EXOPLANET DETECTION AND THE CoRoT MISSION

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Abstract: We give an overview over the different techniques to detect planets in other stars. A special emphasis is given to the transit method and the French/European CoRoT project, which will be the first space mission with a major dedication to the study the extrasolar planets.

1 Introduction

Other worlds have been imagined by humans from the beginning of our existence but the first written reference to them, as worlds different from Earth, is found in the ancient Greek philosophers' texts. However, the term "planet", literally "wandering" in ancient Greek, was not associated to some physical place until the Copernican revolution reliably demonstrated that the Earth was orbiting the Sun, in a way similar to other known planets. G. Bruno was burnt at the stake by the Inquisition in 1600 for believing that other inhabited worlds – we would call them today "exoplanets" – can exist around other stars. The first scientific evidence for such planets came in 1992 when tiny deviations in the frequency of the signal from the pulsar PSR 1257+12 were detected [1], compatible with the presence of at least two planets of masses similar to the Earth. Some years later, in 1995 [11] discovered the first planet around a main sequence star by observing small periodic Doppler variations in the radial velocity of the star 51 Peg. Today, about 200 planets with a wide range of properties have been detected, a quantity completely unexpected only 10 years ago. Among them are several planet systems, several planets around one component of a wide binary system and also 'free flying' objects with planetary masses, not bound to any particular star.

All current working definitions of a 'planet' agree that they are astronomical objects with masses too low to ignite neither hydrogen burning (around 80 M_{Jup}), nor the light element deuterium (about 15 M_{Jup}), nor to maintain any other nuclear reaction with significant energy output. The exact definition of a planet is however still the subject of discussions, especially regarding the requirement that a planet has to be associated to some central star, as is specified in the preliminary definition by the IAU[1].

We will very shortly give here an outline of the most recent results in the field and in the following, describe the different methods used at present to detect planets. We pay a special attention to the space mission CoRoT, which is expected to give a preliminary census of planets in a wide range of masses and distances from its host stars.

1.1 Planet Properties

A continuously updated table of known planets with their basic parameters can be found in the "Extrasolar Planets Encyclopedia"[2], which allows interactive generation of overviews of the planets' basic properties. The large variety of orbital characteristics is certainly the most outstanding feature among the planets that have been detected today. Several authors [3, 4, 5, 6, 7] have analyzed the properties of the detected sample, among which we outline some features:

- Most planets have been discovered by Doppler techniques. This implies that the sample is biased towards large mass planets close to their host stars. The projected mass distribution indicates that the number of planets increases by a power-law as the mass decreases [8]. If this trend is confirmed, large populations of planets may still be discovered by other techniques more appropriate for low masses. It has been argued that $7.3 \pm 1.5\%$ of single stars (among those suitable for radial velocity searches) have planets with periods shorter than 3900 days [9].

- There are no 'Heavy planets' with masses $m \sin i$ larger than $\approx 2M_{Jup}$ on periods shorter than 100 days circling single stars. The few shorter-periodic heavy planets are all around one component of a wide binary system.

- Hot Jupiters (also known as Close-in Extrasolar Giant Planets (CEGP), Hot Giant Planets or Pegasi Planets), that is, giant planets on orbits of a few days period, are relatively easy to detect but they exist only around a small fraction of $0.7 \pm 0.5\%$ of the MS stars [9]. Their periods are concentrated in the range of 2-4 days. The few with periods below 1.7 days were all found by a transit survey on relatively distant stars.

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[1] http://www.ciw.edu/IAU/div3/wgesp/definition.html

[2] http://exoplanet.eu/ . The IAU Working Group on Extrasolar Planets also maintains a list at http://www.ciw.edu/IAU/div3/wgesp/planets.html

- Planets seem to be rare around metal-poor stars, whereas metal-rich ones have a propensity for planetary systems (e.g. [10, 11, 12] and references therein).
- The lightest planets currently known are several times more massive than the Earth. The mass of Gliese 876d ($7.5 M_{Earth}$ [13]) is a lower limit due to the $m \sin i$ factor of the radial velocity technique, and the mass of OGLE-2005-BLG-390Lb ($5.5^{+5.5}_{-2.7} M_{Earth}$ [14]) has a very large uncertainty as it has been discovered by the microlensing technique.
- The accumulation of radial velocity observations over a decade lead to the longest currently known planetary orbit of 12.4 years – a number that may be expected to grow continuously in the future.
- The average orbital eccentricity of the 90 extrasolar planets on orbits larger than 0.15 AU is 0.32. In contrast, planets orbiting within 0.1 AU of their host star all have nearly circular orbits, probably induced by tidal circularization.

These features show that the known planets constitute a very heterogeneous group, and there is still an enormous potential for further discoveries.

