Project: *Search for Other Worlds* - **Course**: *HET 618, June 2006*
Supervisor: *Dr. Laurence Jones* - **Student**: *Eduardo Manuel Alvarez*

Search for Other Worlds

Abstract

Although extremely challenging, the search of *extrasolar planets* ("exoplanets") has already become plentiful rewarding, and best of all, increasingly promising for collecting clues that maybe someday could achieve a definite answer to the essential question about life's existence beyond the Solar System. In such context, the goal of this report is to present an updated description about a handful of the most interesting related topics, at a level readily understandable for any reader with just a basic background in astronomy.

Given that the first and most important subject about practical detection of exoplanets becomes the actual technique to be employed, the discussion of the pros and cons of all possible alternatives embraces the largest part of this report. The remaining corresponds to succinct expositions covering three particular topics: the peculiar properties of the majority of the so-far found exoplanets, a personal guess about the fraction of stars expected to host exoplanets, and finally, the prospects for finding Earth-like planets.

Introduction

Just only fifteen years ago, exoplanets were nothing else than objects with an almost certain probability to exist but yet without any buttressing physical evidence – strictly speaking, the same scenario since the Italian rebel monk Giordano Bruno predicted their existence 400 years ago [**1**]. Prior to their first detection, exoplanets were supposed to be essentially similar to Solar System planets, both in physical and orbital parameters, as they should have resulted from "analogous processes to those that formed the Solar System itself".

Nowadays things are radically different. Since the first discovery by Michel Mayor and Didier Queloz in 1995 of a planet orbiting around a "standard" star [1], an unstoppable flood of new exoplanets has been bombarding media headlines for the last decade [2]. Any average layman currently knows that exoplanets do exist, while any person with some basic interest in general-science has become aware of already found exoplanets have actually nothing to do with planets of the Solar System.

Shortly after trustful data began to characterize new found exoplanets, astrophysicists realized that the obtained information do not match at all with expectations. Physical and orbital data of exoplanet specimens was found to be fundamentally different by Solar System standards, almost impossible to justify by mere extrapolation of evolutionary processes in a similar planetary organization. This empirical and unexpected new context has put a big interrogation mark to the orthodox planet formation theory. It became pretty obvious that old ideas and models must be revised at once.

Consequently, exoplanetary science has been catapulted from yesterday occasional and speculative guesswork to present-day prolific reality, becoming one of the richest astronomical research fields, both conceptually and observationally. No other astronomical subject currently generates such demand for meetings and workshops, promotes so many technical papers, or request so much time to access world-class telescopes.

The world-wide exoplanet hunt has begun. Even serious astronomers are participating. Everyone seems to be interested. Chances are that this present fascination will not stop, at least not before the final prey could be caught: *Earth-like planets*. Then, and only then, perhaps one of the most ancient and fundamental questions for mankind – *"Are we alone in the whole universe?"* – could find a definitive answer.

---

[1] Actually, three years before it had already been found "objects" orbiting around a pulsar, but such surely lifeless exoplanets did not generate the world-wide expectation that following detected exoplanets around standard stars certainly did [**2**].

[2] Also making that common people has lost interest in the subject, in the same way that after the first manned landing on the Moon, following lunar missions (leaving aside the particular Apollo XIII case) notoriously decayed in public attraction.

Current observational techniques

Searching methods for finding exoplanets can be either *direct* (where their presence would result from the detection of some radiation from themselves, either reflected or emitted) or *indirect* (where their existence would result from the inference of some influence from themselves on observed stars).

Direct methods

Direct detection of exoplanets results essential for deriving many of their physical properties, as size, temperature, chemical composition, etc. However, two drawbacks simultaneously concur to make exoplanets almost undetectable by direct methods for our present technology: on the one hand, the low-level radiation that actually reaches the Earth from them, and on the other hand, but most important, their intrinsic proximity to parent stars, always a source that largely overflows their emissions at any given wavelength [3].

There are basically two direct methods for finding exoplanets: *direct imaging*, and *polarimetry*.

a) Direct imaging

Direct imaging from space would only become suitable for detecting planets relatively far from their stars, where the stellar glare is less severe. However, from ground, the case is far more complicated, as atmospheric turbulence smears a star’s light into an arcsecond-wide blob that hides potential planets in its glare, which is millions of times brighter than any planets would be, even on nights with the best seeing. This makes ground direct imaging of exoplanets a totally losing battle, unless some especial technical aid comes to the rescue.

The first and simplest of such techniques is *to imaging in the infrared*. Young planets are still warm from their formation, making them brightest in the IR. Moreover, many stars are dimmer at these wavelengths than they are in visible light, thus potentially lowering the brightness ratio from typical 300 million to one, down to a more manageable 10,000 to 1 [**3**]. By means of IR imaging, even planetary atmospheres could be detected.

Other currently available aiding techniques, all of them highly sophisticated, are *coronagraphy*, *adaptive-optics*, and *interferometry*. The coronagraphy technique, the oldest one, has been particularly developed for suppressing starlight from an image by creating at will an immediate artificial eclipse. A coronagraph consists on special masks interposed between the objective of a telescope and the image plane, in order to selectively reduce the intensity in the image of the bright object appearing centered.

Adaptive-optics technology makes it possible to eliminate in real-time, almost completely, the random distortion provoked by the atmospheric turbulence by means of making the incoming light to reflex on a flexible mirror that on purpose is been continuously deformed exactly in the opposite way. This technique allows ground telescopes to nearly achieve diffraction-limited perfection [**4**].

The final technique, interferometry, is based on the wave nature of light. While this fact becomes an annoyance in coronagraphy because of diffraction, interferometry harnesses it for its goal to suppressing starlight. In this case, the crests of the light waves collected by one telescope are made to coincide with the troughs of the waves from a second one. The combined waves cancel each other out, but only along a line that passes through the center of the image, where the star is precisely located. Farther away from this central line, the nulling effect becomes increasingly diminished, thus leaving potential exoplanets to come visible [**3**].

