Chapter 1

Introduction

1.1 Introduction

In modern times, if any field of astrophysics has spurred the interest of the scientific community and the general public at large, it is the discovery of worlds orbiting other stars. With the first confirmed planet orbiting a solar-type star (51Peg-b) being discovered in 1995 (Mayor & Queloz 1995), these 'extrasolar' planets (ESPs) are scientifically intriguing, not only in their measured characteristics, but also in their physical locations within their host star system. This first extrasolar planet, along with many others discovered since, exist in regions where previous planetary formation theories (which, pre-1995, the Solar System was the only example) indicated that they simply should not. Although currently presenting a significant challenge to explain, a huge amount of research on new theories of planet formation, migrational history and dynamical evolution have appeared since this first detection, revolutionising our understanding of these enigmatic bodies.

In 1992, before the first confirmed planet around a main sequence star was discovered, an announcement was made of a multiple planetary system associated with a 6.2 millisecond pulsar, PSR1257+12 (Wolszczan & Frail 1992). This immediately raised questions e.g. how could planets possibly exist in a system with a history as violent as that of a supernova? Detected via the spin-down rate of the pulsar, this system seems to contain three bodies with masses approaching terrestrial. The mere presence of these bodies suggests that planetary formation is a very robust process. Perhaps these objects are the left-over remains of once giant planets, or maybe they have formed independently since the supernova explosion. Either way, they would suggest that planet formation is also a very rapid process. Whatever their real origin, these objects provide a clue as to the possible diversity of planetary systems. As time went on, these discoveries did not prove the only to surprise astronomers, and recent observations have proved the existence of a large number of giant Jupiter-like planets associated with nearby Solar Neighbourhood

stars, which are located in very un-Jupiter-like places (Basri 2004).

Many ongoing radial velocity (RV) searches (see section 1.3 for details of this method) have revealed this new class of planet, unlike anything seen in our own Solar System. These so-called 'Hot Jupiter' (HJ) planets are quite common, seemingly associated with one out of every 125 stars searched (Basri 2004). Having orbital periods of a few days, and hence semi-major axes of around 0.04 AU, ($\sim$10% of Mercury's distance from the Sun) these Jupiter-mass planets are baked by extreme temperatures as they race around their host stars at incredible speed. With these discoveries come intriguing questions: How did these planets come to be in such a strange place? Did they originally form there or did they migrate inward over time? As there is no analogue in our own Solar System, this discovery questioned the whole basis of our understanding of planetary formation and evolution. Although the detection method is naturally biased towards finding planets like these, it was becoming clear that our own Solar System was not at all a good example of what has been seen in the Solar Neighbourhood to date.

Since these first tantalising discoveries, radial velocity searches have revealed a multitude of these Hot Jupiter planets. They seem to be surprisingly frequent in the Solar Neighbourhood, and as the accuracy of observations continues to increase, many research groups are working to detect many more ESPs at ever increasing distances from the Sun. At the current time, there are 135 ESPs known, associated with 109 stars. Some are clearly multiple planet systems. As the length of continued observation increases, the discoveries made include planets with much longer orbital periods and lower mass planets, which more data can conclusively reveal. The near future is bound to hold many interesting new discoveries.

Hot Jupiter planets present us with an intriguing prospect. If one of these planets is suitably oriented so that it passes in front of its host star as seen from Earth, it follows that the star will regularly undergo a temporary drop in brightness, every time the planet passes in front. Lasting for a couple of hours, these 'transits' would be easily visible from ground-based telescopes. As the geometric probability of a transit being visible is directly proportional to the orbital semi-major axis, these HJ planets are perfect candidates to be discovered this way.

Using transiting planets as a laboratory, this thesis answers some important questions concerning the formation and survivability of such worlds in a target location very different to the heavily sampled Solar Neighbourhood. By searching for transits in the globular cluster 47 Tucanae, this work provides results with a direct bearing on the HJ frequency in such low metallicity and highly-crowded regions of the Universe. The astrophysical interpretation of the result is one that places important constraints on the locations where these objects are likely to exist and bear directly on where to look in the future to maximize the likelihood of a successful detection.