2 Detection methods

Currently, the vast majority of extra-solar planets have been detected by measuring radial velocity variations in stellar spectral lines. However, the first discovery of a planet-sized object orbiting a star was made by measuring the ultra high precision clocking of a pulsar's radio signal [1]. More recently, significant discoveries have been made by other techniques, namely by the transit method, imaging and by microlensing observations. Many further methods and combinations among them are at various stages of development, as described in several reviews [16, 17]. In the early days of exoplanet detection, the detection of a planet *per se* was the driver for most of the works. This objective remains valid, and is now leading to large samples allowing statistically meaningful results on planet and host-star characteristics. Beyond this, current detection projects employ a variety of methods aimed at detecting new *types* of planets: planets with characteristics (e.g. masses, orbits) beyond the detected ones; planets at special stages in their formation; planets around certain classes of stars or planets which are especially suited for detailed studies. The results from this variety of methods, and the possible combinations among them, leads to the expectation that the most important discoveries are still to come.

We will describe in the following some of the different techniques used to put in evidence these elusive astronomical objects, together with the latest results in the field. Following the paragraphs dedicated to transits we will describe in some detail the CoRoT mission, which is the first one dedicated to obtain ultra high precision photometry from space.

2.1 Imaging

In this section we consider techniques that intend to detect a planet by some kind of imaging technique; sometimes also referred to as 'Direct Detection' or 'Direct Observation'. Simple calculations show that the light reflected from a Jupiter-sized planet is about 9 orders of magnitude (≈23 mag) fainter than the central star. At the corresponding planet-star separation – on the order of an arcsecond for Jupiter-like planets around nearby stars – the reflected light of the planet will disappear within the noise of the fringes of the stellar image. Efforts are being made to suppress the stellar light with coronographic techniques, aided by adaptive optics to minimize the effects of the atmospheric turbulence for ground-based telescopes. A further option is the gaining of contrast by observing at longer wavelengths – basically the near/mid IR – where thermal radiation from the planet can be observed, and star-planet brightness ratios may be 10-100 times lower than in visible light. Imaging techniques are therefore mostly suited for 'bright' planets with large separations from their central star. It should be noted that this is reverse to several other important methods (radial velocities, transits), which are more sensitive to close orbits. Imaging a planet's thermal emission in the IR is especially suitable when the central star has a low temperature, and the planet a relatively high one; this is the case if the star is young and the planet still in its formation stage. Currently, 3 planet-like objects have been detected with this method (GQ Lup, 2M1207, AB Pic), all around low-mass stars, but there are still some doubts on whether these are planets or low-mass brown dwarfs [18]. Coronographic [19] and interferometric techniques for exoplanet detection are currently a major driver for instrumental development on large telescopes and for space-based missions. An attractive variation to coronography is the employment of an occulter of several ten meters diameter in space, flown at a large distance (several $10^4 km$) from an observing telescope. This may allow the direct detection of Earth-like planets at nearby stars, with relatively little new technical developments [20]. Interferometry may be considered a version of imaging, where only certain spacial frequencies are observed, depending on the number of interferometer elements and the distance between them. In the mid-to-far future, it might become the most important technique for finding and analyzing planets, and numerous projects in the form of searches or dedicated instruments on large telescopes or space missions are on going [21, 22]. The *Darwin* Infrared Space Interferometer[3] is considered by the European Space Agency as a high-priority but long-term programme [23]. It uses the principle of nulling interferometry introduced by [24] to enhance the planet/star

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[3] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=28

signal. The system, consisting of 3 free-flying space telescopes of at least 3-m diameter, has the goal of detecting Earth-like planets around the brightest and nearest stars, and to obtain very low resolution spectra of them. These spectra will be used to put in evidence bio-tracers [25], such as ozone, water, carbon dioxide, etc ..., in their atmospheres, and may give the first observational evidence for the presence of life outside the Solar System. NASA is considering another ambitious mission, the 'Terrestrial Planet Finder'[4], first with a coronographic device (TPF-C), and being completed by a multi-telescope interferometer (TPF-I) about 10 years later. The proposed 100-m ground-based OWL telescope[5] could be able to detect Earth-like planets around the nearest 100 stars based on a system with one million actuators [26]. The ultimate imaging system may be a 'hyper-telescope' like the one proposed by [27], with 150 telescopes of 3m class in space, with separations of 150 km. Figure 1 shows a simulation of our Earth seen at 10 light years. Still decades away from realizing this or similar projects (for an overview, see [21]), we shall then be able to study the planetary surface with spatial resolution and to obtain planetary spectra that may give rather strong evidence for the presence of life around the nearest stars.

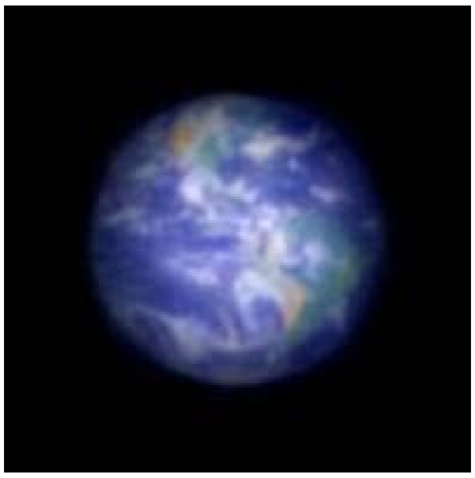

Figure 1: Earth as seen from a star 10 light years away with a hyper-telescope [27].