Infrared imaging, adaptive-optics, and either coronagraphy or interferometry can be used combined from ground observatories in order to improve the chances to image exoplanets. In fact, by means of infrared and adaptive-optics, the first image of an exoplanet was successfully obtained in April 2004 [**5**]. However, the great potential

---

[3] The very same reason explaining why nobody can see with naked eyes the 5th magnitude Galilean satellites.

for direct imaging of exoplanets lies in space, from where several interferometry planned missions expect to obtain copiously images of such elusive models within the next 10-15 years.

b) Polarimetry

Light emitted from a star is *unpolarized* – the electromagnetic radiation oscillates in any plane. But light emitted from a planet, which is actually reflected starlight, undergoes a process of bouncing off its atmosphere. Such interaction causes the light to be sent off with some grade of polarization, depending on the orbital scattering angle, the planetary atmosphere, the planetary surface, and the wavelength. Therefore, the total light received from both star and planet varies its polarization at the planet's orbital period, and such small but not insignificant change directly comes from the detected exoplanet [**6**].

The polarimetry method for detecting exoplanets is the newest technique developed for such goal. It has strong potential, not only for detecting but also for characterizing exoplanets, as from polarization studies it would be possible to determine optical properties, size, and perhaps even the chemical nature of the reflecting particles in the planet's atmosphere [**7**]. Anyway, this promising technique still has to improve its practical development.

Indirect methods

There are currently five indirect methods for finding exoplanets. Two of them – *astrometry* and *Doppler spectroscopy* – are based on measuring the reflex effect that orbiting planets cause in their parent stars; another two – *transit photometry* and *gravitational microlensing* – are rather similar, as both rely on unexpected changes on some changes in star brightness to reach their goal, although the former looks for increases in luminosity, while the latter for drops; while the last one – *pulsar timing* – is based on measuring shifts in radio signals.

a) Astrometry

According to classical celestial mechanics, every time a planet orbits around a star one, no matter their relative difference in mass and distance, in reality both objects are simultaneously revolving around their common center of mass. As the star and planet are always aligned with respect to the center of mass of the system, the *eccentricity* (e) and *period* (P) of both orbits are the same. Given that

$$M \text{ x } a_s = m \text{ x } a_p \tag{1}$$

where M and m are the *masses* of the star and planet, and a_s and a_p are the *semimajor axes* of the star and planet, respectively. It becomes clear that for the usual case of $M \rangle\rangle m$, it consequently results $a_p \rangle\rangle a_s$.

Thus any planet will induce its parent star to move around a small orbit, independently of the star's proper motion – its steady drift across the sky – provoking a tiny superimposed wobble to be always present [4]. As shown in Figure 1, the detection and measurement of such minute displacements on the celestial sphere – the plane of the sky – at a series of times is the goal of astrometry.

The *maximum angular size displacement* (b) of the star's orbit that can be observed – in case its major axis were laying perpendicular – equals a_s / d, where d is the *distance* to the star. From equation {1} it results

$$b = \frac{a_s}{d} = \frac{m}{M}\frac{a_p}{d} \approx \frac{m}{M}\frac{a}{d} \tag{2}$$

---

[4] Of course this can come out only after data resulting from measurements has been corrected absolutely for their dependence on the rotation of the Earth itself and its annual tour around the Sun.

where a_p has been replaced by the sum of both semimajor axes ($a = a_p + a_s \approx a_p$). From Newton's laws of motion and law of gravity it can be shown that

$$a = \left(\frac{GM}{4p^2}\right)^{1/3} P^{2/3} \qquad \{3\}$$

Replacing equation {3} in equation {2} it results [**8**]

$$b \approx \left(\frac{G}{4p^2}\right)^{1/3} \left(\frac{P}{M}\right)^{2/3} \frac{m}{d} \qquad \{4\}$$

As expected, the angle b becomes greater for large m/M ratios, large periods, and small distances, meaning that the astrometry technique for finding exoplanets would achieve promising results only just for massive planets in large orbits around low-mass stars, close enough in our galactic neighbourhood.

For instance, the orbital displacement of the Sun due to Jupiter observed from a 30 light-year distance results in an angle of 5.3×10^{-4} arcsec. This is a very minute angle that certainly poses a hard challenge to state-of-the-art equipment[5] – and it takes almost 12 years to obtain it! Consequently, no single exoplanet has yet been discovered by means of astrometry. Considering also the practical limitations imposed to ground-based astrometry due to the atmosphere – turbulence plus altitude-depending refraction – clearly this technique for finding exoplanets only achieves attractive potential if applied from space and with better resolution than nowadays available ones.

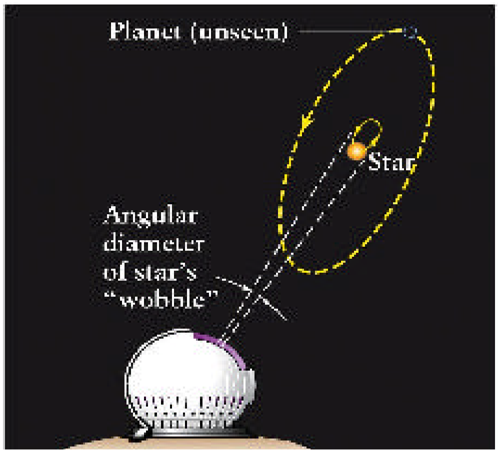

Figure 1
The orbital motion of the star makes it to "laterally" wobble on the plane of the sky.

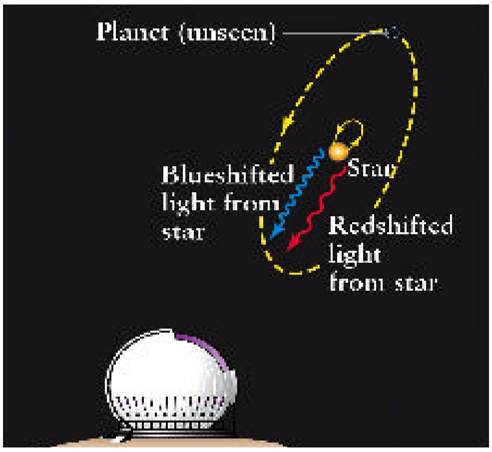

Figure 2
The orbital motion of the star makes it to approach and recede at variable speeds.

b) Doppler spectroscopy

This indirect technique is based on detecting the *radial velocity component* of a star's induced motion due to invisible orbiting planets[6]. As sketched in Figure 2, such radial velocity can be readily obtained by means of measuring the Doppler effect of the star spectrum.