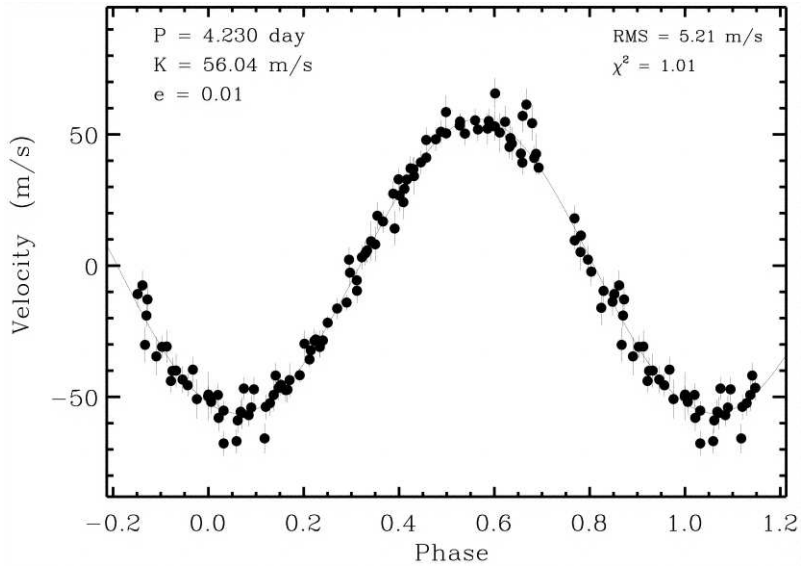

Figure 1.1: The first direct detection of an extrasolar planet with the radial velocity method, identified by Mayor & Queloz (1995). It is clear that the star (51-Pegasi) is undergoing a reflex motion with an amplitude of 59m/s, with a period of 4.23d. The object responsible has a minimum mass of only 0.5 that of Jupiter. (Image from Marcy et al. (1997))

1.2 Extrasolar Planet Trends

1.2.1 Metallicity

As more planets are discovered, it is becoming clear that they seem to obey certain trends. These trends could be giving us clues as to their formation and evolutionary histories and seem to suggest that the planets being discovered outside our Solar System are very different to our Earth's direct neighbours.

Perhaps the most important observational trend for this work is that planet-bearing host-stars seem to be more metal rich (higher [Fe/H]) than the general surrounding population of stars (Gonzalez 1997; Laughlin 2000; Santos et al. 2001; Fischer & Valenti 2003a). The phenomenon is shown in Figs. 1.2 and 1.3 and is proving to have important consequences for planet formation theories in the literature. As can be seen in those figures, the frequency of planets increases quite dramatically as the stellar metallicity increases. An important consideration is whether or not this is simply an observational selection effect. As radial velocity searches can only sample nearby bright stars (due to technological limitations at the present time), it follows that those same stars are galactic disk stars, and hence would have an intrinsically high metallicity. Would this trend still be seen if the sampled stars in the Solar Neighbourhood were more metal-poor?

It would appear so. After accounting for this volume-limited selection effect, the trend is still seen (Santos et al. 2001). A further consideration is whether this trend is an initial condition (a primordial effect) or a byproduct of planet

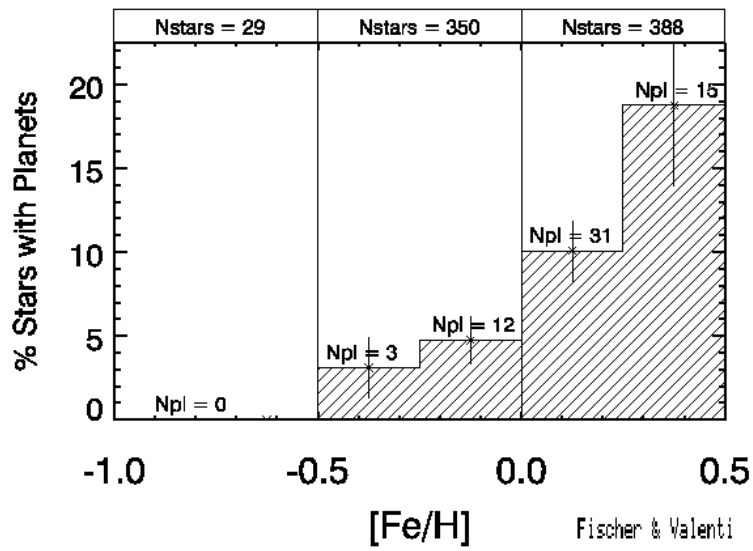

Figure 1.2: A histogram showing the number of discovered planets plotted against metallicity of the host star (Fischer & Valenti 2003a). It is clear that the frequency of planets increases proportionally with the stellar metallicity. This provides the first important clue to the formation mechanisms for extrasolar planets.

accretion onto the star in the past? It could be that these stars are of higher metallicity because they have previously swallowed up a planet, adding this gas-depleted material onto the photosphere of the star, and also hence adding to the observed metallicity. This accretion hypothesis can be verified by observation. Stars of spectral-type F have smaller convective zones than their G and K-type counterparts. If a planet is accreted onto the star, the net result will be that planet-bearing F-type stars will have a higher metallicity than the planet-bearing G and K-type stars. Similarly, subgiants will have diluted convective zones. If the metallicity of planet-bearing subgiants is significantly lower than that of planet-bearing main sequence stars, this would also add to the evidence of the accretion scenario for this metallicity trend. These obsevations are a work in progress by Fischer & Valenti (2003a) and coworkers. The near future should provide observational evidence to discriminate between these two theories.