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[4] http://planetquest.jpl.nasa.gov/TPF

[5] http://www.eso.org/projects/owl/

2.2 Radial Velocities or Doppler displacements

Undoubtedly the method which has contributed most to the current development of the field of exoplanets has been the measurement of the Doppler shifts of spectral lines of stars, induced by the stellar radial velocity variations due to the presence of orbiting planets.

The expected radial velocity amplitude K of a star of mass M_* being orbited by a planet of mass M_p at an inclination angle i with orbital period P and eccentricity e is:

$$K \;=\; (\frac{2\pi G}{P})^{1/3}\frac{M_p \sin i}{(M_p+M_*)^{2/3}}\frac{1}{(1-e^2)^{1/2}}$$

For example, for the Jupiter-Sun system with a period of 11.9 years, this gives $K = 12.5\ m/s$, and the Earth-Sun system with a corresponding one year period gives $K = 9\ cm/s$. Since i is generally unknown, the method provides only "projected masses", $M_p \sin i$ and hence only lower limits to a planet's true mass. Given the requirement that radial velocities need to be observed over at least a large part of a planet's orbit, it becomes obvious that short-periodic planets can be detected more swiftly. The method allows the detection of long-period planets with slight degradations in sensitivity only (see above equation), but requiring proportionally longer observing spans. Radial velocity detections are however limited to cool stars because the small number of absorption lines in hot stars prevents the use of cross-correlation techniques required for accurate Doppler shift measurements. Also, active stars and fast rotating ones have to be excluded for most detection attempts. Radial velocity measurements require very specialized instruments with precise wavelength references, and rather large telescopes when faint stars are to be observed. As an example, the HARPS instrument at the ESO 3.6m telescope obtains precisions of 2m/s on a 12 mag star in one hour of integration, with limiting precisions well below 1m/s. A new approach is the 'Exoplanet Tracker'[6], which is based on a combination of a Michelson interferometer and a medium resolution (R=6700) spectrograph which overlays interferometer fringes on a long-slit stellar spectrum. This instrument can obtain higher throughputs (up to 50%) than the traditionally used Echelle spectrographs, and is well suited for multi-object surveying with fiber-optics feeds. One planet, called ET-1, has been found with a prototype setup [28], and an All-Sky survey of millions of stars is planned. Overviews about radial velocity detection projects can be found in [21, 22].

Today the radial velocity method continues to dominate the discovery of planets, both in terms of number of detections and smallest sizes (except for $M_p \sin i$ being unknown). This situation may be expected to continue at least until the operation of

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[6] http://www.astro.ufl.edu/et/

the space missions CoRoT and Kepler, which use the transit method. Radial velocity measurements will however be also extremely useful for these missions, since they will be able to confirm the satellite-detections in an independent way.

2.3 Timing methods

Timing methods are similar to the Radial Velocity method (where the stellar velocity is measured), with both arising from the distance variation of a star due to an orbiting planet. In timing methods, we measure variations in the light-travel time of the stellar light. This is possible if stellar systems have a precise clock reference, such as the radio signal of a pulsar, or the time of minimum of an eclipsing binary. In these cases, periodic departures from a lineal ephemeris may deduce the existence of an orbiting object; be it a star (see for instance the case of the system SZ Lyn [29]) or a planet, as is the case of the pulsar PSR 1257+12, with at least two objects with Earth-like masses. Evidence has been given by [1] for the existence of a third planet in this system, and by others [30, 31] for terrestrial planets around pulsars PSR B0329+54 and PSR B1620-26 respectively. For eclipsing binaries, an analysis of the minimum times of the eclipsing binary CM Dra, from observations in the period from 1994-99, gave indications for the presence of a circumbinary planet of several Jupiter masses [32]. The photometric space mission Kepler (see section 2.6) may also be well-suited to such an analysis of the eclipsing binaries [33].

2.4 Astrometry

In all planetary systems, the induced motion of the central star has a lateral component on the sky, described by an ellipse whose angular semi-major axis is given by:

$$\alpha \;=\; \frac{M_p}{M_*}\frac{a}{d}$$

where α is in arcseconds, a is the planet-star distance in AU and d the distance to the system in parsecs. For a Jupiter/Sun system at a distance of $10pc$ this value is on the order of $500\mu as$ (microarseconds), whereas it would be $0.3\mu as$ for an Earth/Sun system at a similar distance. Astrometry is therefore, similarly to imaging techniques, best suited for long-periodic planets. Contrary to radial velocities, astrometric detections would lead to a well-determined planet mass, since planetary orbital parameters can be derived completely. The limit of these techniques is imposed by the very high positional precision needed. It is limited by the non-uniformity of the stellar surfaces, which gives raise to displacements of the photometric centroid, mimicking orbital companions.