---

[5] The current best resolution for telescopes on high-altitude sites is about 10^{-4} arcsec, that is, as just seen, barely enough to detect the effect of a Jupiter-sized planet orbiting at 5 AU from a solar-type star, from a distance of 30 ly.

[6] Thus explaining the alternative name of *radial velocity method* of wide use for the Doppler spectroscopy technique.

Considering a star and a planet orbiting around the center of mass of the system in circular orbits of radii a_s and a_p, both move at constant speeds and their separation a is always the same ($a = a_p + a_s$). If the star has an orbital speed v, there must be some force directed towards the center of value Mv^2/a_s. Such required force has to be equal to the gravitational attraction exerted by the further orbiting planet, thus becoming

$$\frac{Mv^2}{a_s} = \frac{GMm}{a^2} \qquad \{5\}$$

From equations {1} and {3}, and applying the substitution $a \approx a_p$, it results [**9**]

$$v \approx m\sqrt{\frac{G}{aM}} = \frac{m(2pG)^{1/3}}{P^{1/3}M^{2/3}} \qquad \{6\}$$

Thus, the mass, orbital period, and orbital radius of exoplanets can be determined by measuring the amount and period of the shift of the star spectrum. However, equation {6} can be considered a good approximation for the actual radial velocity (v_r) on condition that the star's orbit appears *perfectly edge-on*. Any other inclination will make decrease it as

$$v_r = v \sin(i) \qquad \{7\}$$

where i (*orbital inclination*) is the angle between the perpendicular to the plane of the orbit and the line towards the observer, varying from the best convenient case of 90° (the orbit appearing exactly edge-on) all down to the worst case of 0° (the orbit appearing exactly face-on [7]).

As there is no way to find out the real orbital inclination of the system with respect to the observer, the actual measured radial velocity from Doppler spectroscopy will also transfer such implicit uncertainty to the derived computation for finding the mass of the orbital companion. Therefore, with this method it is only possible to obtain lower limits – $m \sin(i)$ – to the mass of found exoplanets [8].

Leaving aside the orbital inclination matter, from equation {6} it results that the search for exoplanets via Doppler spectroscopy becomes favoured by large m/M ratios (as in the case for astrometry), but also by small periods (just conversely to astrometry). Small periods come with the added bonus of data potentially been acquired quicker. And the cherry on the top for this technique is that it does not depend on the distance to the star.

Making the same computation as before (a Jupiter-sized planet orbiting edge-on at 5 AU from a solar-type star), the obtained radial velocity is 12.5 m/s, which gives a $\Delta l \,/\, l$ ratio of just 4.2×10^{-8} (for a spectral line of 500 nm, it is required to measure a shift of just 2×10^{-5} nm!). In practice, for effective exoplanet detection is required an accuracy of ± 3 m/s [1]; however, as impressive as it sounds, state-of-the-art equipment can currently measure radial velocities as low as 1 m/s [**10**].

c) Transit photometry

The key idea of this method is to detect the pass of an exoplanet exactly in front of its parent star – a transit – by measuring the tiny periodical reduction in the star brightness that such episodic phenomenon provokes.

Assuming a uniform brightness for the surface of the star, in case the whole of the planet passes across the stellar disc as shown in Figure 3, then the *maximum fractional reduction* (f) in apparent brightness becomes the ratio of the respective cross-sectional areas [**11**]

---

[7] If the plane of the orbit is exactly perpendicular to our line of sight, the induced orbital motion in the star never approaches or recedes from us.

[8] Although it is true that we don't know sin i and hence we would only have minimum masses for exoplanets found by this technique, in practice it is likely that the values of sin i will be quite close to one – the actual masses of planets not too far off the minimum masses – because we are biased to find them in edge-on orbits, where radial velocity amplitudes will be higher.

$$f = \frac{pR_p^2}{pR_s^2} = \frac{R_p^2}{R_s^2} \qquad \{8\}$$

where R_p and R_s are respectively the *radii* of the planet and star. R_s can be estimated in accord with the fundamental equation

$$L = 4pR_s^2 s T_e^4 \qquad \{9\}$$

where L is the star *luminosity*, and the factor $s T_e^4$ represents the *power radiated per unit area of the star surface* (the Stefan's constant s times the effective temperature to the four power).

Therefore, it becomes possible to obtain the radius of the transit planet – a feat not allowed by astrometry or Doppler spectroscopy. Given that its mass can be derived from both such methods[9], its density also becomes known – a crucial issue which places important constraints on the global composition of the found exoplanet. Its orbital period is obtained by measuring the interval between successive dips, and once the mass becomes know, the orbital semimajor axis can also be computed.

From equations {8} and {9} it comes out that the transit photometry technique, which does not rely on the distance to the star, is particularly suitable to detect large exoplanets orbiting small (dwarfs) stars (although for any other case it still results potentially useful, whenever the essential condition of transit were accomplished).

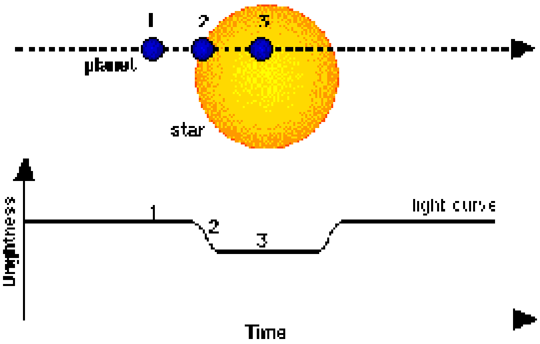

Figure 3
The transit of a planet causes a slight brief decrease in the received light from the star.

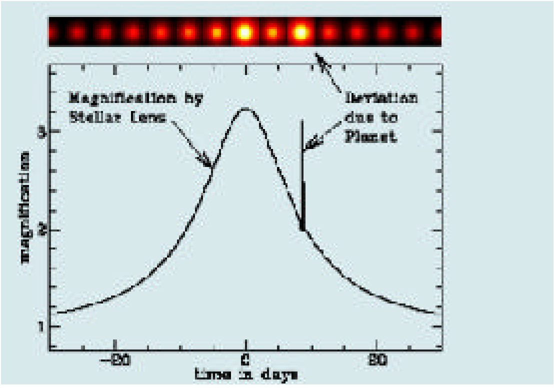

Figure 4
Microlensing causes a variable amplification in the light received from a background star.

