Chapter 1

Introduction

1.1 Searching for extra-solar planets

The search for, and study of, planets outside the solar system have developed into one of the most active topics in modern astronomy over the past decade.

Before any discussion can begin, it is necessary to adopt a definition of the word planet. Where does the boundary between brown dwarfs and planets lie? Is it purely a question of internal structure (i.e. mass), or does the formation process have to be taken into account as well? For the present work, I have used the working definition adopted by the IAU Working Group on Extrasolar Planets[1]:

1. *Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.*
2. *Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed nor where they are located.*
3. *Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).*

A variety of names and spellings for planets outside the solar system can be found in the literature: *extra solar planets*, *extra-solar planets*, *extrasolar planets*, *exoplanets*, *exo-planets*... For consistency, *exo-planets* has been adopted throughout the present thesis, though the choice is arbitrary.

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

The first detection of an exo-planet orbiting a main-sequence star was made using the radial velocity (hereafter RV) method by Mayor & Queloz (1995), and was soon confirmed by Marcy & Butler (1995). Further detections rapidly ensued (Marcy & Butler 1996; Butler & Marcy 1996; Butler et al. 1997; Cochran et al. 1997, to cite only the first few), with the first exo-system (one star orbited by more than one known planet) discovered by Butler et al. (1999). These discoveries have provided the first hints of answers to a number of fundamental questions previously relegated to the realm of pure speculation, though only the very tip of the iceberg has been uncovered. We can now start to ask whether the solar system is a typical one, and are in a much better position to understand how it came to be what it is now: until 1995, planetary system formation scenarios had only one example to model themselves on.

More than a hundred stars are now known to harbour planets. A number of regularly updated websites act as useful information repositories on these systems: J. Schneider's Extrasolar Planets Encyclopedia[2], the California and Carnegie Planet Search Almanac[3], as well as the list maintained by the IAU Working Group on Extrasolar planets[4]. Little by little, the range of parameter space which has been explored widens, the initial selection effects (such as the predilection for short-period planets induced by the limited duration of the RV search programmes) lessen, and the numbers become sufficient for significant conclusions to be drawn from the distributions of the observable characteristics of the planets (see for example Zucker & Mazeh 2002; Udry et al. 2003b; Santos et al. 2003; Eggenberger et al. 2004).

However, as the number of known systems and our knowledge of their properties has increased, more questions have been raised than answers found. The best known example of this is the question of the 'Hot Jupiters': the discovery of relatively large numbers of gas giant planets, orbiting close to their parent star. This poses a striking contrast to the solar system, where the gas giant planets are found beyond 5 AU, and has sparked intense and ongoing debate: can such large planets form that close to their star? If a migration mechanism is invoked, so that they could have formed further out and moved to their current positions later, what would stop the migration at the observed radius?

This is only one of the puzzles raised to date. Many more detections are expected in the next few years, with the advent of a number of ground-based searches using the transit method, which can be used to survey large areas of the sky simultaneously. Other methods, such as microlensing, probe totally different areas of parameter space, being capable of detecting lighter, smaller planets orbiting more distant stars with larger orbital distances. In all cases, two observational parameters are of

[2] http://www.obspm.fr/encycl/encycl.html
[3] http://exoplanets.org
[4] http://www.ciw.edu/boss/IAU/div3/wgesp/planets.shtml

key importance: precision (whether spectroscopic, photometric or astrometric) and time coverage (both high time sampling and long baselines are necessary).

This thesis summarises the author's attempts to contribute to the drive towards the next generation of planet discoveries via the transit method, with a particular emphasis on habitable planets. As the radii of interest are small (the planets have to be terrestrial rather than gaseous) and the periods of interest are a few months or longer (to ensure that liquid water can exist at the surface), the detection of habitable planets implies a significant step both in precision and in time coverage, and therefore dedicated instrumentation. It also requires a significant effort in terms of data analysis, which is the focus of the present work.

1.1.1 Context and motivation

The first RV searches for exo-planets were pursued for a decade before the first detection. There were compelling reasons to expect exo-planets to exist (and to be detectable), and therefore to pursue the projects further. Indeed, planetary formation scenarios in the early 1990s (as outlined for example by Udry 2000), though first developed centuries before the first exo-planet was known, predicted that they should be common.

The 'solar nebula' model, developed by Kant and Laplace as early as the 18th century, invokes mechanisms which are still considered important in star- and planet-formation scenarios today. Local instabilities in a gaseous cloud drive its collapse to a (number of) centrally concentrated 'nebula(e)'. As gas is accreted onto the proto-star at its centre, conservation of angular momentum induces the nebula to collapse to a differentially rotating disk, in which planets can form. This implies the coevality of a given star and its surrounding planets, an idea that is supported by the coincident ages measured for various components of the solar system (the Sun, the Earth, the Moon, meteorites) via independent methods. If planets are a natural by-product of star-formation, they must be nearly as pervasive as stars themselves. The discovery of exo-planets would confirm this prediction. Increasing the number of 'laboratories' in which to observe the products of planetogenesis would also undoubtedly lead to surprises, and thus changes to, and refinement of, the model.

More detailed observations could then be used to study the atmospheres and internal constitution (density, composition) of exo-planets, and compare them to what is known about solar-system planets. Finally, and perhaps most importantly for the wider public, it would provide insights into the ubiquity or otherwise of Earth-like environments, or of the different types of environments that may support life, and therefore of life as we know it.

1.1.2 Exo-planet detection methods

Numerous reviews have covered the variety of exo-planet detection methods over the last few years (see for example Marcy & Butler 1998; Perryman 2000). Although the following repeats what has been said many times before, a brief summary of the principles, characteristics and current prospects of these methods is nonetheless needed to place transit searches in context.

1.1.2.1 Direct observation

The problem with trying to directly image even nearby exo-planets arises from their small projected separation (50 mas for a Sun-Jupiter system at 100 pc) and high brightness contrast ($\sim 10^9$ in the optical, $\sim 10^6$ in the IR) to their parent star. This method is thus, for most systems, impractical with today's technology, though efforts are underway to develop instruments for this task using high Strehl ratio adaptive optics combined with coronography, or interferometry. The problem of contrast is reduced in the infrared domain, especially for young planets which may emit significant amounts of intrinsic, as well as reflected thermal radiation. Recently, Chauvin et al. (2004) reported the detection with VLT/NACO of a candidate $5\,M_{\mathrm{Jup}}$ giant planet near a brown dwarf in the TW Hydrae association. A spectrum of the candidate exo-planet shows signs of water molecules, indicating it is a cool object, but further observations are required. Planned instruments both from the ground (e.g. VLT/Planet Finder) and from space (Darwin/TPF) make use of the advantages offered by the infrared domain.

Both contrast and projected separation issues are less critical for planets orbiting white dwarfs. Recent studies showed a planet could survive the late stages of stellar evolution, its orbital distance increasing proportionally to the amount of mass loss by the star, resulting in a potentially detectable system (Burleigh et al. 2002), though no detection has been announced so far.

Given the difficulty of obtaining direct observations, most exo-planet searches to date have concentrated on indirect methods, several of which rely on detecting the motion of star around centre of mass of the star-planet system.

1.1.2.2 Astrometry

The transverse component of the reflex motion of the star causes it to follow an elliptic trajectory on the sky, which can be measured astrometrically. This method is particularly sensitive to orbital planes perpendicular to the line of sight, and to planets in relatively long period orbits. This makes it complementary to, but difficult to confirm by, other methods. Jupiter orbiting the Sun, when viewed from 10 pc away perpendicular to the line of sight, would result in an amplitude of 0.5 mas (milli-arc second) per year.

Measuring such a small displacement over a time baseline of years from the ground is very challenging and, though candidates have emerged over the last few decades, none have been confirmed. Ground based projects expected to deliver sub-mas precision in the next few years include VLTI and ALMA, but the potential of this method is much increased from space. Data from Hipparcos, which surveyed over 100 000 stars to mas precision, has already been used to constrain masses derived from other methods (Frink 2003). In the future, the pointed interferometric mission SIM will be ideally suited to providing tight constraints on the orbits of previously detected exo-planets, while the survey mission GAIA, designed to achieve μas precision, is expected (under reasonable assumptions) to detect tens of thousands of Jupiter-mass planets astrometrically (see Perryman 2000, and references therein).

1.1.2.3 Pulsar timing

The motion of the central star about the centre of mass of the system causes variations in light-travel time across the orbit. However, only objects showing intrinsic, periodic brightness modulation, such as pulsars, provide a sufficiently precise frequency reference to measure this effect. In particular, precise timing of millisecond pulsars allows the detection of terrestrial mass planets, two of which were found by Wolszczan & Frail (1992) around PSR1257+12, the first detection of a planet outside the solar system. Additional planets were detected in that and other systems in the intervening years. These systems provide interesting constraints on planetary system formation and evolution, but the method only applies to this very distinct class of objects.

1.1.2.4 The radial velocity method

The most successful exo-planet detection method to date has been the radial velocity (RV) method, which consists in measuring periodic shifts in the wavelengths of spectroscopic lines due to the star's reflex motion. This method can be implemented from relatively small telescopes ($\sim$ 1 m and above) for the brightest target stars, though 8–10 m-class telescopes are needed for fainter targets and/or to resolve lower RV amplitudes. It requires high resolution spectra to be compared over a long period of time, implying a very stable spectrograph and accurately controlled temperature environment, as well as a very precise wavelength calibration, which sometimes achieved by inserting in the optical path a cell containing a gas producing absorption lines of well known wavelength (e.g. iodine cell). High throughput and sensitive detectors are also vital to gather a sufficient number of photons. These factors concurred to delay the use of the RV method for exo-planet searches until the mid- to late-eighties.

The RV method is most sensitive to high mass planets in close orbits, although the bias towards short period reduces as the baseline of observations of the existing programs increases. While RV measurements provide the period and eccentricity of the orbit, a significant drawback is that only a lower limit on the mass, $m \sin(i)$ where i is the inclination of the orbit relative to the line of sight, can be measured. This degeneracy can be lifted only through complementary observations, for example by the astrometric or transit methods.

One limitation of this method arises from the intrinsic velocity fluctuations at the surface of the star. These lead to an observed jitter in the RV measurements (Saar et al. 1998; Paulson et al. 2002), which could hinder the applicability of the method to active (very late type or young) stars. It also limits the achievable precision for Sun-like stars, making the detection of terrestrial mass planets with this method impossible. The lowest mass planet detected to date was a 14 $M_{\oplus}$ planet, found with the recently commissioned HARPS instrument, which achieves sub-1 $\mathrm{m\,s^{-1}}$ precision (Santos et al. 2004). The necessity to monitor a single star at a time, and the requirement that the star be bright enough to perform very high resolution spectroscopy, also limit the volume of space probed by the RV method to the immediate solar neighbourhood.

1.1.2.5 Microlensing

Microlensing programs aim to measure the temporary magnification of a background star (the source), as a foreground star (the lens) passes in front of it and its gravitational potential bends the light emanating from the source. If the lens is orbited by a planet, a distortion to the well known magnification profile will be observed. The amplitude of this distortion is maximum if the planet's orbital distance is close to the lens's Einstein radius, which for a late-type star is a few AU. This signal is brief and rare, but it is not particularly small, and even a moon can produce a detectable signal. The microlensing method thus requires high time sampling photometry of a large number of stars. A number of ground based microlensing programs have discovered candidate planets, but the sampling of the light curves is not sufficient to exclude other types of events. Going to space, as proposed with the GEST spacecraft, would improve the chances of a detection because it avoids interruptions in the observations.