Though astrometry has not produced any certain planet detection yet, several experiments are in course: Operating from the ground CHARA[7], a Y-shaped interferometer of six 1-m telescopes on Mount Wilson, gives at present a resolution of $200\mu as$. The Keck Interferometer[8] is a NASA-funded project to combine the two 10-m Keck telescopes in the near-infrared (10 μm) to perform nulling interferometry in order to measure the quantity of exozodiacal emission around nearby stars and to detect Hot Jupiters by their direct emission [34]. The Very Large Telescope Interferometer (VLTI)[9] takes advantage of the coherent combination of at least three out of the four VLT Unit Telescopes and/or the four moveable 1.8m Auxiliary Telescopes. Some fringes have been captured with the VINCI test instrument, indicating results for bright stars compatible with precisions of 0.04 *mas* [35]. The interferometric combination of the light paths of the two primary mirrors of the Large Binocular Telescope (LBT) will provide a resolution of an equivalent 22.8-meter telescope, and the first light was achieved in October 2005. Its Nulling Interferometer (NIL)[10] will be able to directly image faint zodiacal dust disks as well as gas giant planets.

The only astrometric space mission launched to date, Hipparcos [15], provided positions for 120 000 stars with milliarcsec accuracy. In the microarcsec class are the NASA mission SIM[11], which is focused to planet-search, and the ESA mission GAIA - mainly dedicated to research about the galactic structure, but also able to detect massive planets. A sub-milliarcsec space mission DIVA[12] from Germany is now under consideration.

2.5 Microlensing

Light does not travel along a straight line if it passes close to a gravitating body, but instead follows a geodesic path along the distorted space-time. This effect is called gravitational lensing. If the body responsible for the lensing effect is not a galaxy but a single star the phenomenon is called microlensing. Very precise alignment between background and lensing star is required to detect measurable brightness increase and the probability to produce an alignment is consequently very low, on the order of 10^{-6} for a given star in the galactic bulge, even if all the dark matter is made of lensing objects [36]. Stellar lensing time scales depend on the distance between source and lensing objects, but for stars at 8 kpc and with solar masses, events last on the order of several weeks. Planet detection by microlensing is based on observations of deviations from the normal brightness amplification during a lensing event. Once a stellar

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[7] http://www.chara.gsu.edu/CHARA/

[8] http://planetquest.jpl.nasa.gov/Keck/

[9] http://www.eso.org/projects/vlti/

[10] http://planetquest.jpl.nasa.gov/lbti/

[11] http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

[12] http://www.ari.uni-heidelberg.de/diva/news.html

lensing event occurs, the probability that a planet around the lensing star causes an observable amplification (one that raises the stellar amplification by at least 5%) is about 20% [37]. A Jupiter-like planet around a lensing star 5 kpc away may cause a brightening of up to 3 mag during about 3 days, whereas an Earth-equivalent may cause brightenings of 1 mag and last about 4 hours. Once a high-magnification stellar lensing event has been detected, its fairly long time duration gives the opportunity to initiate surveying with higher temporal resolution in order to catch the short events from planets. This is the strategy that has been followed by the PLANET network[13]. Although the first event claimed to be a planetary microlensing was given by [38], the first clear evidence was the discovery in 2003 of the planet OGLE 2003–BLG–235 [39]. More recently, the exoplanet with possibly the lowest mass known (Figure 2), of $5.5^{+5.5}_{-2.7} M_{Earth}$ was found by microlensing [14]. Summaries of microlensing searches are given in [21] and [22]. Microlensing stands out for being the method that can detect planets over the largest distances and allowing the detection of sub-Earth mass planets. Its major drawback comes from the uniqueness of a microlensing event, making further observations practically impossible. The observations of astrometric variations due to a lensing event, lasting much longer than the photometric signal, has however been proposed for the case of free-floating planets [40]. The errors in the derived planet masses are also typically rather large, and may be on the order of the mass itself. The potential of microlensing lies therefore in surveys on planets in different (distant) stellar populations and in the detection of unbound planetary-mass objects.