If a Jupiter-sized planet were to be observed to transit its solar-type parent star, then *f* would be about 0.01. In order to be properly detected, the star radiation should be measured with a precision of a few parts in 10^3, which is currently easily achieved – even with serious amateur equipment, which becomes particularly apt[10] [**12**].

Given its feasibility and potential, finding transiting planets is one of the present most intended methods. There are more than 20 world-class planet-transit survey projects currently operating, and so far only 10 exoplanets

---

[9] For a transit planet $i \approx 90$ °, so that the $m\sin(i)$ factor calculated from Doppler spectroscopy results its real mass.

[10] The equipment to do this sort of search is certainly within the range of amateurs. For this work having a small telescope is actually an advantage. The reason is that the important thing is to be able to observe as large a number of stars as possible at one time. In general a small telescope will be able to observe the same number of stars as a larger field. However, the small telescope will observe brighter stars over a wide field, while the larger telescope will observe fainter stars over a narrower field. But it is much more valuable to find planets around bright stars as this allows much more detailed follow up observations to deduce their properties [**13**].

have been found – which means that at least half the searches have had no success yet. The problems include obtaining high quality photometry from the images and processing the large quantity of data collected, followed by more observations to confirm any transit candidates found [**10**].

d) Gravitational microlensing

This method is based on the effect on the light received from a more distant star, provoked by a foreground object that happens to be interposed in exact alignment. As predicted by Einstein, the gravitational field of the interposed object bends the light that passes near it, thus acting as a “gravitational lens” which causes the light from the background star to be temporarily amplified following a characteristic gauss-bell curve[11], as appears in Figure 4.

The *amplification* (*A*) of the light received from the background star results [**14**]

$$A = \frac{x^2 + 2}{x\sqrt{x^2 + 4}} \qquad \{10\}$$

where *x* represents *the fraction of the angular separation on the plane of the sky between the background star and the lensing star*. The good news is that the amplification only depends on *x*, thus peaking at closest alignment.

Therefore, given the proper alignment condition, an exoplanet accompanying the interposing lensing star can induce a *secondary brief brightening*, resulting in an easily observable distortion in the otherwise almost perfect stellar gauss-bell light curve. The height of such secondary peak is greater the closer the planet is to the image trajectory – totally independent of its mass – while its duration (t_p) results related to the overall time of the lensing episode (t_s) by a simple equation that finally allows obtaining the planet’s mass:

$$\frac{t_p}{t_s} = \sqrt{\frac{m}{M}} \qquad \{11\}$$

From equations {10} and {11} it results that a lensing exoplanet could produce a brief amplification but as large as the lensing star itself, on condition that *x* were small enough. This property makes gravitational microlensing to be the only method that for now and in the near future could detect Earth-mass planets, even in large orbits around stars that are thousands of light years away (far beyond the reach of Doppler spectroscopy and transit photometry).

As in the case of transit photometry, gravitational microlensing does not require the use of large telescopes at all, thus also becoming within the reach of amateurs [**15**]. The other side of the coin is that the microlensing technique yields very little information about the detected exoplanet or its host star, and certainly no opportunity for follow-up studies.

e) Pulsar timing

The strong radiation emitted by *pulsars* – rapidly-spinning neutron stars – is focused into two oppositely-directed beams. Were such rotational beams intercepted by the Earth, brief pulses of radiation arriving exactly at the same rate are observed. Therefore, if some tiny periodic changes could appear in the pulse timing (a sort of wobble in the otherwise perfect pulsar’s rhythm), then the presence of at least one planet around the pulsar would be infer, also giving clues about its orbital semimajor axis, and a lower limit for its mass (as for Doppler spectroscopy).

In fact, by using this method the very first exoplanet, and even the first multiple exoplanetary system, were found in 1992 by the Pole Alexander Wolszczan around the pulsar PSR 1257+12 [**2**].

---

[11] Luckily, such particular light curve is very different from the normal pattern of *variable stars*.

Final comparison

The following table summarizes head-to-head the suitability of each one of the five indirect methods for finding physical and orbital data of detected exoplanets. All techniques share the common requirement of knowing in advance the mass of the host star. The bottom line underlines the particular characteristics of the host star and corresponding planet that most likely will benefit exoplanet detections.

Physical and orbital data	*Astrometry*	*Doppler spectroscopy*	*Transit photometry*	*Gravitational microlensing*	*Pulsar timing*
Mass of the exoplanet	***yes***	$m \sin(i)$	***no***	***Yes***	$m \sin(i)$
Detection of its atmosphere	***no***	***no***	***yes***	***No***	***no***
Radius of the exoplanet	***no***	***no***	***yes***	***No***	***no***
Period of orbital revolution	***yes***	***yes***	***yes***	***no***	***yes***
Semimajor axis of the orbit	***yes***	***yes***	***yes***	*projected*	***yes***
Inclination of the orbit	***no***	***no***	***yes***	***no***	***no***
Eccentricity of the orbit	***yes***	***yes***	***no***	***no***	***no***
Necessary condition	*nearby stars*	*~ edge-on orbits*	*occurring transit*	*proper alignment*	*~ edge-on orbits*
Method strongly biased to	*big planets* *large orbits* *small stars*	*big planets* *close orbits* *small stars*	*big planets* *close orbits* *small stars*	*any type of planets and host stars*	*big planets* *close orbits* *small stars*

Finally, the following Figure 5 depicts the present and near future exoplanet finding potentiality for all possible techniques, according to the mass of the considered targets.