This method is sensitive to relatively small, far-out planets orbiting distant stars, and as such is radically different from the others. While the planet mass and orbital distance can be deduced from the light curves, measurements are not repeatable, and cannot be confirmed by other methods. The main potential for this method is thus to use the results to constrain period and mass distributions in a statistical manner, if sufficient numbers of candidate detections become available.

1.1.2.6 Reflected light

This method, principally applicable to giant planets, consists in measuring the modulation of the light emitted by the star and reflected by the planet as it follows its orbit. The amplitude of this modulation depends on the albedo of the planet, and may be detectable from the ground for 'hot', close-in planets in the IR, where it is strongest, for stars already known to harbour planets. One important advantage of this method is that, although the light variations are strongest for orbits close to the line of sight, the planet does not have to be transiting to be detectable. Given the low amplitude of the signal, its real potential lies in space-based observations, for example the MOST satellite (a small asteroseismic mission which has a number of planet host stars on its target list) or space-based missions primarily designed for planetary transit searches.

1.1.2.7 The transit method

If a planet's orbit is aligned with the line of sight, it will partially obstruct the disk of its parent star once per orbit. This will cause a periodic, temporary dip in the observed stellar brightness, known as a planetary transit.

A significant advantage of this method is that many thousands of stars can be monitored simultaneously, and (depending on the size of telescope used) relatively distant stars can be probed. Like the RV method, the transit method is most sensitive to large, close-in planets, though long time bases and high precision photometry reduce these biases. The geometry of a planetary transit is illustrated in Figure 1.1, and its implications in terms of transit probability, depth and duration are explored below.

Transit probability: First of all, for a transit to occur, its orbit must be aligned with the line of sight. To compute the probability of this occurring, we assume that planetary orbits are isotropically aligned, so that the inclination i (which is measured, in Figure 1.1, from the $+z$-axis), is drawn at random from a distribution uniform in $cos i$ between 0 and 90°. A transit occurs if

$$b = a\,|\cos i| \leq R_{\rm crit}, \tag{1.1}$$

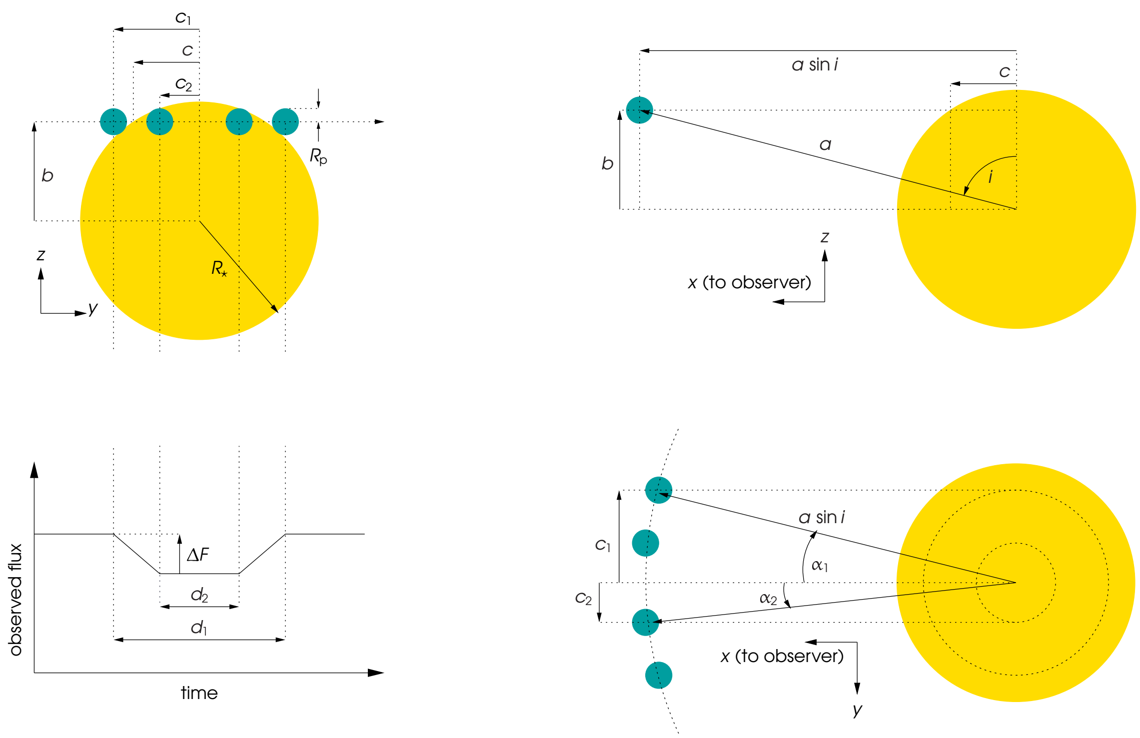

Figure 1.1: Geometry for a transiting planet with a circular orbit. Clockwise from top left: face-on view (as seen by the observer), side-on view, downward view and corresponding light curve. The star and planet radii are $R_\star$ and R_p respectively, the orbital distance a and the inclination i. The planet is shown at the four contact points (start and end of ingress and egress) in the top left and bottom right panels, and in mid-transit in the top right panel. The total transit duration is d_1, the duration of totality d_2 and the transit depth ΔF. Note that the base of the 'observed flux' axis does not correspond to zero flux. The relative size of star and planet shown here would correspond, for a Sun-like star, to a 1.08 R_{Jup} planet. The effects of limb darkening are ignored here.

where b is the impact parameter, i.e. the closest distance between the star and planet centres, projected onto the y–z plane, a is the planet's orbital distance, and R_{crit} is a critical radius. Depending on whether one is considering only full transits, where the planet's disk fully overlaps with that of the star for some time, or whether grazing transits are also considered,

$$R_{crit} = R_\star - R_p \qquad \text{or} \qquad R_{crit} = R_\star + R_p. \tag{1.2}$$

Taking $R_{crit} = R_\star$ provides a rough estimate which is suitable for most purposes, as usually $R_p \ll R_\star$.

Assuming an isotropic distribution of inclinations, the probability for a transit to occur is then given by

$$P\,(\text{transit}) = \frac{R_\star}{a}. \tag{1.3}$$

We can use Kepler's third law

$$\left(\frac{p}{2\pi}\right)^2 = \frac{a^3}{G\,(M_\star + M_\mathrm{p})}, \tag{1.4}$$

where p is the orbital period, G is Newton's constant of gravitation and $M_\star$ and M_p are the star and planet mass respectively, to express Equation (1.3) in terms of period:

$$\mathrm{P\,(transit)} = \left[\frac{R_\star^3\,4\pi^2}{p^2\,G\,(M_\star + M_\mathrm{p})}\right]^{1/3}. \tag{1.5}$$

The transit probability is thus a steeply decreasing function of orbital period. It can be as high as $\sim$ 30 % for a 3 Myr old system containing a Jupiter-mass planet in a 3 d orbit around a solar-mass star (the pre-main sequence stellar radius, which is significantly larger than that of a main-sequence star of the same mass, was taken from Rhode et al. 2001). On the other hand, an Earth-like planet orbiting a Sun-like star at a distance of 1AU has a transit probability of 0.3 %.

Transit depth: If the planet's disk is fully aligned with that of the star at any point during the transit (i.e. excluding grazing events), the transit depth is given by the ratio of the areas of the planetary and stellar disks (ignoring limb darkening), i.e.

$$\frac{\Delta F}{F} = \left(\frac{R_\mathrm{p}}{R_\star}\right)^2, \tag{1.6}$$

where F is the mean out-of-transit flux observed. The transit method thus provides a direct measure of the ratio of planet to star radius. This depth is generally small, of the order of 1 and 0.01 % for Jupiter- and Earth- sized planets respectively (if orbiting a star of solar radius). Giant planets are thus detectable from the ground with this method, while terrestrial planets can only be detected from space, as atmospheric scintillation limits the achievable photometric precision (see Young 1967 and Gilliland & Brown 1992 for a formula to estimate scintillation noise for a given airmass, telescope diameter, observatory altitude and exposure time).

Transit duration: The total duration of the transit is:

$$d_1 = p\,\alpha_1/\pi, \tag{1.7}$$

where α_1, as illustrated in the bottom right panel of Figure 1.1, is the angle between the line connecting the centres of the star and of the planet at the first or fourth contact point (beginning of ingress or end of egress) and the x-axis (observer's direction), projected onto the x–y plane. In turn,

$$\alpha_1 = \arcsin\left(c_1/a \sin i\right), \tag{1.8}$$

where

$$c_1 = \sqrt{\left(R_\star + R_\mathrm{p}\right)^2 - b^2}. \tag{1.9}$$

Therefore

$$d_1 = \frac{p}{\pi} \arcsin\left[\frac{1}{a \sin i}\sqrt{\left(R_\star + R_\mathrm{p}\right)^2 - (a \cos i)^2}\right] \tag{1.10}$$

$$= \frac{p}{\pi} \arcsin\left[\frac{R_\star}{a \sin i}\sqrt{\left(1 + \frac{R_\mathrm{p}}{R_\star}\right)^2 - \left(\frac{a}{R_\star} \cos i\right)^2}\right]. \tag{1.11}$$

Similarly, the duration of totality is given by

$$d_2 = \frac{p}{\pi} \arcsin\left[\frac{R_\star}{a \sin i}\sqrt{\left(1 - \frac{R_\mathrm{p}}{R_\star}\right)^2 - \left(\frac{a}{R_\star} \cos i\right)^2}\right]. \tag{1.12}$$

If we assume, as before, that $R_\star << a$, α_1 is small and $\arcsin \alpha_1 \simeq \alpha_1$, Equation (1.11) becomes

$$d_1 = \frac{p R_\star}{\pi a \sin i}\sqrt{\left(1 + \frac{R_\mathrm{p}}{R_\star}\right)^2 - \left(\frac{a}{R_\star} \cos i\right)^2}. \tag{1.13}$$

For a central transit ($i = 90°$), this further simplifies to

$$d_1 = \frac{p\left(R_\star + R_\mathrm{p}\right)}{\pi a} = \left(R_\star + R_\mathrm{p}\right)\left[\frac{4p}{\pi G\left(M_\star + M_\mathrm{p}\right)}\right]^{1/3}. \tag{1.14}$$

The transit duration is thus a slowly increasing function of orbital period. The total transit duration for a Jupiter-like planet orbiting a Sun-like star in a 3 d orbit with an inclination of 90° is ~ 2.6 hr. If the planet is Earth-like and has an orbital period of 1 yr, it is ~ 13 hr.

Practical implementation: From the ground, the transit method can be implemented using small telescopes which are no longer in heavy demand for other purposes, or *very* small telescopes, purpose-built using off-the-shelf, commercially available components. However, it is only recently that advances in detector technology and data reduction techniques (to obtain stable, high precision photometry over wide fields of view), and in data storage and processing capabilities (dealing with to the huge quantities of data to be stored and analysed) have made the implementation of this method possible.