2.6 Transits

Planet detection by transits is based on the observation of the small weakening of a star's brightness when one of its own planets crosses (or 'transits') in front of it, temporarily occulting some light from its stellar disc. The brightness loss can approximately be given by the ratio of the planetary and stellar cross-section area:

$$\frac{\Delta L}{L} \approx (\frac{R_p}{R_*})^2$$

where effects of limb darkening [41] are neglected. The brightness loss is about 1%, or 10 mmag, for a Jupiter-sized planet transiting a solar-like star, and 0.1 mmag for an Earth-like planet. Of course, transits can only be observed when a planet's orbit is aligned nearly edge-on to the observer (i.e. an inclination close to 90^o). The probability that a planet system, with unknown inclination is aligned in such a way that transits are observable, is given by:

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[13] http://planet.iap.fr/

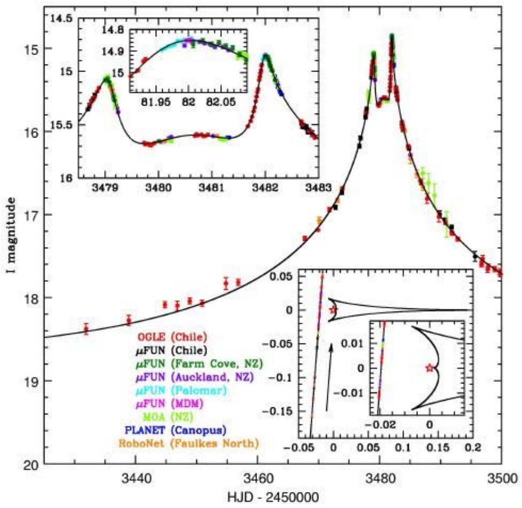

Figure 2: Microlensing event OGLE-2005-BLG-390, from [14].

$$p = R_\star/a_{pl} \equiv \cos i_{min}$$

For an Earth-Sun system this corresponds to a probability of 0.47%, or requiring an inclination larger than 89.73^o. Short periodic hot Jupiter planets have however a much higher detection probability, with $p \approx 5\%$. This probability may also be raised if we look at transits in eclipsing binaries, assuming alignment between the binary and the planetary orbital planes [42]. The transit of the Earth across the Sun takes 13 hours when seen by a distant observer; for other systems this duration can be estimated when the spectral type of the central star, and hence M_* and R_* are known, by:

$$\tau \quad = \quad 13h \; (\frac{M_*}{M_{sun}})^{-1/2}(\frac{a}{1AU})^{1/2}(\frac{R_*}{R_{sun}}) \cos\delta \;,$$

where δ is the latitude of the transit on the stellar disk. For hot Jupiter planets, this gives durations of 2 – 4 hours.

The potential of the transit method lies in the wealth of information that can be gained from these planets and in the possibility of detecting rather small planets from space-based observations. Transits give directly the size of the planet relative to the star. Knowing the period from the observations of several transits, we can derive (if R_* is known) the absolute planet size and the orbital inclination. If, additionally, a radial velocity detection is obtained, this allows to fix the planetary mass and to derive the planetary density. The first detection of a transiting planet was made in 1999 simultaneously by two teams [43, 44], around the star HD 209458. This hot giant planet, and two further ones orbiting bright stars, TrES-1 [45] and HD189733 [48], are today by far the best studied extrasolar planets. Transiting planets, especially those around nearby bright stars allow numerous follow-up studies and have led to the first detections of atmospheric constituents from spectroscopy during a transit [49, 50, 51] or detection of their infrared emission by observing the secondary transit [52, 53, 54]. Transit light-curves may also show spots on the central star [20] or be used to obtain the stellar limb-darkening coefficients [41].

Numerous ground-based experiments dedicated to the detection of transits using wide-field CCD photometry are being advanced (for lists on such projects, see [56, 21, 22]). The number of confirmed detections is however still below 10, which is very small when compared with early predictions [56] – indicating that at least ten times more planets should be known to date. The origin of this discrepancy has probably several causes [46]: Simplifying assumptions in the noise properties that govern the detection limits in previous predictions – in many cases red instead of white noises may be dominating [47]; unaccounted errors in aperture photometry on auto-guided telescopes; overestimates on the fraction of stars that are suitable as targets for transit surveys; and underestimates of the required duration of observations. Another topic whose consequences have only been recognized during the course of the first transit searches is the problem of false alarms caused by other stellar combinations that may produce transit-like light curves. Of these, the most notorious case may be that of an eclipsing binary star that is located within the point spread function (*psf*) of a brighter star [57]. An increasing number of tools are now available to recognize false alarms: Precise analysis of transit shapes or durations [58, 59, 60], color signatures [61, 62, 63] or variations in the positioning of the stellar point spread function [64, 65]. The effectiveness of several of these tools depends strongly on the information (e.g. temperature, radius) that is available for the host star, and underlines the need for auxiliary observations in transit detection experiments.

The best photometric observations from the ground are limited by the local variations of the sky transparency. Noise levels of 0.3 mmag have been obtained at certain frequencies after multiple frequency fittings for some multisite campaigns of the best so far observed δ Scuti star FG Vir. [66]. In the time-domain, the best ground-based transit observations reached a noise level of 0.67 mmag in a combination of Strömgren v and b filters [41]. Scintillation finally imposes a limit around 0.1 mmag beyond which the observations have to be made from space.

The acquisition of data with very noise-levels, and without day-night or bad-weather interruptions, is desirable in order to detect smaller and/or longer-periodic planets. Detection of planets as small as the Earth has been the major motivation for several space transit surveys.