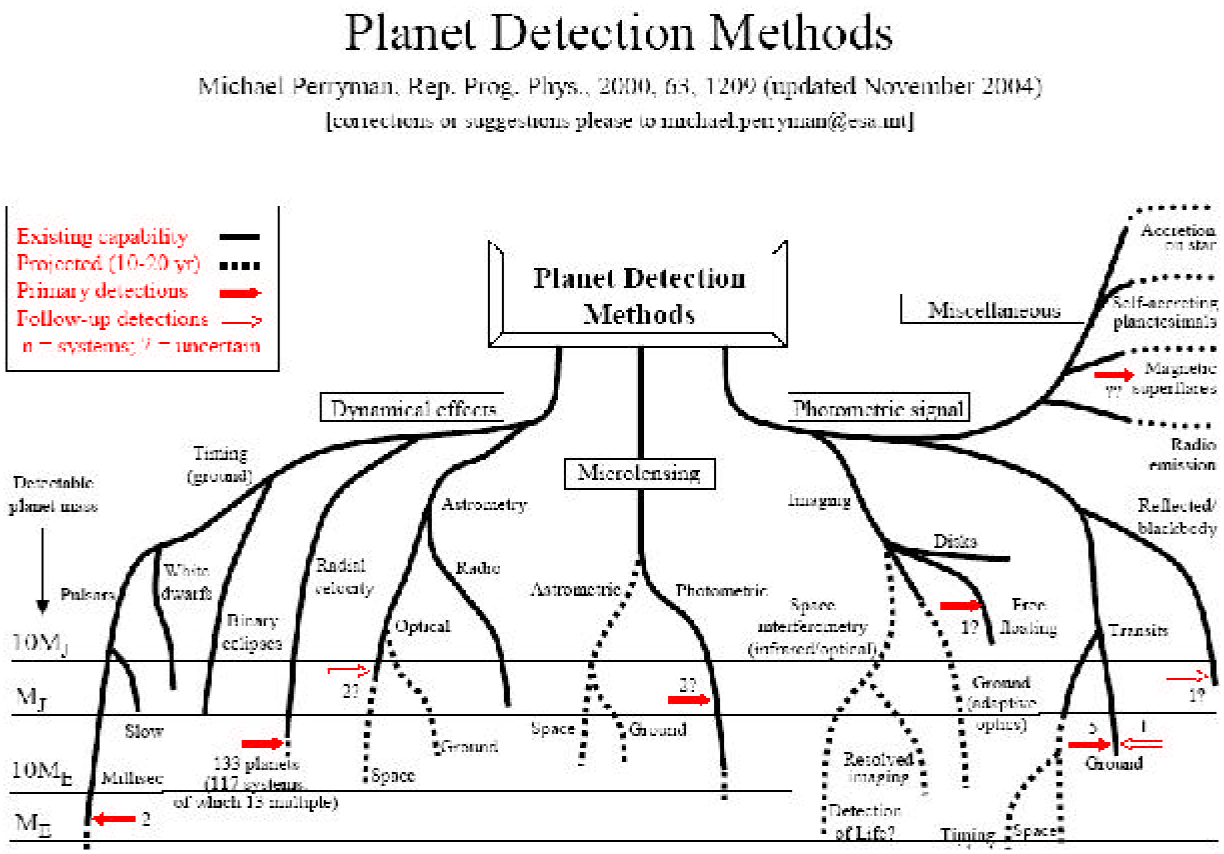

Figure 5
Detection methods for exoplanets
The lower extent of the lines roughly indicates the detectable masses that were within reach in 2004 (solid lines), and those that might be expected within the next 10-20 years (dashed).

Up to date results

There are 193 confirmed exoplanets discovered as of June 3, 2006 [http://exoplanets.eu/catalog.php] from 165 different planetary systems, 20 of them particularly happening to be *multiple* systems – at least two confirmed exoplanets orbiting around the same parent star. Most of the found exoplanets have very short – some a matter of a few days – orbits around their stars. This is both due to the detection techniques – the immense majority (181) have been detected by using the Doppler spectroscopy method – and to the fact derived from the recentness of the discoveries – there are not yet enough data to find planets that have longer orbital periods.

Given that the Doppler spectroscopy technique is strongly biased to find high mass exoplanets with small orbits, at the beginning it was somehow reasonable to expect such featured exoplanets as the first ones to be detected. However, as press discovery titles started to diminish both letter sizes and prominence places, the tendency of incoming new members of the exoplanet family has stubbornly continued to belong to totally untypical types, if compared to our own sibling planets of the Solar System.

Although not completely updated, but anyway fairly representative of their 2004 contemporary exoplanet population, Figures 6 and 7 clearly show that the great majority of found planets are quite massive and possess unusual orbital parameters. The former figure presents mass logarithm distribution, and the latter eccentricity distribution, both plotted against the distance logarithm to the central star. It comes out that all of the shown exoplanets are at least several tens of times more massive than the Earth – the great majority even several times more massive than Jupiter itself – while with just only one exception all of them are closer to host stars than Jupiter to the Sun – many of them even much more closer than Mercury to the Sun [12].

Correlating both graphs it results that there are three broad groups of exoplanets that dominate the whole sample:

(a) those closely grouped at the lower left of Figure 7 – shown enclosed within the red dash circle – thus orbiting just within 0.05 AU at nearly circular orbits. Given that they are so close to parent stars, they have become to be named as *hot Jupiters*;
(b) those loosely scattered at the right side of Figure 7 – shown encircled within the green dash ellipse – thus orbiting beyond 0.15 AU with – in most cases – notable orbital eccentricity [13] . Given that they also happen to be the more massive specimens – as Figure 5 clearly shows – they are called the *eccentric super-Jupiters*;
(c) those that do not belong to any of the previous classes, thus orbiting at intermediate distances and having an average mass about as Jupiter itself. This third group has been nicknamed as *Jupiter analogues*.

Of the three exoplanet groups, only the Jupiter analogues can be eventually explained by the *standard planet formation theory* – the model describing how an original cloud of interstellar gas and dust evolved via gravitational collapse to finally give rise to form planets as those of the Solar System [14]. Neither hot Jupiters, nor eccentricity super-Jupiters could have been materialized from just and only the same evolutionary process.

For the case of hot Jupiters, once assuming the almost sure scenario that they are really *Jovian* – mostly constituted by hydrogen and helium, and having a density about the same as Jupiter [15] – and not giant terrestrial planets [16], two different alternatives have been proposed for explaining the most likely origin further from the star – past the ice line at about 5 AU. The first one – *orbital migration* – would be valid as long as the protoplanetary disk still exists, while the second one – *gravitational encounters* – would correspond once the protoplanetary disk has already dissipated completely. Both models coincide in the idea that observed low eccentricities have to be due to tidal circularization by the host star.

---

[12] The average distance from Mercury to the Sun is less than 0.4 AU.