Available parameters: As shown by Equation (1.6), transit observations provide a direct measure of the ratio of planet to star radius. In a recent paper, Seager & Mallén-Ornelas (2003) show that three additional parameters can be derived directly from observables using Equations (1.4), (1.6), (1.11) and (1.12): the ratios of impact parameter b and orbital distance a to the star radius, and the stellar density $\rho_\star$. They go on to show that, provided the transit period is known from repeat observations, the stellar mass is known (e.g. from spectroscopy), and given an assumed mass-radius relation for the star, one can solve for five physical parameters of the system: the stellar mass $M_\star$ and radius $R_\star$, the planet radius $R_{\rm p}$, the orbital distance a and the inclination i.

Without going into that level of detail, one can immediately see that the observation of a transit implies an inclination close to $i = 90^\circ$, particularly if the period is long. If combined with RV observations, a planet mass measurement free of the inclination degeneracy can thus be obtained. Small departures from strict periodicity can indicate the presence of additional (non-transiting) planets in the system, while detailed observations can reveal the presence of moons and rings.

Limitations: The transit method does suffer from a number of limitations. First, the combined effects of transit probability and duration imply that, with a given observation strategy (duration and time sampling of the observations), the probability of obtaining any in-transit observations of a given planet decreases rapidly with orbital period. This means that many stars must be monitored for long periods for a detection to be likely.

There are also numerous phenomena that can mimic transits, for example high mass ratio eclipsing binaries, or binaries whose eclipses are diluted by a third star, whether spatially close by (triple system) or fortuitously aligned ('blend'). Some of these effects can be ruled out by close examination of the light curve, others require radial velocity measurements to exclude stellar or sub-stellar mass companions. Intrinsic brightness variations of the the parent star can also hinder transit detection, or be a source of confusion, particularly for small transit signals.

Status: A large number of ground based projects are underway. The transit of a known RV-planet was first discovered by Charbonneau et al. (2000) and five *detections* via the transit method have been confirmed as of August 29$^{\rm th}$ 2004: four were candidates announced by the Optical Gravitational Lensing Experiment (OGLE) collaboration (Udalski et al. 2002a,b, 2003; Konacki et al. 2003a, 2004; Bouchy et al.

2004; Pont et al. 2004), and one was found by the Trans-atlantic Exoplanet Search (TrES) network (Alonso et al. 2004a), the latter being the first exo-planet discovered by the transit method from very small (10 cm) aperture telescopes. The specificities of the various projects, as well as the lessons learnt from their operation so far, will be discussed in Section 1.2.1. Several dedicated satellites are also at the planning or construction stage (see Section 1.2.2).

1.1.3 Properties of known extra-solar planets

The properties of the exo-planets detected so far are starting to provide interesting constraints for planet formation and evolution scenarios. A brief summary is given here in order to put in context the expected impact of future detections via the transit method.

The first noticeable characteristic of the known exo-planets as a whole is their variety. Few of the regions of parameter space within the current limits of the various detection methods have been found empty (and consequently, those that have and are not due to selection biases are of significance). This state of affairs represents a marked change on the situation ten years ago, when the known planets neatly divided into relatively close-in, terrestrial planets, outer gaseous giants, and smaller icy planets in the outer reaches of the solar system, all of which had eccentricities lower than 0.25 (0.2 if Pluto is classified as a Kuiper Belt Object).

1.1.3.1 Orbital parameters and planet mass

There is much to be learnt from scatter plots and histograms of the orbital parameters (orbital period or semi-major axis and eccentricity) and masses (or minimum masses, as given by radial velocity measurements) of known exo-planets. A set of such plots is shown in Figure 1.2. These plots were produced from the catalogue of known planets orbiting main sequence stars kept by J. Schneider (Extrasolar Planets Encyclopedia), which was cross-checked against the list maintained by the IAU Working Group on Extra Solar Planets. All planets announced before August 29th 2004 are included, but detections which remained uncertain or controversial at that date (as indicated on either list) were left out. Similar plots were discussed in much greater detail in several recent articles and reviews (see for example Udry et al. 2003b and Eggenberger et al. 2004), and only the main points of interest are highlighted here.

Hot Jupiters: Many exo-planets have been found in very short period orbits (less than 100 d, or even than 10 d). These very close-in planets, now known as 'Hot Jupiters', were not at all expected. The formation of Jupiter-mass planets was gener-

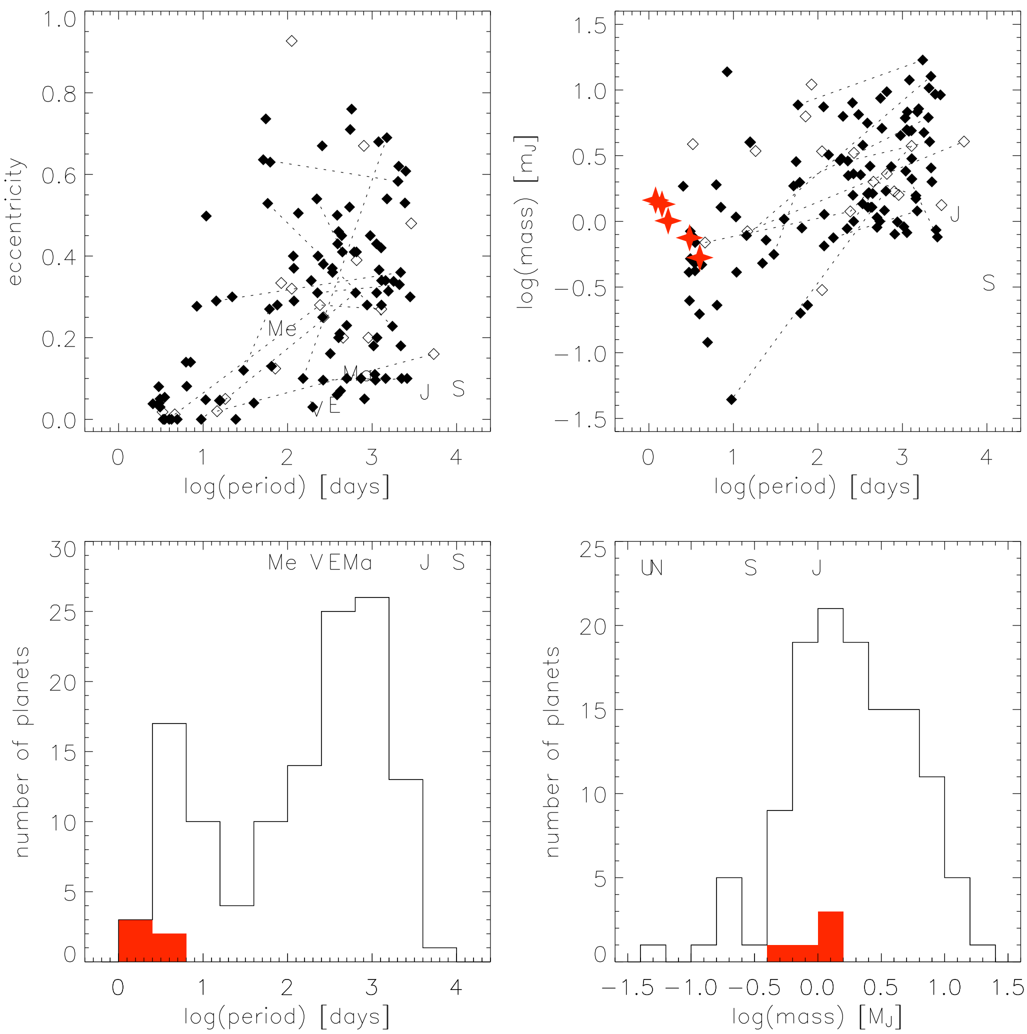

Figure 1.2: Scatter plots and distributions of eccentricity, orbital period and mass for all exo-planets known as of August 29th 2004 around main sequence stars (data from J. Schneider's Extrasolar Planets Encyclopedia). Filled symbols: planets orbiting single stars. Hollow symbols: planets orbiting multiple stars (from Eggenberger et al. 2004). Red symbols/area: planets detected via the transit method. Dotted lines link planets orbiting the same star. Letters mark the positions of solar system planets on each diagram.

ally thought to proceed via a two-step process (Pollack 1984; Lissauer 1993) of core formation (via collisions of smaller rocky or icy bodies) followed by runaway gas accretion once a critical mass has been reached. The core formation timescale is strongly dependent on the abundance of solid materials, which increases with distance from the central star, so that a core in the inner parts of a disk would not reach the critical mass before the disk evaporates (see Boss 1996, and references therein). It is therefore necessary to invoke a migration process to explain the existence of hot Jupiters: the planet forms at several AU from the star, but migrates inward due to gravitational interactions with the protoplanetary disk it is embedded in (Goldreich & Tremaine 1979, 1980; Papaloizou & Lin 1984).

How migration stops before the planet is engulfed by the star is the subject of ongoing debate. There appears to be a critical period of 3 d, below which very few planets are found, and just above which a 'pile up' is observed. The recent discovery of a planet around HD 73256 with P = 2.54 d (Udry et al. 2003a) and of the three OGLE transiting planets (Udalski et al. 2002b, 2003) suggests that the cutoff may be less steep than previously thought, but it remains significant. This is not an observational bias: the planets on the shortest orbits should be the easiest to detect. It may be interpreted as a critical (stellar mass dependent) radius, where migration is halted. Several mechanisms for halting migration have been proposed (see for example Terquem 2004, and references therein). They include, amongst others, interaction with a magnetospheric cavity, reversal of migration in close-in eccentric orbits, interaction with a turbulent disk, tidal interaction with a rapidly rotating star, and mass loss through Roche lobe overflow – the latter an interesting possibility in view of the recent detection of an extended atmosphere of escaping hydrogen around the transiting planet HD209458b (Vidal-Madjar et al. 2003) – and the loss of the material in the disk – a scenario that would see many generations of protoplanets fall into the star and only the last 'lucky' ones survive. Again, how to remove the disk on a sufficiently short timescale for that to happen is an open question.

Eccentric orbits and multiple planet systems: The circular orbits of very close-in planets, as well as the range of eccentricities of planets in slightly longer orbits (periods between 6 and 21 days) can be explained by tidal interaction with the star (see for example Rasio & Ford 1996; Dobbs-Dixon et al. 2004). In the former, dissipation of the tidal disturbance induced by the planet within the star leads to circularisation and synchronisation of the orbit with the stellar rotation period, while the tides induced by the star within the planet lead to 'puffing up' of the planet which, in certain cases, can result in mass loss through Roche lobe overflow and the consequent expansion of the orbit (a possible explanation for the 3 d cutoff at the low end of the period range). In the latter, dissipation is shared between star and planet, leading to either damping or excitation of the eccentricity depending on the rotation period of the star.

The eccentricity distribution is uniform between 0 and 0.7 for periods longer than 21 d, a situation that is very different form the solar system. Planet-planet interactions within a disk can induce high eccentricity, specially if the planets' orbits are coupled through resonances (see for example Chiang 2003). This is supported by the fact that at least one planet of each multiple system (linked by dotted lines) has significant eccentricity, and that several of the known systems have been found to contain planets in resonant orbits. Under certain circumstances, single planet-disk interactions can also excite eccentricity rather than damp it (Goldreich & Sari 2003).