The first mission to be launched, in late 2006, will be CoRoT which is described in more detail in the next Section. Eddington [67], a larger and more flexible instrument, was and accepted by ESA for launch, but cancelled in 2003 for budgetary reasons. Kepler by NASA[14], with launch foreseen for 2008, is a mission specifically dedicated to the detection of Earth-like planets (in the sense of Earth-size and on orbits at distances that may allow development of life). With a 0.95-m telescope and a 105 $\deg^2$ field of view, it will continuously monitor for 4 years more than 100000 stars with precisions on the order of 10μmag, and expects to detect around 1000 terrestrial planets. Meanwhile, there is continued development of new concepts for space missions based on transit detections [68].

3 The CoRoT mission's planet finding experiment

Figure 3: The CoRoT satellite at assembly

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[14] http://kepler.nasa.gov/

3.1 Overview

CoRoT[15] [69] is a mission led by the French space agency CNES with participation by ESA and several other countries (Belgium, Germany, Austria, Spain and Brazil). Its launch is foreseen for October 2006 with a prototype of the Soyuz 2-1B rocket (this model will later be used for launches from ESA's site in Guyana) from the Russian space center in Baikonur and the mission will last 3 years in a polar orbit. The main part of the satellite has been constructed in France and Spain provides part of the ground segment manufactured by GMV SA. The mission has two independent scientific objectives: asteroseismology and planet detections, both requiring photometry of very high precision. CoRoT is basically a small folded telescope (see Figure 3) of 27 cm diameter, and with 590 cm^2 effective pupil size. It has two CCD cameras optimized for each objective, that will survey simultaneously two side-by-side fields, each with a size of 3.4 deg^2.

3.2 CoRoT's Planet finding objectives

CoRoT will be the first space mission with a major dedication to the discovery of extrasolar planets. As such, it is supposed to achieve objectives which ground-based observations cannot obtain, by taking advantage of the absence of the atmosphere, and the absence of the day-night cycle. CoRoT has a small telescope, and very high signal-to-noise observations can only be achieved for bright stars, with the limits set by the stellar photon noise. Precisions of 10^{-4} for a 14th magnitude star will be obtained in one hour of integration, and the faintest stars surveyed by CoRoT will have about 16 mag[16]. It has been estimated [70] that, based on the Milky Way model of [71], hot terrestrial planets[17] should be mainly discovered around 14-15th magnitude K2-M2 stars, that Uranus-class ones will be found around 15th mag G2 stars and giant planets around 15-16th mag F7-G2 stars. The signal-to-noise ratio required to reliably detect transits and to discriminate against false alarms implies a limit to the detection of planets to about $2R_{Earth}$, as was shown by simulations with several detection methods [72]. In Figure 4 the theoretical expectations for CoRoT are shown and in Table 1 integrated detection numbers are given, both from [70]. Besides detecting planets smaller than hitherto possible, a second advantage of a space mission is the high duty-cycle that can be achieved over extended periods. Requiring 3 observations of a transit, and with CoRoT's pointings having a maximum of 150 days, all sufficiently large transiting planets with periods up to 50 days should be

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[15] http://corot.oamp.fr; http://smsc.cnes.fr/COROT ; http://www.iaa.es/corot

[16] The stellar sample's brightness limit varies somewhat with the spectral class. Since late type main sequence stars are smaller, transiting planets cause deeper transits - hence the sample can go 'deeper' for these stars

[17] By 'Hot terrestrial planets' we understand rocky planets with a maximum radius of $2.5-3R_{Earth}$ and surface temperatures too high to be able to support life.

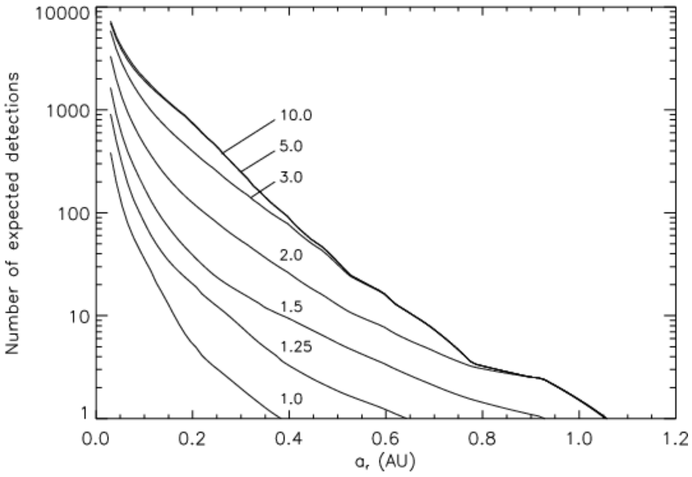

Figure 4: Number of expected detections for the entire mission as a function of the reduced orbital distance a_r for various planetary radii (expressed in units of the Earth radius), from [70] . The reduced orbital distance is defined by $a_r = a(L\star/L\odot)^{-0.5}$, so that a planet at a given distance a_r would receive as much flux from its star (and have a similar surface temperature) than a planet at distance a in the Solar System. It is assumed that every star has one planet of the labeled radius positioned at the considered distance.

detected. Planets with periods up to 75 days may also be detectable with decreasing probability, depending if 3 or only 2 of their transits fall within the 150 days observing window. The ability of CoRoT to obtain simultaneous photometry in 3 passbands may also allow the detection of planets from a single transit based on the subtle variations in stellar colour caused by a transiting planet [61]. This requires however observations of color differences with high S/N and can therefore only be expected to work for large planets on bright stars.