[13] For comparison, Jupiter and the other giant planets in the Solar System have eccentricities less than 0.05.

[14] In reality, the most accepted idea explaining such phenomenon – the *core accretion* model – has also a present alternative proposal – the *disk instability* model – which predicts planet formation much more rapidly, but faces problems with internal chemical compositions [**16**].

[15] Jupiter's density (1,300 kg/m^3) becomes more than four times lesser than that of the Earth (5,500 kg/m^3).

[16] A luckily transit detected in 2003 for a hot Jupiter proved that its density is 1,400 kg/m^3 – thus eliminating the possibility of a terrestrial-like planet – and even showing a very gaseous atmosphere – thus confirming a gas giant planet and not a *brown dwarf*. Consequently, it has been assumed that most – if not all – of those known hot Jupiters are like this [**17**].

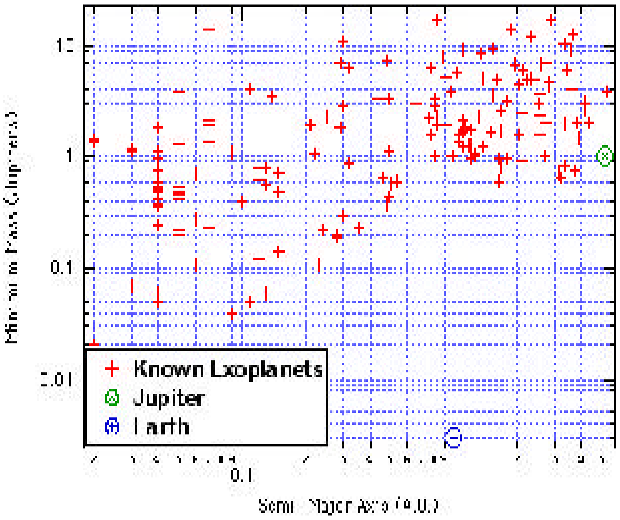

Figure 6
Relation between minimum mass and distance for known exoplanets (circa 2004).

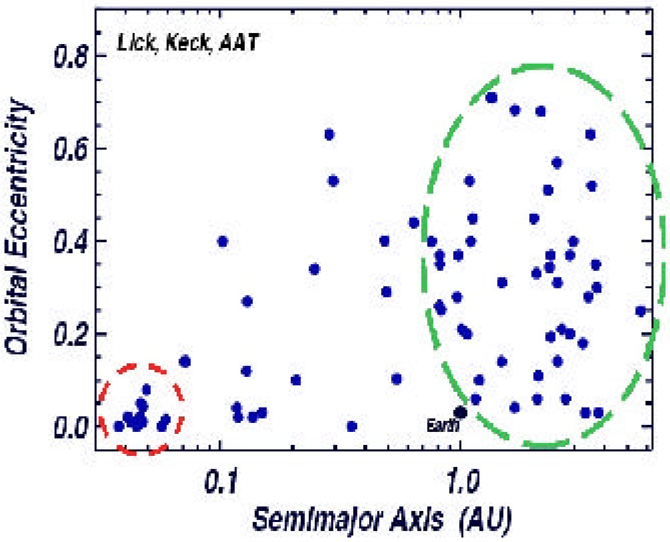

Figure 7
Relation between orbital eccentricity and distance for known exoplanets (circa 2004).

The idea of the orbital migration is that after been formed, the giant planet migrates inwards through the disk (gravitational interactions between the planet and the protoplanetary disk induce the creation of higher density regions, which in turn make the planet to spiral towards the central star), until some halting mechanism [17] finally acts avoiding the otherwise swallowing ending. On the other hand, gravitational encounters could have taken place between protoplanets after the protoplanetary disk had dissipated, and such perturbations might have conducted planets onto very small orbits, which finally ended near-circular due to tidal interactions [**18**].

The issue of the high eccentricities observed in eccentricity super-Jupiters is far more complicated, and there is currently no model good enough to convince everyone. Clearly, much more information is required to disentangle such topic, and the natural source for corresponding clues resides in the 20 already known exoplanet multiple systems – where many orbital resonances have already been confirmed [**19**] – and the much more that surely are about to be discovered in the near future.

One other important point to observe is that it has been found a strong correlation observed between star *metallicity* – the proportion of elements heavier than hydrogen and helium in the star – and the probability of the star having a planet – the higher the metallicity, the higher the probability [18].

Clearly, many processes have likely operated at different levels, producing a plethora of outcomes in planetary systems. Considering that any given system's evolution would have depended sensitively upon initial conditions, the conclusion is that no single mechanism will have prevailed in every circumstance. Therefore, regarding planetary systems formation, from the present exoplanetary evidence it can be objectively inferred that
(1) so far all found systems are unlike the Solar System, meaning that there are a great diversity of them, and
(2) interactions have certainly played an important role.

Based on just those two modest conclusions, the bottom line is that our current understanding about planetary systems formation is still rudimentary.

---

[17] Due to the increasing proximity to the star it could be either the stronger star's fast rotating magnetic field, or tidal star-planet interactions, or planetary mass loses through its Roche lobe, or even a combination of all three [**18**].

[18] At least, giant planets in close orbits are rare among stars with [Fe/H]< 0:1, while they are present in more than 10% of the metal-rich stars [**20**]. This is exactly what the core accretion model predicts, because the heavy elements are the ones needed to make a core; at the same time it becomes a serious problem to the disk instability model, for whom metallicity should not have any incidence in the probability of finding exoplanets.

How many stars do have planets?

In guessing how many stars actually host orbiting planets, the first clue to consider is which percentage of those stars already scrutinized has been effectively confirmed as having exoplanets. From such information at least an empirical low limit can be objectively obtained, thus giving a trustful base from where further extrapolations embracing the whole galaxy population might be intended (although always risking that the greater the gap, the greater the final uncertainty).

From a Doppler spectroscopy survey of 1,330 nearby main-sequence stars with masses lesser than 3 solar-mass (spectral classes F, G, K, and M) performed previously to 2005, 75 stars (almost 6 %) were actually found to have planets [**21**]. In another similar Doppler spectroscopy research comprising about 1,800 nearby Sun-like stars, approximately 90 of them (5 %) were found to host exoplanets massive enough to be detectable [**22**].