Mass and distance dependence of migration: We have already established that migration is important to explain the properties of the known exo-planets, in particular those of hot Jupiters. The mass-period plot (top left panel of Figure 1.2) shows a lack of massive ($M_{\rm pl} > 2\,M_{\rm Jup}$) planets on short orbits ($P < 100\,$d), and of low mass planets ($M_{\rm pl} < 0.75\,M_{\rm Jup}$) on long orbits ($P > 100\,$d). Together with the valley in the period distribution for $10 < P < 100\,$d, these suggest (in agreement with some theoretical predictions, see Udry et al. 2003b, and references therein) that migration rate increases with decreasing mass. Neither trend is an observational bias, but the first could also be explained if massive planets do migrate in but then disappear, either because their migration is not halted and they fall into the star, or because they lose a significant fraction of their mass. However, the second, with its sharp cutoff in mass, makes the mass-dependent migration explanation more compelling. Eggenberger et al. (2004) point out that outer low mass planets may yet be found at large radii or very low masses currently beyond the reach of RV searches.

Mass distribution: The mass distribution (bottom right panel of Figure 1.2) still suffers from incompleteness below $1\,M_{\rm Jup}$. Above that limit, a clear increase in frequency toward lower masses is observed, with a more or less linear trend in dN/dM. More precise measurements of this mass function, as the number of known planets increases and the completeness limit goes down, will provide important constraints for theoretical formation scenarios.

1.1.3.2 Properties of planet-host stars

Planets in binaries: Planets orbiting components of stellar binary systems are marked by hollow symbols in the top panels of Figure 1.2. As pointed out by Eggenberger et al. (2004), close inspection shows that their eccentricity is damped (< 0.1) out to longer periods ($P < 60\,$d) compared to planets orbiting single stars (filled symbols), and that planets in binaries with periods $> 100\,$d have moderate rather than high eccentricities. The most massive planets in close-in orbits also tend to be in binaries. This suggests that migration and/or mass accretion rates might be enhanced (and eccentricity damped) by the presence of a companion to the parent star, but the number of systems available for study is still relatively small (15).

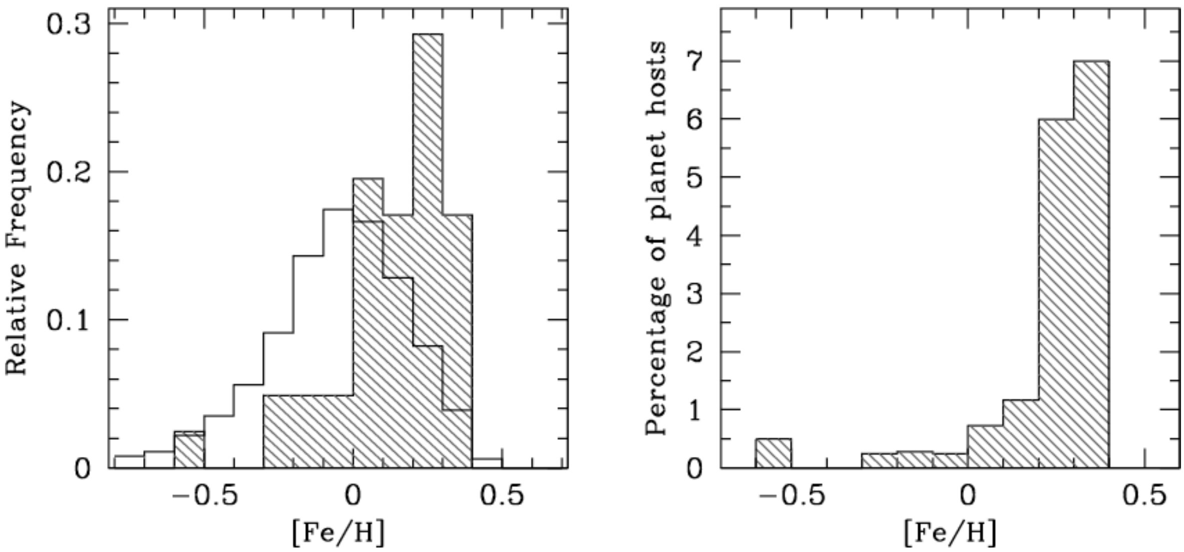

Figure 1.3: Left: Metallicity distribution of stars with planets belonging to the CORALIE planet-search sample (shaded histogram) compared with the same distribution for a volume limited sample of ~1000 stars not known to host planets, observed with the same instrument. Right: Percentage of stars in the CORALIE planet search sample that have been found to harbour planetary-mass companions as a function of metallicity. Reproduced from Santos et al. (2003).

Host star metallicity: That planet-host stars appeared more metal rich than non planet-host stars was suspected early on (Gonzalez 1997, 1998), though small number statistics and the difficulty of obtaining an unbiased sample of metallicities for comparison have delayed the firm establishment of this result. However, recent studies (Santos et al. 2003; Fischer et al. 2004), where much attention has been paid to the removal of systematic effects and biases, seem to confirm that planet host stars are more metal rich than stars without planets, or conversely that more metal rich stars are more likely to harbour planets than more metal poor stars, as illustrated by Figure 1.3. One should of course keep in mind that this only applies to the type of planets currently detectable, i.e. gaseous giant planets in orbits less than ~ 5 AU.

This may be due to 'pollution' by infalling proto-planets at early stages, whose metal content is diluted into the stellar convection zone. This scenario is supported by the existence of binaries whose components appear to have different metallicities. On the other hand, it may be of primordial origin, planet formation mechanisms being more effective in metal-rich disks. No particular trend is observed in the metallicity of planet host stars with convective envelope depth, which supports the latter interpretation (Santos et al. 2003). In turn, the importance of metallicity in the formation process favours planetesimal formation through core accretion (see for example Pollack et al. 1996), rather than the alternative suggested by Boss (2000) of formation through gravitational instability.

No statistically significant trends between metallicity and orbital parameters, mass, or membership of a multiple planet or multiple star system have yet emerged, suggesting that migration is not strongly influenced by the metal content of the disk, though this may change as more planets are detected.

1.1.3.3 Where the transit method will make a difference

As shown through the very brief overview presented in Sections 1.1.3.1 and 1.1.3.2, many questions arise from the properties of the known exo-planets and their host stars. Plausible theoretical interpretations have been proposed for most of them, but there are very few cases where a single mechanism can fully explain a given aspect of the problem. Several processes can usually be invoked and often, the same process can have widely divergent consequences depending on small shifts in some parameters (for example, resonant planet-disk interactions can either damp or excite eccentricity). In the present section, we explore how detections via the transit method are particularly likely to contribute to the field.

Removal of the mass-inclination degeneracy: As pointed out earlier, the RV method only provides a minimum mass measurement for the planet, because of the degeneracy between mass and orbital inclination. All but 6 of the masses shown in Figure 1.2 are thus lower limits. Transit observations limit the inclination to a very narrow range close to 90°, thus breaking the degeneracy. Not only is this important to ensure the companion is really of planetary mass, it provides (given the radius measurements also available from transit observations) a means to determine the mass-radius relationship for exo-planets.

Spectroscopy of transiting planets: Transmission spectroscopy consists in taking spectra of a planet host star in- and out-of-transit and comparing them. During a transit, a small fraction of the light emitted by the star passes through the planet's atmosphere before reaching the observer. Absorption lines corresponding to elements that are particularly abundant in the planetary atmosphere will be stronger in the spectra taken during the transit than in those taken out-of-transit. This can be viewed as the planet having a wavelength-dependent radius, resulting in a wavelength-dependent transit depth. For close-in giant planets, this effect can be detectable.

If clouds are present in the planet's atmosphere, only the species prevalent at altitudes above the clouds, or those which absorb in spectral regions where the clouds are not opaque, will produce a detectable effect. The amount of additional absorption by a given element that is observed in-transit is thus determined not only by the abundance of that element in the atmosphere but also by the altitude at which the absorption occurs (Brown 2001). Transmission spectroscopy therefore yields some information about the vertical structure, as well as the composition, of exo-planetary atmospheres.

A very weak detection of neutral Na in the atmosphere of HD209458b by Charbonneau et al. (2002) was thus interpreted as indicating that sodium was only present in significant amounts in the lower part of the atmosphere. Detection of more significant absorption by hydrogen (Vidal-Madjar et al. 2003) and oxygen and carbon (Vidal-Madjar et al. 2004) followed, and was shown to originate outside the Roche lobe of the planet, leading to an interpretation as an escaping comet-like tail. Taking into account the effect of evaporation of planetary atmospheres could significantly reduce their expected lifetimes compared to earlier theoretical predictions (Baraffe et al. 2004), planets with masses below a critical (orbital distance dependent) value being eventually evaporated out of existence.

In the longer term, low resolution spectroscopy of terrestrial exo-planet atmospheres is seen as the most promising method to detect life on another planet, concentrating on specific signatures such as the simultaneous presence of CO_2, O_3 and H_2O in the atmosphere, which are thought to be explainable only by the widespread presence of oxygen-consuming life on the planet (Selsis 2002).

Peculiarity of the first OGLE planets: As shown by the red symbols at very short periods on the top-right panel of Figure 1.2, the first three 'OGLE planets' (planets initially detected via their transits in OGLE data) occupy a distinct region of the mass-period diagram, at very low periods and fairly low masses. Their density is markedly higher than that of less close-in hot Jupiters (Konacki et al. 2003a; Bouchy et al. 2004; Konacki et al. 2004; Moutou et al. 2004b), and their predicted mass loss rates through evaporation up to four times higher than that of HD209458b (Moutou et al. 2004b), which may place them in a critical stage of their evolution.

The two more recently discovered transiting exo-planets (TrES-1 and OGLE-TR-111b, also shown in red on Figure 1.2) have orbital characteristics more similar to the hot Jupiters discovered via the RV method (with orbital periods of 3.03 and 4.0 d respectively), and have been presented as the missing link between RV and transiting planets. Importantly, their derived radii are closer to those of the three very close-in OGLE planets than to that of the first known transiting exo-planet, HD 209458b. These lower radii imply higher densities and may explain why so few planets to date have been found via the transit method: they may, on average, cause shallower transits and hence be harder to detect, than had initially been predicted on the basis of observations of HD 209458b's transits.

Improved statistics: We have seen that the detection of transits of a given planet paves the way for a wealth of detailed follow up observations, which have wide theoretical repercussions. The simple fact of increasing the number of known planets is also important. Many of the trends discussed in Sections 1.1.3.1 and 1.1.3.2 are still uncertain due to the low numbers involved. If the transit method lives up to its expectations, its ability to be applied to many thousands of stars simultaneously should lift the field of statistical studies of exo-planets out of its infancy: it will help place rigorous constraints on theoretical models by fitting the shapes of distributions of the various parameters, and break the potential degeneracies between the many parameters involved.

Exploring new regions of parameter space: Ground based transit and RV searches probe fairly similar regions of the mass-period diagram, but the parent stars of planets discovered via transits can be much more distant. The increased photometric precision achievable from space will also allow space-based transit searches to reach much smaller radii, hence masses. The absence of interruptions in the observations will also lessen the decrease in sensitivity towards longer periods, which is a problem for ground-based searches. The sensitivity of the method as implemented in various current and planned projects will be discussed in more detail in Section 1.2.

1.2 Current and planned transit searches

1.2.1 Ground-based

1.2.1.1 Projects and expected detection rates

The large number of ground-based transit search projects either recently completed or currently operating makes it impossible to discuss them all here in detail. Instead, those which have to date produced particularly important results, or with which I have had some interaction, are used to illustrate general characteristics of these projects as a whole. The hardware in use varies widely, with telescope apertures between 5 cm and 4 m, but as pointed out by Horne (2003) the projects can be crudely divided into two broad categories: 'wide' and 'deep'.

