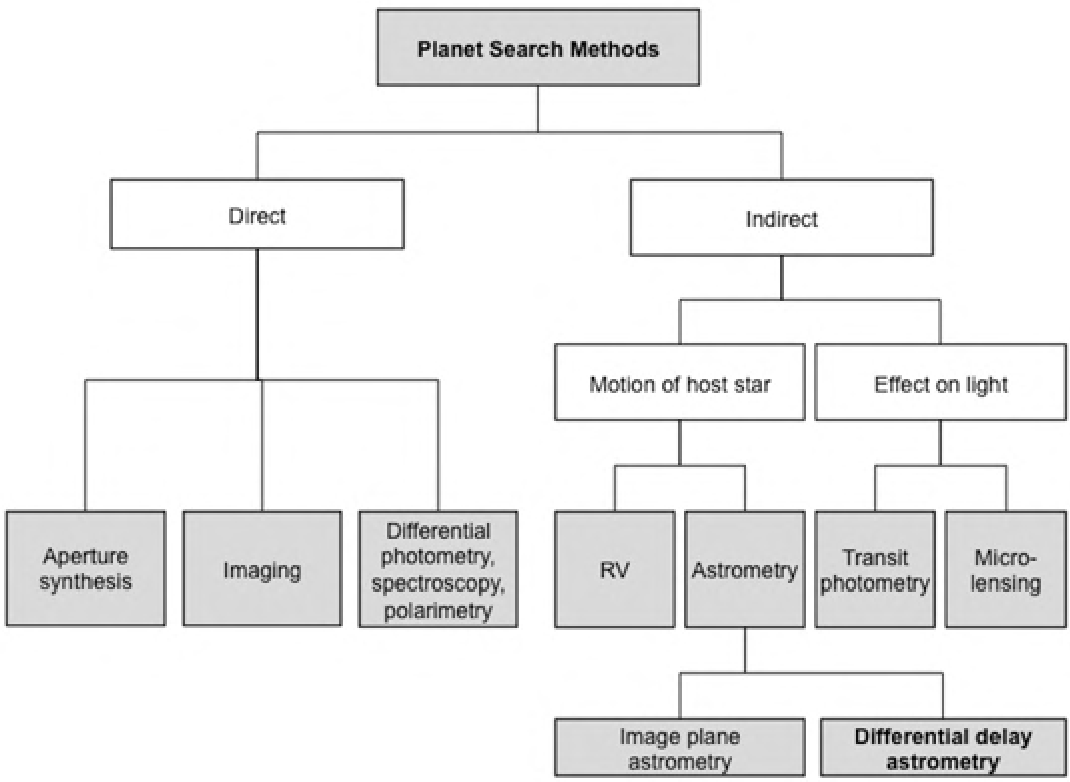

Figure 13: Flowchart of different planet finding techniques. Image taken from [11]

Earth-size planets in or near the habitable zone of stars. And to determine how many stars in our galaxy have such planets. This information will help scientists place our solar system (and our Earth) within the continuum of planetary systems in the universe.

The Kepler Mission looks for transits around stars. For an earth size planet orbiting a star, the probability of a transit occurring is about 0.5% (the probability that an orbit is properly aligned is equal to the diameter of the star divided by the diameter of the orbit). Kepler is looking at over 100,000 stars, so that earth like planets, even if rare, can be detected.

The mission expects to find about 50 planets if they are the same size as the earth and about 185 planets if most are larger, 1.3 times the size of the earth. As of Feb 2, 2011, Kepler has found 1235 planet candidates with 15 confirmed planets [5].

4.3 Conclusion

With these new methods and missions, ever more data on stars has become available. The Kepler Mission is scanning only a portion of the sky, yet it is looking at tens of thousands of stars. The CoRoT, launched by CNES in 2006, is also scanning the sky for transits, looking at over 120,000 stars. Added to these mega missions, are numerous ground-based initiatives, including many for radial velocity. The amount of data is exciting, and there is promise that scientists can begin to tackle the statistics of planet formation and evolution, orbital dynamics, and the prevalence of Earth-like (potentially containing life) planets in the Universe. The amateur astronomer can take a look, and make a contribution to this data mining expedition, at planethunters.org. There the user can help scientists find planets by perusing the data and marking periodic behavior. This helps scientists focus their time on stars more likely to have planets orbiting them.

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