Considering the particular constraints applied to both surveys (necessarily of brief duration [19], detection threshold of only 3 m/s, unknown orbital inclinations, etc) such obtained "low" percentages appear rather deceptive [**23**]. In reality, those stars so far remaining without detected exoplanets do not mean that they are lonely as some sort of celestial Robinson Crusoe; in any case, all that can be said is that their possible companions could not have been discovered yet. Not surprisingly, in both surveys the occurrence rates of the planets considerable rose for those having the lowest detectable masses – just below the mass of Saturn.

Therefore, supported by such biased, restricted, and limited observational data, the fraction of nearby Sun-like single stars that actually have planets can be conservatively estimated as 50 % [20]. This is the basic guess that will buttress the next extrapolation attempting a rough answer for the heading question.

In order to obtain a minimum value for the *total number of stars having planets in our galaxy* (N_{S+p}) it can be conservatively assumed that a necessary but not sufficient membership condition for such exclusive club is to be a *Sun-like star lying in the galactic disk*, as those are the stars that have undergone through similar evolutionary processes – essentially *population I* stars with high metallicity like the Sun – that have already proved to admit planetary systems. Such stars can be either *singles* or *multiples*, as exoplanets orbiting wide binary systems have also already been found, although in a low percentage [21] [**24**]. Hence, such minimum number can be expressed as

$$N_{S+p} \geq N_S \times f_{disk} \times f_{Sun-like} \times \left(f_{single} \times f_{gs} + f_{binary} \times f_{gb} \right) \qquad \{12\}$$

where N_S is the total *number of stars in the galaxy*, f_{disk} is the *fraction of stars lying in the galaxy disk*, $f_{Sun-like}$ is the *fraction of galactic-disk stars with similar physical and evolutionary characteristics as the Sun*, f_{single} and f_{binary} are respectively the *fractions of stars forming part of single or binary systems*, and f_{gs} and f_{gb} are respectively the *fractions of single and binary Sun-like galactic-disk stars that actually have planets*. All previous factors are already known with an acceptable certainty, except for the last two.

f_{gs} , the fraction of single Sun-like galactic-disk stars that actually have planets, is the first and easiest factor to quantify, just by considering the obtained "local" outcome as equally valid for the whole galaxy disk. f_{gb}, the fraction of binary Sun-like galactic-disk stars that actually have planets, is going to be conservatively guessed as 0.1. Therefore, substituting in equation {12} it results

$$N_{S+p} \geq 300x10^9 \times 0.9 \times 0.1 \times \left(0.35 \times 0.5 + 0.65 \times 0.1\right) = 6 \text{ billion stars}$$

That is, at least 2 % of all the stars in the galaxy have planets around. This present conservative calculation should become transformed into a more precise estimation, most likely resulting in a much larger final number, as more sensitive, long-duration, and large-sampling exoplanetary searches will be performed in the near future.

---

[19] The surveys were performed during just 6-9 years in average, that is, durations hardly greater than the half time of the 12 years it takes a 5 AU far away Jupiter-like planet to revolve around its central Sun-like star.

[20] There are papers even proposing a full 100 % for such fraction [**20**].

[21] Due to mutual stellar interaction, particularly in close binary systems, potential exoplanets are much harder to detect [**24**].

The prospects for finding Earth-like planets

The Holy Grail of the search of other worlds is to find a conclusive proof about alien life existence. Despite never catch it, the proper way for at least an asymptotic approach to such chimera begins by looking for terrestrial-like exoplanets – if life beyond the Solar System does exist, those kind of worlds will certainly be its habitat [22]. Thus, not in vain almost all our front-line astronomical arsenal is aiming at such objective.

Currently, the search for potential exoplanets is being concentrated around solar-like stars (both in spectral type and age) [**25**]. The reason for this preference is, on the one hand, that those stars are the most promising for shelter life-bearing planets; on the other hand, that it becomes hard to search for planets in more massive stars, because these have fewer spectral lines to work on [23].

However, as previously said, the search for terrestrial-type planets (those reaching down to 1 Earth-mass) still is an endeavour that exceeds our technical resources. Given the low bright of potential Earth-like exoplanets, they are currently well out of range for ground direct imaging; given their low mass, the same happens for astrometry and Doppler spectroscopy methods. Only a very fortuitous coincidence would make them appear occasionally by means of transit photometry or gravitational microlensing.

The undisputed champion method for finding exoplanets – Doppler spectroscopy – is currently capable of detecting radial velocities of about 1 m/s, at least on the brightest stars. At this level, it should be technically possible to detect exoplanets about 5 Earth-mass in short period orbits. However, there is an intrinsic hindrance to allow less massive exoplanet detection. A 1 m/s sensitivity is probably the practical limit for the Doppler spectroscopy technique, as the star itself introduces velocity shifts at this very level associated with stellar activity and stellar oscillations [**26**]. Indeed, terrestrial-type exoplanets becomes a truly hard category.

Therefore, the real chance for a successful and prolific detection of Earth-like planets in the near future lies in systematic stellar surveys made from space particularly by means of transit photometry. According to a 2005 ESA-ESO report, *"planned space experiments promise a considerable increase in the detections and statistical knowledge arising especially from transit and astrometric measurements over the years 2005-15, with some hundreds of terrestrial-type planets expected from transit measurements, and many thousands of Jupiter-mass planets expected from astrometric measurements"* [**25**].

Planned space missions from ESA that will perform (either exclusively or partially) Earth-like exoplanet searches within the next 20-25 years are: Gaia (by means of astrometry and transits, launch date scheduled for December 2011[24]), Corot (by transits, for early 2006), Eddington (by transits, no launch date), and Darwin (by interferometry imaging, for 2015). NASA's counterparts are: Kepler (by transits, for October 2008), Space Interferometry Mission (SIM) (by interferometry imaging, currently unscheduled), and Terrestrial Planet Finder (TPF) (both by interferometry and coronagraphy imaging, currently unscheduled) [**27**].

Conclusions

Although direct methods for finding exoplanets can potentially obtain more and better data compared to indirect methods, in practice the currently available technique almost does not allow to do it. Nearly 200 exoplanets have been so far found detected, the immense majority by means of the indirect Doppler spectroscopy method, and the count goes on quickly. In the near future it will have been exponentially increased by surveys from space.