The 'wide' surveys make use of (often dedicated) small telescopes (0.5 m and below) with a very wide Field Of View (FOV) and large pixel scales to cover large areas of the sky. Given their small apertures, they can only detect giant planets out to a few hundred pc, but they can target any part of the sky while remaining within the galactic disk scale height. STARE, a 10 cm aperture telescope with a $\sim$ 33 sq.deg. FOV, currently operating in Tenerife, was the first to observe a planetary transit (that of the previously known RV planet HD209458b, Charbonneau et al. 2000). Two such projects to which I aim to apply the transit search tools developed in this thesis in the near future are: SuperWASP, consisting of eight cameras with 11 cm aperture, observing adjacent parts of the sky, each with a FOV of over 60 sq.deg., which started regular operations in La Palma in April 2004; and the University of New-South Wales planet search on the Automated Patrol Telescope at Siding Springs Observatory, a 0.5 m telescope with a 6 sq.deg. FOV, which has been monitoring 5 fields over the past three years. A large number of variable stars, periodic and aperiodic, were detected in light curves from 5 nights of APT data in the field of the open cluster NGC 6633 using software developed by M. Irwin and myself (Hidas et al. 2003).

The 'deep' surveys make use of larger telescopes (1 m and above) with less extensive fields of view (and usually available only for limited duration observations). They are capable of detecting hot Jupiters out to several kpc, so that they target specific areas of high density in the Galactic plane or in stellar clusters. Of note among these is the OGLE III project, which produced the first transit candidate to be confirmed as a planet by RV measurements (Udalski et al. 2002b; Konacki et al. 2003a). It uses the 1.3 m Warsaw telescope at the Las Campanas Observatory in Chile, and has a 0.35 sq.deg. FOV. A dataset obtained by the University of St Andrews Planet Search, which had already been analysed for variable stars and transits (Street et al. 2002, 2003), was used to train and refine variable star and transit search tools presented in this thesis. It consists of approximately 20 nights of observations of open cluster NGC 6819 using the Wide Field Camera (0.3 sq.deg. FOV) on the 2.4 m Isaac Newton Telescope in La Palma.

The expected hot Jupiter discovery rate of a number of these projects was compiled by Horne (2003), with results typically in the range 3–10 per month for both categories, though this estimate does not take into account the effect of 'impostors' (events that imitate planetary transits) or crowding (which limits the photometric accuracy).

1.2.1.2 The challenges ground based transit searches

Data storage and memory We have already emphasised the fact that, among the recent technological developments that have made planet-searching via the transit method possible, improvements in data storage and processing have a determining place. Despite these improvements, this area is still problematic. Data are usually stored onto tapes at the telescope, and reading the tapes onto disk is often the main bottleneck in the production of light curves (Mallén-Ornelas et al. 2003). Restricted disk space availability affects the production of light curves as well as their archival and retrieval for analysis. A significant part of the financial resources of many ground-based transit searches have to be channelled into the acquisition of storage and computing capacity.

Achieving high precision photometry over very wide fields: Ultra-wide field detectors with large pixel scales exacerbate the problems of standard CCD photometry (see for example Bakos et al. 2004). The impact of variable extinction across the field and of crowding is much increased. The very short focal lengths of many of the small telescopes in use also imply significant vignetting and image distortion across the field. In these conditions, particular care must be paid to the extraction of flux measurements and the corrections applied for systematics.

Different teams have opted for different photometry techniques (PSF fitting, difference imaging, aperture photometry). The results are constantly improving, and several projects are now achieving relative photometric precision of 2–3 mmag over several nights of data at the bright end of the range of magnitudes surveyed (Hidas et al. 2003; Lister & the SuperWASP collaboration 2004).

Most of the data processing pipelines include a post-processing stage to minimise systematics in the light curves, due to the variation of image and extinction parameters (in time and across the field), and the difficulty of calibrating data from several nights or runs to the same magnitude system. This stage is sometimes considered separate from the processing pipeline and applied as a pre-processing step for the transit search (Kovács et al. 2004).

The transit detection itself: The automated detection of transits in light curves from ground based experiments has proven more difficult than initially expected, so much so that some groups have opted, at least initially, for the examination of the light curves by eye (see for example the EXPLORE team, Mallén-Ornelas et al. 2003). This is a very time-consuming process when tens of thousands of light curves containing hundreds of data points each are concerned, and one which is probably less sensitive than searches performed by algorithms, and affected by intractable biases.

The irregularity of the sampling is an unavoidable consequence of ground based observations. Unless they are coordinated from multiple sites around the world, which requires large, well organised collaborations and can only be achieved for limited periods of time, this problem complicates the analysis. The transit search algorithms developed in the present thesis were designed with irregularly sampled data in mind.

Another problem is the definition of a reliable threshold for detection. The most interesting events – those most likely to be of planetary origin – are also often those with the lowest significance, but the cost of follow-up observations means that false alarms must be minimised. In white Gaussian noise, thresholds that give the desired false alarm rate can be estimated a priori (Jenkins et al. 2002) or found through Monte Carlo simulations. In the presence of unknown or complex noise characteristics, the best approach is to perform a posteriori completeness tests by inserting artificial signals into real datasets and attempting to retrieve them.

Follow-up of transit candidates: We have seen that the RV method can only monitor a limited number of stars. However, it is necessary to use this method eventually to confirm the planetary nature of transit candidates, as a number of more massive objects can mimic planetary transits. For example, brown and white dwarfs have radii similar to planets, and hence similar signatures. Stellar eclipsing binaries with a very large (early-type or giant) primary and a late-type dwarf secondary can also have eclipse depths of only a few percent, consistent with planetary transits, as can grazing binaries of higher mass ratios, or eclipsing binaries whose eclipses are diluted by a third star coincident with the line of sight. All these eventualities must be excluded, for example by measuring the mass of the secondary with the RV method. However, to avoid making excessive demands on highly sought after RV facilities, the identification of transit candidates must be as reliable as possible, and follow-up must be done in a rational and careful fashion. In some cases, the targets stars of transit searches based on relatively large telescopes may be too faint for the companion mass to be determined by RV observations, though upper limits may be placed. The 'wide' surveys which target brighter stars do not suffer from this limitation.

1.2.1.3 Published planetary transit candidates and their follow up

The present status of the many ground based projects in operation is hard to gauge, because many – though not all – choose to publish their transit candidates only after follow-up observations are complete.

Two significant non detections are worth mentioning first of all.

Gilliland et al. (2000) found no transit candidates in 8.3 d of Hubble Space Telescope (HST) observations in the field of the globular cluster 47 Tuc. This is, of course, a space-based project, but it is discussed in the present section because the range of parameter space probed corresponds to that of other ground-based searches rather than that of future space missions. The relative photometric precision, which reached 3 mmag at the bright end of the range of magnitude surveyed, was amply sufficient to detect close-in giant planets. The absence of detection implies that the frequency of hot Jupiters in 47 Tuc is at least an order of magnitude lower than that deduced from RV surveys in the solar neighbourhood. One possible interpretation is that planet formation may be inhibited in low metallicity environments (47 Tuc has (Fe/H) = −0.7).

The low mass binary CM Draconis has its orbit almost aligned with the line of sight, and therefore makes a very favourable transit search candidate. Possible eclipses by a planetary mass objects were announced by Guinan et al. (1996), but detailed monitoring by the TEP (Transits of Extrasolar Planets) project (Doyle et al. 2000) ruled out the presence of planets orbiting the binary with radii larger than 3 $R_\oplus$ and periods of 60 d or less at the 90% confidence level.

The 'founding fathers' of the field were the Vulcan and STARE projects, which were the inspiration for a plethora of small aperture wide angle searches. The Vulcan project uses a dedicated 5 cm aperture photometer equipped with a 49 sq.deg. FOV CCD detector. Monitoring a number of fields, each containing $\sim$ 6000 stars, at the rate of 8 observations per hour for $\sim$ 3 months each, they have detected and carried out spectroscopic follow-up on several tens of eclipses with depths of a few percent to date (Posson-Brown et al. 2000; Borucki et al. 2001; Latham 2003). Most of these were shown to be due to high mass ratio eclipsing binaries or triple systems where the light of the third star diluted the eclipses of the first two. The follow-up was inconclusive in a few cases, where no RV signal was detected – which leaves the possibility of a planetary mass companion open – but the transits were relatively low signal-to-noise ratio events and therefore need confirmation.

The STARE project, as already mentioned, was the first to detect a planetary transit, albeit in a system already known from its RV modulations (the transit was observed almost simultaneously by Henry et al. 2000a, and was found in Hipparcos data by Robichon & Arenou 2000). Since then, the STARE team have discovered a number of candidate δ-Scuti stars (Alonso et al. 2002), but until July 2004, they had announced no confirmed detections.

The most widely publicised project, of course, was the one whose candidates were the first to be confirmed. That example also serves to illustrate the complexity of the follow-up process.

The OGLE collaboration has announced 137 candidates to date, from the 2001 and 2002 seasons of monitoring in the Galactic centre direction and in the Carina region of the Galactic disk (Udalski et al. 2002a,b,c, 2003). Konacki et al. (2003b) followed-up the initial 59 galactic centre candidates, of which 8 showed clear signs of a luminous (hence stellar) secondary outside the eclipses, one was shown to be a duplicate entry, 4 had only one transit and hence no known period, and 7 were considered too faint for spectroscopic follow-up, leaving 39 for spectroscopic follow-up. Relatively low resolution spectroscopic observations with several epochs showed that 8 were early type (A–F) primaries, ruling out a planetary radius for the transiting objects, and 25 showed radial velocity variations at the $\mathrm{km\,s^{-1}}$ level or double lined profiles which indicated they were grazing binaries. They obtained high precision radial velocity measurements with Keck/HiRes for 5 of the remaining 6 candidates, and concluded that two were likely to be binary star eclipses diluted by a third star (blends), including one which was suggested as a good planetary candidate by Dreizler et al. (2002) in a parallel investigation, but whose OGLE light curve showed hints of a secondary eclipse; two showed no radial velocity modulations and remained possible planetary candidates or blends; and one, OGLE-56-TR, showed significant RV modulations consistent with a planet (Konacki et al. 2003a). This last result was confirmed by additional Keck/HiRes observations by Torres et al. (2004). Similar follow-up observations were obtained for the Carina field candidates, in which Bouchy et al. (2004) reported two confirmed planets, OGLE-TR-132 and OGLE-TR-113 (the latter also independently confirmed by Konacki et al. 2004).

A number of other groups have presented transit candidates together with subsequent follow-up observations: an ADS search reveals results from the Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS, Burke et al. 2003), the EXPLORE project (Mallén-Ornelas et al. 2003), the University of St Andrews Planet Search (Street et al. 2003), a Danish group working with the NOT telescope (Bruntt et al. 2003), and the Berlin Exo-planet Search Telescope team (Rauer et al. 2004). However, none have confirmed detections: all candidates are either identified as stellar or substellar from the spectroscopic follow-up, or in need of additional observations to confirm the existence of the transits. It is likely that several more groups are currently investigating transit candidates, the chances of a true detection improving with time as observing, analysis and follow-up strategies are refined. For example, the UNSW transit search group are analysing spectroscopic data of 5 candidates in the field of NGC 6633 at the present time.