The objectives of the CoRoT exoplanet detection can therefore be summarized as *the detection of planets that may be smaller and on longer periods than currently known transiting ones*. These planets may be considered warm or hot planets, with sizes from gas giants to large terrestrials, or 'Super-Earths'. Also expected is the detection of a considerable number of hot Jupiter type planets, similar to those found already by ground-based searches.

R_P (in R_{Earth})	Integrated number of detections
1.0	5–6
1.25	12–18
1.5	26–37
2.0	70–95
3.0	189–240
5.0	300–367
(10.0)	(311–382)

Table 1: Integrated number of detections for the entire mission as a function of the planetary radius, from [70] (which should also be consulted for details on the assumptions on which these numbers are based on). Stellar crowding within the CoRoT photometric apertures is expected to remove ≈10% from the detections quoted here. The value for 10 R_{Earth} is given for completeness only, as the abundance of such planets is known to be much lower than the one used in [70].

3.3 Technical design of the exoplanet detector

The scientific payload of CoRoT is a camera that contains an array of 2x2 CCD detectors. Two of the CCDs are dedicated to asteroseismologic studies, and two CCDs constitute the exoplanet detector. Each CCD covers a field of about 1.7 deg^2; hence the total field is 3.4 deg^2 each for both experiments. On the exoplanet detector, a small bi-prism in front of its CCDs will make stellar images appear as very low resolution spectra (Figure 5). On-board aperture photometry will divide these spectra for most stars (expect those at the faint end of the sample range) into 3 zones, which correspond to color bands. This photometry is based on apertures whose shape is adapted to the spectral type of each sample star. Images are obtained every 32 seconds, but due to limitations on download bandwidth, photometric values are transmitted as averages over 16 images (512 seconds). For a limited number of objects however - like candidates for further transits - time series with 32 sec resolution may be transmitted. CoRoT's photometry should be dominated by the photon noise corresponding to a 590 cm^2 aperture; however there are other non-negligible noise sources like the zodiacal light, light reflected from Earth, instrument jitter, cosmic rays etc. Also, during every orbit, that is every 6100 seconds, the satellite passes through the South Atlantic Anomaly where shielding by the Earth's magnetosphere is poor and high doses of particle fluxes will lead to degraded data for a few minutes. A more detailed overview about technical and observational parameters of the mission is given in the 'CoRoT handbook'[18]

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[18] http://corotsol.obspm.fr/web-instrum/payload.param/index.html

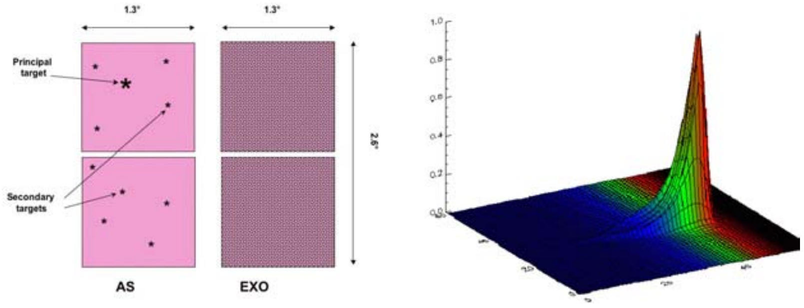

Figure 5: *Left:* The CoRoT focal plane with the asteroseismology (AS) and exoplanet (EXO) CCDs; *Right*: The stellar *psf* on the exoplanet CCDs

3.4 Observing plan

Figure 6: Sky regions where CoRoT observations are planned: The "CoRoT eyes"

The polar orbit of CoRoT requires that the fields to be observed are within two relatively small regions of about 20^o diameter, at opposing directions in the sky (Figure 6). Due to the motion of the Earth around the Sun, a switch between these two regions is required twice a year. The location of these regions has been the subject of careful studies during the mission's development, finally setting their centers near the two crossings between the galactic plane and the celestial equator ($= 0^o$ declination), at 18h 50m and at 6h 50m RA. This corresponds to a direction near the galactic center and anticenter. Alternating every 6 months between these regions, a total of 5 'Long Run' pointings of 150 days duration[19] each will be surveyed during CoRoT's lifetime of 2.5 years. All these pointings are constrained by surveying a 5-6th mag prime target