Found exoplanets are very unlike compared to familiar members of the Solar System. Clearly, many processes operate at different levels, thus producing a plethora of different planetary systems. At least 6 billion stars in our galaxy have planets – a good number to test required new and better models. Finally, promising life-bearing Earth-like exoplanets still are beyond our detection capabilities, but not for much long time ahead.

---

[22] At least for life as we know, that is, necessarily based on carbon and liquid water.

[23] Hot stars are dominated by very strong broad hydrogen lines but few other lines, thus complicating Doppler measurement.

[24] Scheduled dates are those from the respective official websites at the time of this report (early June, 2006)

References

[1] Michel Mayor and Pierre-Yves Frei, *"New Worlds in the Cosmos: The Discovery of Exoplanets"*, Cambridge University Press, 2003, pages 32-35
[2] Ibid., pages 103-106
[3] David Shiga, *"Imaging Exoplanets"*, Sky & Telescope, April 2004, pages 44-52
[4] Govert Schilling, *"Adaptive Optics Comes of Age"*, Sky & Telescope, October 2001, pages 30-40
[5] Robert Naeye, *"Extrasolar Planets: Pictured at Last?"*, Sky & Telescope, August 2005, pages 38-42
[6] Hans Martin Schmid, Markus Feldt, Thomas Henning, Daphne Stam, Rens Waters, and Raffaele Gratton, *"Polarimetry of extra-solar planets"*, IAUC 200, October 3-7, 2005, Nice, France
[7] Daphne Stam and Joop Hovenier, *"Characterizing terrestrial extrasolar planets using polarimetry"*, IAUC 200, October 3-7, 2005, Nice, France
[8] Barrie W. Jones, *"Life in the Solar System and Beyond"*, Springer & Praxis Publishing Ltd, 2004, pages 186-194
[9] Ibid., pages 194-203
[10] Jeremy Bailey, *"Why such precision?"*, Private communication, May 22, 2006
[11] Barrie W. Jones, *"Life in the Solar System and Beyond"*, Springer & Praxis Publishing Ltd, 2004, pages 203-205
[12] Robert Naeye, *"Amateur Detects New Transiting Exoplanet"*, Sky & Telescope news, July 7, 2005, at http://skyandtelescope.com/printable/news/article_1546.asp
[12a] Robert Naeye, *"Amateurs Help Discover Transiting Exoplanet"*, Sky & Telescope news, May 22, 2006, at http://skyandtelescope.com/printable/news/article_1733.asp
[13] Jeremy Bailey, *"Amateur discoveries of exoplanets?"*, Private communication, May 22, 2006
[14] Barrie W. Jones, *"Life in the Solar System and Beyond"*, Springer & Praxis Publishing Ltd, 2004, pages 205-208
[15] Robert Naeye and Edwin L. Aguirre, *"Amateurs Help Discover Exoplanet"*, Sky & Telescope, October 2005, pages 96-97
[16] Michel Mayor and Pierre-Yves Frei, *"New Worlds in the Cosmos: The Discovery of Exoplanets"*, Cambridge University Press, 2003, pages 157-163
[17] Sara Seager, *"Unveiling Distant Worlds"*, Sky & Telescope, February 2006, pages 28-34
[18] Michel Mayor and Pierre-Yves Frei, *"New Worlds in the Cosmos: The Discovery of Exoplanets"*, Cambridge University Press, 2003, pages 163-168
[19] Robert Naeye, *"Planetary Harmony"*, Sky & Telescope, January 2005, pages 44-50
[20] D. A. Fischer and J. A. Valenti, *"Metallicities of Stars with Extrasolar Planets"*, Scientific Frontiers in Research on Extrasolar Planets, ed. D. Deeming & S. Seagar, ASP Conference Series, 294, page 117
[21] Marcy,G.W; Butler,R.P; Fischer,D.A; and Vogt,S.S: *"A Doppler Planet Survey of 1330 FGKM Stars"* , Extrasolar Planets: Today and Tomorrow, ASP Conference Proceedings, Vol 321, 30 June - 4 July 2003
[22] Charles H. Lineweaver and Daniel Grether, *"What Fraction of Sun-like Stars Have Planets?"*, The Astrophysical Journal, 2003 December 1, Vol 598, Issue 2, pages 1350-1360
[23] R. Paul Butler, Geoffrey W. Marcy, Eric Williams, Chris McCarthy, Preet Dosanjh, and Steven S. Vogt, 1996, *"Attaining Doppler Precision of 3m/s"*, Publications of the Astronomical Society of the Pacific, June 1996, Vol. 108, pages 500-509
[24] Michael Schirber, *"Planets with Two Suns Likely Common"*, Science Tuesday, May 17, 2005, at http://www.space.com/scienceastronomy/050517_binary_stars.html
[24a] Alan P. Boss, *"Gas Giant Protoplanets Formed by Disk Instability in Binary Star Systems"*, Dec19, 2005, at http://arxiv.org/PS_cache/astro-ph/pdf/0512/0512477.pdf
[25] ESA, *"Report by the ESA-ESO Working Group on Extra-Solar Planets"*, arXiv:astro-ph/0506163 v1, June 8, 2005
[26] Jeremy Bailey, *"Why such precision?"*, Private communication, May 22, 2006
[27] Gaia: http://gaia.esa.int/science-e/www/area/index.cfm?fareaid=26
Corot: http://www.esa.int/esaSC/120372_index_0_m.html
Eddington: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=47
Darwin: http://sci.esa.int/science-e/www/area/index.cfm?fareaid=28
SIM: http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm
Kepler: http://kepler.nasa.gov/
TPF: http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm

Figures:
1 – http://www.star.ucl.ac.uk/~rhdt/diploma/lecture_2/
2 – http://www.star.ucl.ac.uk/~rhdt/diploma/lecture_2/
3 – http://www.star.ucl.ac.uk/~rhdt/diploma/lecture_2/
4 – http://www.star.ucl.ac.uk/~rhdt/diploma/lecture_2/
5 – http://www.eso.org/gen-fac/pubs/esaesowg/espwg_report.pdf
6 – http://burro.astr.cwru.edu/stu/advanced/esol_trends.html
7 – http://exoplanets.org/ecc_vs_a_col.html