On August 25^{th} 2004, the TrES network (to which STARE belongs) announced the first confirmed detection of a transiting planet with small aperture, wide field telescopes (Alonso et al. 2004a). A few days later, the planetary nature of another OGLE candidate, OGLE-TR-111, was confirmed by Pont et al. (2004).

1.2.1.4 Lessons from the results to date

Wide versus deep: Although the first confirmed detections have emerged from a 'deep' survey, a consensus seems to be emerging that the highest numbers of detections overall are to be expected from the 'wide' surveys using dedicated telescopes (Pepper et al. 2003). This can be explained in simple terms from the expected detection rates compiled by Horne (2003): the detection rates per month are similar for both categories, but it is very rare to gain access to a 2 or 4 m telescope for a whole month, let alone the round-the-year access that is permitted by dedicated instruments. Indeed, the OGLE survey, the most successful to date, has exclusive access to the 1.3 m telescope it is operated on.

The role of the 'deep' surveys, in this context, is to test the frequency of close-in giant planets in specific high density environments such as stellar clusters, in which the high angular resolution achieved by larger telescopes is required. These targets constitute laboratories with relatively well-controlled parameters such as stellar age, metallicity, spectral type and density. The detection rates and the characteristics of detected planets in these environments can then be compared to those from RV surveys and the 'wide' transit surveys in the field.

Observation strategy and false alarm rates: The ratio of confirmed detections to announced transit candidates so far is rather low: 3 to 137 for OGLE, zero for many other projects. There have been suggestions that this is in part due to imperfections in the selection of transit candidates (Drake 2003; Sirko & Paczyński 2003), several of the OGLE candidates being single, partially sampled events at the beginning or end of a night, or showing clear signs of out-of-eclipse variations (the tell-tale sign of a stellar companion).

Sampling and phase coverage are therefore of prime importance. To exclude the effects of night-to-night variations and imperfect extinction correction, at least one of the ingress or egress plus (part of) the flat bottomed portion of a candidate transit event must be sampled. As pointed out by Seager & Mallén-Ornelas (2003) (and discussed in a simplified context in Section 6.4.3.3), it is possible to place limits on the density of the eclipsed star from the light curve alone (thereby excluding at least some stellar binary events) provided the time sampling is high, the photometric errors small and at least two complete transits are observed.

A fraction of the OGLE false alarms were due to high mass-ratio or grazing eclipsing binaries. Some of these might have been excluded on the basis of the eclipse shape, but the signal-to-noise ratio in the light curves was not always sufficient for this. Multi-colour observations during the eclipse would exclude all but the equal mass stellar binaries, and newly set-up transit searches as well as planned space missions are increasingly considering the use of at least two bandpasses as standard.

A significant fraction of the false alarms found by several projects were due to blends, as noted by Brown (2003); Alonso et al. (2004b). These cannot always be excluded even with multi-colour time series, and the probability of their occurrence increases with the number of background stars within the magnitude range of the survey and the effective area of the aperture or PSF used to perform the photometry. Galactic plane or galactic centre surveys are thus likely to be prone to this type of false alarm to a greater extent than those pointing out of the plane.

Efficient follow-up strategies: Surveys can minimise false alarms by optimising their observation strategy – target field, time sampling, use of colour – or data analysis tools, but a carefully designed follow-up strategy can also weed out most of the non-planetary companions early on, thereby minimising the requests made of large facilities necessary in the last stages of confirmation via RV measurements.

Early transit candidate list announcements generated a lot of excitement in the exo-planet community, and a rush to RV facilities ensued. Experience has shown that many of the candidates could have been excluded on the basis of less time-consuming observations from smaller telescopes.

Given a transit candidate, there are a number of checks to perform. They are summarised in Table 1.1, together with the type of observations required. Any of the characteristics listed in the table can bring into question the planetary nature of the candidate, some ruling it out altogether.

Table 1.1: Tests of transit candidates and necessary observations.

Test	[a]	Observations
Out-of-eclipse brightness variations	×	Existing light curves
Repeat transits at the predicted times	√	New photometric observations
Different transit depth in different bandpasses	×	Multicolour transit photometry
Several stars within the original target image	×	Higher resolution imaging
Early-type primary	×	Single low to medium resolution spectrum or colours from existing sky survey images
RV modulations of several $\mathrm{km\,s^{-1}}$ (stellar companion)	×	Medium resolution spectra spread over orbital period
Double lined profile	×	Medium to high resolution spectrum
Very narrow line profile (giant primary)	×	Medium to high resolution spectrum
RV modulations of a few $100\,\mathrm{m\,s^{-1}}$ (brown dwarf companion)	×	High resolution spectra spread over orbital period
RV modulations of a few $10\,\mathrm{m\,s^{-1}}$ (absence can imply a faint background eclipsing binary rather than a planet)	√	Very high resolution spectra with special wavelength calibration (iodine cell) spread over orbital period

[a]Ticks or crosses in the central column indicate whether the tests are meant in a positive or negative sense i.e. whether true planetary transits should (√) or should not (×) exhibit the listed characteristics.

These checks can be performed in various orders, but it is most efficient to go from the smallest telescopes to the largest, and from imaging to low and then high resolution spectroscopy. A 4 stage follow-up strategy has been proposed for Super-WASP (Horne, priv. comm.) including checks on the existing light curves, multicolour photometry from a 1–2 m telescope, low to medium resolution spectroscopy (with a few epochs) from a 2–4 m telescope, and repeated high resolution spectroscopy with a 4–8 m telescope. Some projects have opted for a small dedicated follow-up telescope to perform multi-colour photometry and check the repeatability of the transits rapidly (Kotredes et al. 2003).

1.2.2 Space-based transit searches

1.2.2.1 Why go to space?

Space-based observations are free from the noise induced by atmospheric scintillation. One of the best results in terms of time series photometry achieved from the ground was a coordinated monitoring campaign of M67 using several large telescopes (Gilliland et al. 1993). The precision reached over then entire monitoring time of 156 hrs was 20 ppm (parts per million). By contrast, the precision required to detect an Earth like planet, which causes 13 hr long transits of depth 84 ppm, with a signal-to-noise ratio of at least 6 over three transits, is 14 ppm over 39 hrs, i.e. 7 ppm over 156 hrs. The precision achievable form the ground is thus insufficient to detect terrestrial planets. Consequently, going to space is the only means of achieving the photometric precision required to detect terrestrial planets, which have much smaller radii than their gaseous giant counterparts – recalling that transit depth scales as the inverse of planet radius squared (for a given stellar radius).

Another important reason is the absence of significant interruptions in coverage, provided a suitably chosen combination of satellite orbit and target field is used. As the orbital period of a planet increases, transits become rarer for two reasons: first is the obvious one, that is that a transiting planet only causes one transit per orbit; the second is the decrease in the alignment probability for wider orbits (see Equation 1.3), which goes from $\sim$ 10% at 0.03 AU to $\sim$ 1% at 1 AU (for a Jupiter-sized planet orbiting a Sun-like star). The probability of observing more than one transit of a given system – a requirement for the reliable detection of shallow transits – is thus a very strongly decreasing function of orbital period if the observations are confined to observing runs of limited duration, themselves with daily interruptions. Uninterrupted runs of several months with continuous high time sampling, as can only be achieved from space, thus provide a much more favourable platform for the detection of planets orbiting at a greater distance from their star, i.e. planets in Earth-like orbits, opening the possibility of detecting *habitable* planets.

Existing space-based optical imaging facilities such as HST are primarily aimed at high resolution applications and have fields-of-view that are too narrow for transit searches in all except the most concentrated environments (such as globular clusters). It is therefore necessary to launch dedicated transit search missions with wide fields of view and orbits that allow prolonged continuous viewing of a given field. The basic design of these missions involves no significant technological development: relatively small telescopes and wide field optical CCD detectors with low dark current and readout noise have been in existence for several years, so the cost of the missions can be kept reasonably low.

1.2.3 Terrestrial and habitable regimes:

At this stage, it is useful to establish a working definition of a terrestrial and a habitable planet. We follow here the reasoning of Borucki et al. (1997) – there are fluctuations in the limits of both regimes as quoted in the literature, but they do not significantly differ from those given here.

A terrestrial planet is one whose mass is insufficient to trigger runaway accretion of H and He. This is thought to occur for $M_{\rm pl} \geq 10\,M_{\oplus}$, which corresponds to an upper radius limit for terrestrial planets of $R_{\rm pl} \sim 2.2\,R_{\oplus}$.

For a planet to be habitable, it is additionally required to have a mass that is sufficient to sustain plate tectonics, as these are thought to have played an important role in the evolution of life on Earth, and to retain a significant atmosphere. This results in a lower mass limit of $M_{\rm pl} \sim 0.5\,M_{\oplus}$, i.e. a lower radius limit of $R_{\rm pl} \sim 0.8\,R_{\oplus}$. It must also lie in the 'habitable zone'. This zone is usually defined to ensure the existence of liquid water on the surface of the planet, the inner edge being due to loss of water through photolysis and hydrogen escape, and the outer edge to the formation of CO_2 clouds in the upper atmosphere, which increase the albedo and thus lead to a drop in surface temperature (Kasting et al. 1993). Franck et al. (2002) compute age-dependent habitable zone limits, requiring the surface temperature to be in the range 0 to 100 °C and taking into account the change in luminosity of a star while on the main sequence. They give the following orbital distance ranges for the habitable zones of 4.5 Gyr old stars: 0.5 to 1 AU (0.8 $M_{\odot}$, K2 star) and 0.9 to 1.3 AU (1.0 $M_{\odot}$, G2 star). A similar but simplified calculation (K. Horne, priv. comm.) using a single luminosity value, and converting to period using the mass range 0.5 to 10 $M_{\oplus}$, yields the periods corresponding to the centre of the habitable zone as 1.2, 0.6 and 0.3 years for G2, K0 and K5 stars respectively.

A full definition of habitability must take into account many additional factors. To cite but one example, the interplay between stellar and planetary magnetic field (if the latter is present) is thought to play a major role in the survival of the planet's atmosphere, and hence its habitability. However, in the first approximation the limits established here provide a suitable framework to explore the detectability of terrestrial and/or habitable planets by the planned space-based transit search missions.

1.2.3.1 Challenges

Ultra-high precision photometry from space: Space missions are free from the effect of seeing variations (in space and time) and atmospheric extinction, which enables them to achieve much higher photometric precision than ground-based projects, reaching 15 to 20 ppm over the duration of an Earth-analogue transit for the larger projects. However, other noise sources come into play and must be taken into account and, where possible, corrected. The most significant are satellite jitter and the hostile radiation environment the detectors are submitted to.

On-board processing power and telemetry limitations: Telemetry limitations imply that it is impossible to download every image in full. Instead, some of the processing must be done on board and light curves rather than images are downloaded. On the other hand, on-board computing capabilities and power budgets are also limited, so that the processing steps must be kept as simple as possible, and only a limited number of targets per field can be monitored. These problems affect all the planned transit-search space-missions to a varying degree. For example, the telemetry limitations are even more stringent if the satellites are in distant (L2) orbits, which is necessary to allow continuous monitoring of a given field for more than 6 months.

Stellar micro-variability: With the improved precision achievable from space comes a drawback: increased sensitivity to small amplitude variations in the brightness of the parent star itself. The Sun is observed to vary on all timescales from minutes to decades with amplitudes of up to a few mmags, and every star is expect to display some degree of variability if observed with sufficient precision.