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[19] Due to a delay in the mission's start, currently foreseen for Oct15, 2006, the first long pointing in the anticenter direction will have a reduced duration

star on the mission's asteroseismology CCDs (see Figure 5). Hence, the exact location of the exoplanet survey field, which lies side-by-side to the AS one, has been derived from a combination of requirements for the planet detection and for the seismology program (e.g. the presence of interesting secondary target stars). The fields that where thus selected for planet finding have densities of 1500 - 3500 stars/deg^2 (for stars with mag $R < 15$), and avoid zones of high fractions of background giant stars, or regions containing a very bright star. Each of the 'Long Run' pointings will survey a maximum (constrained by telemetry) of 12000 stars simultaneously. In the galactic anticenter fields, stellar densities are lower, and all unconfused stars within the sample magnitude range of 11.5 - 16 mag are surveyed. The center fields, however, have higher densities, and a preselection based on stellar types is being performed, aiming at excluding giant stars. The selection of the sample fields, and of the individual stars observed therein is based on a photometric catalog 'EXODAT' containing a combination of visual colors (obtained in a dedicated observing campaign) and of near IR colors from the 2MASS catalogue, allowing an approximate derivation of spectral class and type [72]. This color information is also used to predefine the aperture masks that are being used in the on-board photometric processing. With five Long Run pointings, a total of 60000 stars will therefore be surveyed extensively for transiting planets. In-between the Long Runs, there will be 1 month-long intervals that will be dedicated to 'Short Runs' of one-to-two weeks duration, which may be useful to detect short-periodic Hot Jupiter planets. The Short Runs are however driven by a variety of objectives, which have been selected from a call for proposals made in the framework of the 'Additional Programs'. Most of them will be related to asteroseismologic or stellar variability studies. The acquisition of a precise light curve of the non-transiting hot Jupiter system HD 46375 is however also among them, with the goal of detecting the first reflected light of a planet.

3.5 Data analysis and follow-up work

The data that will be transmitted to the ground control center correspond to instrumental photometric values. The ground center will apply corrections and calibrations. An initial 'N1' version of the light curves will be generated with little delay. During Long Runs, N1 data will be obtained in several batches; the first ones while the satellite is still observing the same field. These N1 data will regularly be scanned with a rapid transit detection algorithm to find candidates for transits. The aim of this quick analysis is twofold: First, it allows to switch a potentially transiting system to a higher time resolution of 32 seconds, which may lead to improved characterizations of further transits and second, it allows ground-based follow-up observations without a long delay, while the field is still observable from the ground. If not, after the end of a Long Run, follow-up observations would typically have to wait half a year before a given field becomes again observable. Fully processed and calibrated 'N2' data will become available several weeks after the end of a Long Run and will constitute the basis for the work of the involved scientists. This will principally be the detection and characterization of weaker transits not detected in the N1 data, and the scientific analysis related to any of the additional objectives. N2 data will remain proprietary to CoRoT Co-Investigators for one year after their release, after which they will pass into the public domain.

In order to avoid false alarms, all transit events will be examined with the tools mentioned in the Section 2.6. In most cases, CoRoT's 3-color light-curve and the stellar parameters based on preparatory observations should suffice to recognize a false alarm. Follow-up observations will however be required to either reject or independently verify the remaining best planet candidates. The proposed procedure is based on the approach of starting the 'weeding' of candidates with relatively simple observations, and to progress to more complex ones for the remaining candidates only [73]. The follow-up for CoRoT candidates will roughly be in this order: imaging and time-series with higher spacial resolution[20], low resolution spectroscopy (if not known from preparatory observations) and lastly, radial-velocity measurements. This last step may then give an independent verification of the detected planet and besides, it would allow to derive its mass. It should be noted that many candidates are expected to have very small transit amplitudes (for estimates based on an analysis of simulated data, see [74]). Ground-based photometric follow-up of CoRoT planet candidates will however be possible in general, since S/N thresholds for follow-up observations can be much lower than the S/N values required for the discovery of the events. We may therefore expect that CoRoT discoveries cannot only be verified from the ground, but may also give rise to many further observations aimed at a deeper understanding of the discovered objects.

3.6 Outlook

We expect CoRoT to bring the first census and characterization of planets in the small giants (Saturn-Uranus) to large terrestrials (super-Earths) range, besides the detection of a significant number of hot Jupiters. The fraction of terrestrial planets around main sequence stars is still the least known factor in estimating the number of life supporting (habitable) planets in the Galaxy and, consequently, is also important in estimating the abundance of intelligent life having developed technical civilizations [75]. The detection of habitable planets, and of bio-signatures, is the main goal of several advanced space missions, like Darwin or TPF, for which results from missions like CoRoT and Kepler, as well as from the numerous other ground-based experiments, are of most fundamental importance in the definition of their objectives, their designs, sample selection and analysis methods.

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[20] Any moderate sized ground-based telescope will provide relative high spacial resolution in comparison with CoRoT. For some cases, adaptive optics might however be required as well

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