The lack of knowledge available about the observational characteristics – amplitude and frequency distribution for example – and physical mechanisms leading to this complex noise source, which is referred to hereafter as stellar micro-variability, makes it potentially very dangerous for transit searches for small planets. Figure 1.4 illustrates how, if left untreated, it can completely drown out the transit signal. It must therefore be taken into account at the observational strategy, target selection and data analysis stages.

Difficult follow-up: In addition to the relatively faint magnitude of the target stars, which already affects the follow-up of planet candidates from ground-based tele-

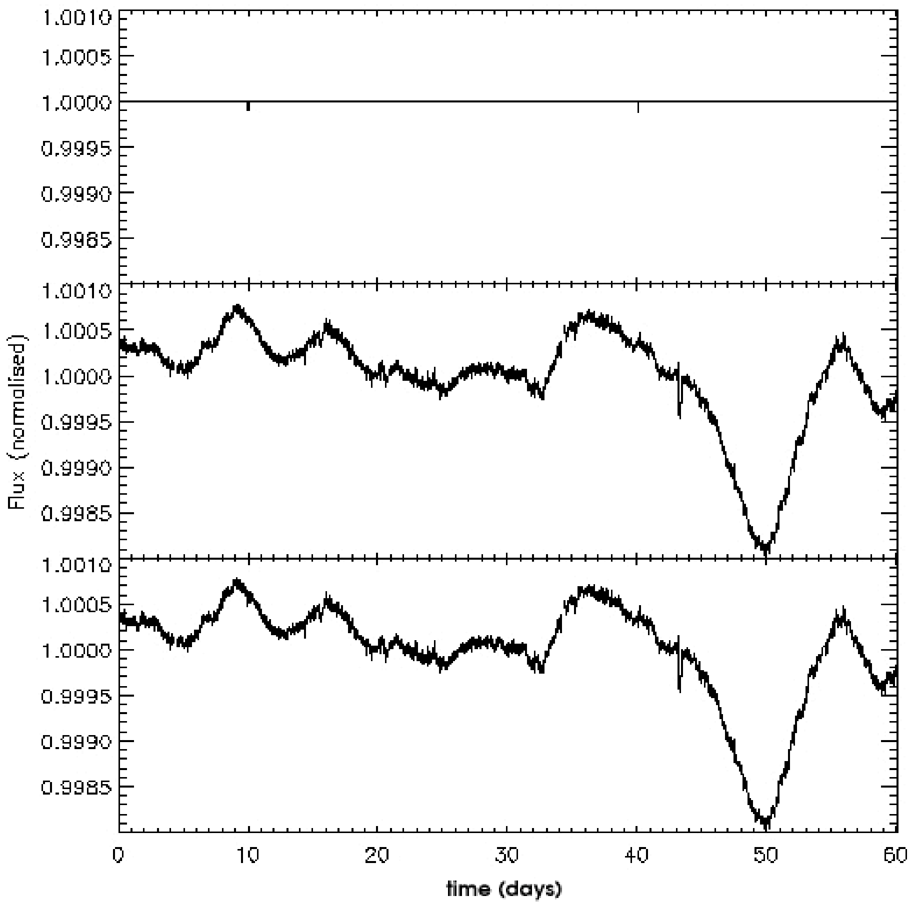

Figure 1.4: Top panel: simulated transits of an Earth-sized planet orbiting a Sun-like star with a 30 d period. Middle panel: a 60 d section of the Total Solar Irradiance (TSI) variations as measured with the PMO6 radiometer on SoHO/VIRGO near the peak of the solar activity cycle. Bottom panel: combined solar and transit light curves. The transits are no longer recognisable to the naked eye.

scopes, the lower masses and longer periods of the planets that can be detected via the transit method from space make them very difficult to follow up via the RV method. The fact that transits as shallow as a few parts in 10^5 are detectable means that a background binary can cause a detectable planetary transit-like signal even if it is fainter than the primary target star by 5 magnitudes or more: the necessity to follow-up candidates is thus even more acute than from the ground.

The best ground based RV facilities can achieve precisions of down to $1\,\mathrm{m\,s^{-1}}$ (HARPS, VLT+UVES, Keck+HiReS). This is enough to measure the signal induced by 'Hot Earths' – terrestrial planets in orbits lasting a few weeks or less – provided the target stars are bright enough – typically $V = 12$ to 14 with HARPS. For fainter targets or planets with lower masses or longer periods, only upper limits will be achievable: enough to exclude stellar or substellar companions, but not to provide mass measurements or to fully exclude all possible stellar blend scenarios. A large fraction of the transit detections made by the larger space-based transit search projects – *Kepler* or *Eddington*– will thus not receive full confirmation from RV observations.

This has two important implications. The first is that the candidates must be thoroughly screened using all available information (in the light curve and from other photometric and spectroscopic observations taken as part of the mission preparation) before requiring additional follow-up observations. The other is that the scientific return of these missions will likely fall into two distinct categories: detailed studies of confirmed planet candidates on the one hand, and statistical studies of the entire sample of candidates, some of which may remain unconfirmed, on the other.

1.2.3.2 COROT

COROT (COnvection, ROtation & Transits) is a small space mission whose primary science goals are to perform asteroseismology of stars across the HR diagram and to detect exo-planets via the transit method. The mission design is described in an article by Baglin & the COROT Team (2003) and on the project website[5]. It is funded mainly by the French space agency CNES, with significant contributions from the European Space Agency (ESA) and from other individual countries (Austria, Spain, Germany, Belgium and Brazil). The third in the PROTEUS series of small CNES missions, it is on track for its planned launch date of June 2006.

The payload consists of a small (27 cm aperture) afocal telescope shielded by a very efficient baffle to minimise Earth-scattered light. The focal plane is occupied by four 2048×2048 pixel EEV CCDs covering a total field of view of $2.8 \times 2.8\,^\circ$, two of which are devoted to asteroseismology and two to exo-planet search (the two programs are carried out simultaneously). It will be launched on an almost polar near-Earth orbit with an altitude of ~ 900 km.

The seismology CCDs will be highly defocussed to allow the observation of bright stars ($6 \leq V \leq 9$), each projecting a ring-like image over ~ 400 pixels. They will be read once per second in frame-transfer mode. The exo-planet CCDs will be slightly defocussed, and the presence of an objective prism in the optical path of that part of the field of view will lead to tear-drop shaped images occupying between 50 and 100 pixels. The exo-planet CCDs will be read every 32 s, and the target stars in that program have $12 \leq V \leq 16$. For the brighter stars, the dispersed PSF will be split into blue and red regions to provide coloured light curves, for the fainter stars only white-light information will be collected.

During its 2.5 yr lifetime, COROT will carry out 5 long (150 day) observing runs,

[5] `www.astrsp-mrs.fr/projets/corot/`

designed to allow the detection of planets with orbital periods up to a few months, as well as a number of shorter ($\sim$ 20 day) runs devoted primarily to seismology or additional science. Due to its orbit, COROT can only follow a given field for up to 6 months, after which it has to be rotated to keep its solar panels facing the Sun. A given field can only be observed if it is at a safe distance from both the Sun and the bright rim of the Earth. This limits the observed fields to a region close to the ecliptic plane. Due to the alternation between one direction and the other every 6 months, they must be contained in two circles of $\sim 10^\circ$ radius on opposite sides of the sky within this region. These 'COROT eyes' were chosen to be centred on galactic coordinates $l = 35^\circ$, $b = 0^\circ$ (close to the galactic centre) and $l = 210^\circ$, $b = 0^\circ$ (close to the anticentre). The low galactic latitudes allow for large numbers of stars in the field, increasing the planet detection probability.

The small number of these long runs makes the choice of the target fields very important. This is a complex process, simultaneously driven by the requirements of seismology and exo-planet programs, and based on a very substantial ground based preparatory observation program. Spectra of every star with $V < 8.5$ in the COROT eyes have been taken and primary seismology targets proposed. An on-going multi-colour photometric survey of the potential exo-planet field area next to each proposed primary target (including all translations and rotations of the field keeping the primary target in the seismology CCDs) provides extinction maps and preliminary spectral types and luminosity classes for the potential exo-planet search targets. These are used to optimise the position of the exo-planet CCDs and to exclude a number of proposed primary targets surrounded by regions where the extinction is too variable. The final CCD positions on the sky also take into account secondary seismology targets. At the time of writing, the CCD positions have been chosen for at least two fields (one in each direction), and the final primary target choice and positions for all 5 long runs should be decided by the end of 2004.

Due to telemetry limitations, images from the exo-planet channel will be co-added to 8.5 min sampling, and photometry performed on board. Up to 12 000 stars can be monitored in each field. In the Galactic anticentre direction, the number of stars per field in the magnitude range of interest is lower than this limit, but the higher stellar density in the Galactic centre direction means that only some of the stars that fall in the appropriate magnitude range in a given field will be monitored in the Galactic centre direction. The preliminary spectrophotometric classification will be used to attempt to preferentially select late-type dwarfs in these cases. At the beginning of each run, a mask optimally encircling the tear-drop PSF (which varies according to brightness and temperature) will be chosen automatically for each star from a template set, and used throughout to perform white-light photometry by summing all the pixels in the mask, or splitting the area within the mask in two in order to get two 'colours'. The resulting light curves will then be downlinked to Earth and noise corrections applied. A small number of stars (typically a few hundred per field) will be observed with higher (32 s) time sampling. The list of 'oversampled' targets will contain additional science program stars, but will be updated regularly to include stars showing suspected transits.

The exo-planet detection potential of COROT has been investigated by Bordé et al. (2003), who estimate maximum orbital distances at which planets can be detected as a function of stellar spectral type, and the number of expected detections as a function of planetary radius and surface temperature, showing that planets with radii of 1–2 $R_\oplus$ are within COROT's reach provided their surface temperatures are $\geq$ 500 K. COROT will thus be the first mission to probe the terrestrial regime, as well as detecting large numbers of gaseous giant planets and, if they exist, close-in giant planets whose atmosphere has been (partially) evaporated by strong high-energy flux from the star (Lammer et al. 2003) or ice-planets with liquid outer layers (speculated 'ocean' planets, Léger et al. 2004).

Although it is less ambitious than the larger missions that will follow it, COROT benefits from a significant advantage: it will be possible to follow-up the candidate planets it will detect with the most sensitive of the ground-based RV instruments, such as HARPS on the 3.6 m ESO telescope at la Silla (Pepe et al. 2004), which can achieve sub-1 m s^{-1} precision, sufficient to study most of the COROT candidate planets.

COROT will also have another, very important role: it will be the first mission to measure stellar micro-variability – that is intrinsic variability with mmag amplitudes and timescales of minutes to weeks – for stars across the HR diagram. Although the smaller Canadian mission MOST, currently operating, is for the first time measuring this type of variations in detail for other stars than the Sun, it will do so only for a small, selected sample of stars. The COROT dataset will be invaluable for the study of the physical processes behind stellar micro-variability, a project which can be carried out at no extra cost as the exo-planet field observations can be used directly (Weiss et al. 2004). It will also be extremely useful to optimise the light curve filtering tools needed for later transit search missions concentrating on habitable planets, where stellar micro-variability will play a major role.

1.2.3.3 *Kepler*

Kepler is a NASA Discovery class mission designed to monitor 100 000 stars for 4 yrs in order to detect transits of Earth-sized and larger planets with orbital distances as large as 1 AU. It has a planned launch date of 2007 and will be launched into an Earth-trailing heliocentric orbit. The mission is described in detail in a number of publications including (Borucki et al. 2004) and on the project website[6].

The design was guided by the requirement that a Sun-Earth system with $V = 12$ should cause at least an $8\,\sigma$ detection. For a 4 yr mission lifetime, this implies a $4\,\sigma$ event for a single transit.

The payload consists of a modified Schmidt telescope including flat-fielders near the focal plane. The corrector has a clear aperture of 0.95 m and the primary a diameter of 1.4 m. This aperture ensures a precision of 1 part in 10^5 for a $V = 12$ G2 dwarf, which satisfies the design requirement above. The detector is composed of 42 1024×2200 pixel CCDs, totalling a 100 sq. deg. FOV. Only white light observations are planned.

Telemetry limitations imply that only pixels illuminated by one of the 100 000 target stars are saved for transmission to Earth, before which images are co-added to produce one measurement per pixel every 15 min. A single field is monitored for the entire duration of the mission. Consequently, the choice of target field is of crucial importance. It is constrained by a 55° sun-avoidance angle. The *Kepler* team have opted to maximise the number of stars in the magnitude range of interest in the target field, while fine-tuning of the detector position on the sky minimises the number of excessively bright stars on the CCDs. A field centred on $l = 68.8^\circ$, $b = 6.5^\circ$, falling in the Cygnus constellation, yielded 450 000 stars brighter than $V = 15$. A ground-based observation program to classify the stars in the field and identify suitable stars to constitute the 100 000 strong target list is underway. The magnitude range of the targets will be similar to that of COROT ($12 \leq V \leq 16$), though the photometric precision at a given magnitude will be much higher.

Classical (matched filter) detection algorithms are envisaged to detect planetary transits in the *Kepler* data (Jenkins et al. 2002). A wavelet-based algorithm designed to adaptively measure and remove non-white noise such as that induced by stellar micro-variability has also been developed (Jenkins 2002). Follow-up of candidate detections will be problematic, as not even the best ground-based RV facilities will be able to measure the Doppler shifts induced by Earth-mass planets. The follow-up procedure will therefore proceed as for other transit search programs (light curve examination, high resolution imaging / centroid analysis, low then high precision RV measurements) but the RV measurements will serve to exclude stellar or sub-stellar objects, and only upper limits will be available on the mass of planetary objects. It may be possible to detect colour changes during the transits using future instrumentation on HST and JWST (James Webb Space Telescope).

To ensure any announced detections are genuine, *Kepler* data will be analysed and transit candidates followed-up internally before the data is publicly re-

[6]`www.kepler.arc.nasa.gov/`

leased, which means that release dates will vary depending on whether the light curves contain clear (deep, short period) transit signals (allowing quick confirmation and hence release approximately one year after the first few transits are detected), are too variable for transits to be detected (allowing release soon after) or contain shallow or long period events (released after the end of the mission only).

At the time of writing, *Kepler* has the best chance of being the first mission to detect habitable planets, and in particular Earth-analogues. It is expected (Borucki et al. 2004) to detect approximately 500 planets in the habitable zones of its target stars if every one of them has such a planet, with (under the same assumptions) 25 of these having the radii equal to or smaller than that of the Earth, and half of those orbiting single stars.

1.2.3.4 *Eddington*

Eddington resembles COROT in that ts combines the two science goals of asteroseismology and planet finding via the transit method, though it is designed on a more ambitious scale. It was accepted as a reserve mission in ESA's science programme in September 2000, with two parallel primary science goals: asteroseismology and exo-planet detection via the transit method. The planned launch date was then very similar to that of *Kepler*. In December 2003, the mission was removed from ESA's Science program for budgetary reasons. Industrial and scientific studies related to the mission are still taking place and there is pressure from the exo-planet community to re-instate the mission should funds become available. Despite the uncertain status of *Eddington* at the present time, it is appropriate to describe it here as much of the work in the present thesis was carried out with applications to *Eddington* data in mind. Latest news on the project can be found on its website[7].

The payload as planned at the time of selection is described in a report by Favata & the *Eddington* Science Team (2000) and consisted of a telescope with a 1.2 m diameter primary mirror, resulting in a collecting area of 0.6 m^2. The detector consisted of 20 740 $\times$ 2900 pixel CCD chips covering a circular FOV with 3° diameter. Hereafter, this is referred to as the old *Eddington* design. Following an industrial study, the planned payload was modified in early 2003, improving the photometric performance. The new design, described in Favata (2004), consists of three identical telescopes (pointing in the same direction) with a total collecting area of 0.764 m^2, each with identical detectors at the focal plane with a permanently covered circular FOV of 19 sq. deg. This modification allows not only shorter focal lengths and wider FOV, but the use of the already designed Herschel bus as the satellite platform. It also enables the use of colour information, which a number of studies recommended

[7] `astro.estec.esa.nl/SA-general/Projects/Eddington`

(see for example Kjeldsen & Tingley 2004), to be implemented in a simple way. Very broad bandpass filters, one excluding only the blue part of the spectrum and one excluding the red, are inserted in the optical path of two of the telescopes. A 'blue' and a 'red' light curve are then obtained for the bright stars by subtracting the light curve from the red-excluding or blue-excluding filter, respectively, from that from the third, white light telescope, while keeping the cost, in terms of photon noise, minimal for the fainter stars. The photometric performance resulting from the old design was used in the present thesis for work carried out in 2002 and before, while that resulting from the new design was used for work carried out in 2003.

The observation strategy was not significantly altered by the change in design. Of a planned lifetime of 5 yrs, 3 yrs are devoted to a single pointing for the planet-finding program, while the remaining two consist of several shorter runs primarily dedicated to asteroseismology (though also suitable to detect planets with relatively short periods). As for *Kepler*, the choice of the planet-finding target field is crucial and some of the simulations described in this thesis were designed to help place constraints on the most favourable stellar content of such a target field. The baseline Eddington orbit is around the L2 Sun-Earth point. Sun-avoidance constraints are similar to those of *Kepler*.

In the planet-finding mode, 8 s integrations are co-added to produce 10 min stacked images and photometry is performed on-board. System performance allows for up to 100 000 preselected planet-finding targets, which means that all the stars in the FOV which are bright enough to reach the photometric precision necessary to detect transits can be observed. The lack of target pre-selection may lower the detection efficiency, but allows for more serendipitous discoveries than the approach of the *Kepler* mission. The requirement of 80 ppm (parts per million) precision over 1 hr (necessary to detect an Earth-like planet with a 3 yr run) is achieved down to $V = 14$, while the magnitude limit of the targets is $V = 17$ (only larger or shorter period planets will be detectable around the fainter stars). The overall dynamic range is approximately $10 \leq V \leq 17$. The data release policy foreseen for *Eddington* was very open – immediate availability to all European teams having requested access in advance through response to an announcement of opportunity and public access one year later. All these characteristics make *Kepler* and *Eddington* complementary, despite having very similar photometric performances, time sampling and duration.

1.3 The broader perspective

The development of tools to search for planetary transits naturally leads one to consider other phenomena which can be detected in the same kind of data as that in which the transits are being sought, as well as the possibility of applying similar tools to other kinds of data.

1.3.1 The time domain in astrophysics

The time domain can arguably be considered the last (relatively) unexplored domain in astrophysics. That is not to say that the study of variations in the observable characteristics – position, brightness, and later spectra – of celestial objects have not played a crucial role in astronomy to date. The motion of the stars and planets across the sky inspired early conceptions of the cosmos, which were soon developed into the capacity to predict specific events – as exemplified by many archaeological remains – and later deciphered in terms of the governing laws of physics which drive the observed movements – starting with Newton's interpretation of Kepler laws in terms of an inverse square law gravitational force.

However, not until very recently have homogeneous times series – of any kind, but most importantly for the present discussion photometric – taken by the same instrument and treated in the same way, been available as a platform for *new discoveries*. There have been *targeted* observations of objects that were known in advance to be potentially interesting targets, but these do not truly enter the 'exploratory' regime which is of interest here. On the other hand, the variable star community have, throughout the 20th century, used repeated observations of a given field to find new variable stars, but technological and organisational limitations have made the acquisition of homogeneous, long duration, high sampling time series difficult.

Two factors have changed this situation relatively recently. One is the advent of high quality CCD detectors which can be coupled to wide field instruments, together with sufficient data storage and processing capacity. The other, I would argue, is the discovery of the first exo-planets. This might be a controversial point. There is a wealth of other fundamental science that requires the same type of data, and for which scientists had been attempting for many years to set up dedicated projects, with success in some cases. For example, a number of very fruitful ground-based microlensing projects have been in operation for several years. However, in particular for space projects, exo-planet science appears to have been a very significant, often decisive factor. Both COROT and *Eddington* were – sometimes under other names – originally asteroseismology projects. However, it is the potential discovery of hundreds if not thousands of 'brave new worlds', which brought this type of observations to the attention of the public eye and created the necessary good will for these projects to be funded.

1.3.2 Additional science from transit search data

High precision, high sampling time series photometry with relatively long coverage are a treasure trove for the study of near-Earth objects, variable stars, gamma ray bursts and variability of extragalactic origin. There are too many types of variable stars to list here. They are not only identifiable from the shapes of their light curves but also from other parameters besides photometry. It is commonly thought that, if observed with sufficient precision, all stars would show some degree of variability. Any sample of light curves which is used to search for transits is therefore bound to contain many forms of variability other than transits. We have already seen that under certain circumstances stellar variability can hinder transit searches; it is also, of course, of interest for its own sake.

It is therefore desirable to identify variable stars, on the basis of global light curve statistics, and to perform a period search. Developing tools for this purpose was a logical extension to the work I have been doing on transit search algorithms. Though they are used to complement transit search methods, they provide a first pass 'filter' that can be followed by more detailed study. The elaboration of automatic variability classification tools is a very active subject (Mizerski & Bejger 2002; Belokurov et al. 2003, 2004), but it is beyond the scope of the present work.

1.3.3 Application of transit search tools to other data

Planetary transit search programmes ground- and space-based are not the only source of large quantities of photometric time series data. Scanning astrometry missions, starting with Hipparcos – whose dataset already constitutes a formidable database – and continuing with GAIA, will provide repeat observations of an even larger number of stars, albeit with much sparser sampling. The variable star and transit detection tools developed in the present thesis were therefore designed to be compatible with, or adaptable to, much sparser sampling that that commonly available for transit searches.

1.4 Structure of the thesis

Chapters 2, 3 and 4 describe the tools I have developed for the purpose of analysing transit search data: transit search algorithms, an empirical model of stellar micro-variability, and micro-variability filters to reduce stellar noise before applying the transit search algorithms.

The rest of the thesis is devoted to the application of these tools. In Chapter 5, various simulations are used to identify promising types of target stars and set rough detection limits for *Eddington* (and by extension *Kepler*) and COROT. In Chapter 6, I describe my participation in the first COROT blind transit detection exercise, where several groups independently attempted to detect transits in a set of simulated COROT light curves whose content was unknown to the testers. Chapter 7 summarises early experiments with ground-based data from the University of New South Wales transit search program. Conclusions and future perspectives are presented in Chapter 8.