Alternatively, the high metallicity of planet-bearing stars could be a primordial condition, that is, the star always was of high metallicity and has not accreted any material during its lifetime. If this is the case, it follows that regions of low metallicity would not harbour planets. While impossible to sample distant low metallicity stars with the radial velocity method, the transit method is perfect for the task, capable of sampling distant stars in old low metallicity open clusters and globular clusters to best effect, given sufficient photometric accuracy, temporal resolution and long contiguous observing windows.

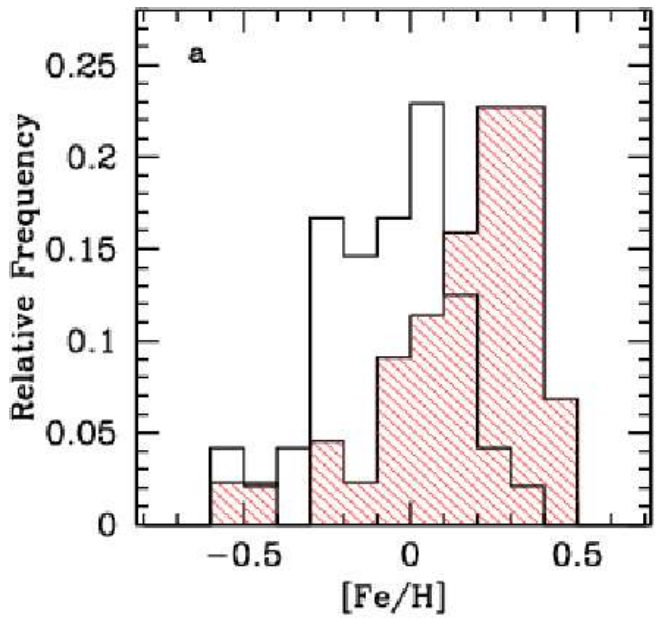

Figure 1.3: The metallicity distribution of planet-bearing host stars (red) compared to non-planet-bearing field stars (clear) for an unbiased volume limited sample. This figure confirms that the metallicity of the planet-bearing stars is significantly higher than the others, taken from Santos et al. (2001)

Santos et al. (2001) carried out a uniform, unbiased spectroscopic comparison between stars with and without planetary companions in a volume limited sample. The conclusion was to confirm that planet-bearing stars are significantly metal-rich, and that the source of the metallicity was very likely primordial, hence regions of low metallicity are much less likely to harbour planets. Fig. 1.3 shows the Santos et al. (2001) result. The difference between the two distributions (planet bearing stars and field dwarfs for which no planets have been detected) is clear.

Furthermore, Santos et al. (2001) produced simple models composed of adding significant quantities of iron (which is a function of stellar metallicity) to a stellar sample. The resulting metallicity distribution did not match the observations, suggesting that the enhanced metallicity is a primordial effect and not caused by accreting matter onto the star. Despite the simplicity of the models, the generally accepted view at the present time is that the metallicity enhancement is a primordial initial condition of the star rather than the subsequent accretion of material.

So, if the enhanced metallicity is primordial, how would this work? If the protostellar disk is of higher metallicity, would this increase the probability of forming a planet? There are two main accepted scenarios that can explain planetary formation, that of core accretion and disk instability, which can shed light onto these questions. Core accretion (Boss 2001) requires that protoplanetary disks are very

long lived in order to form Jupiter-like planets, and so would tend to predict (since observations show that protoplanetary disks are short-lived (Haisch et al. 2001)) that gas giant planets are relatively rare as a whole. Also, the planets produced with this model would be of very high mass. Cleary, this does not match observations. The models presented by Lin et al. (1998) show that disk instability could provide a likely means for the widespread formation of gas giant planets, and they should be (and are) abundant in the sampled stars. However, this theory predicts that the planetary atmospheres should be much more extensive than is observed (Boss 2001). Clearly, both formation theories have flaws which are currently the subject of further work.

If disk instability is the preferred method for forming the nuclei of proto-planets, it would seem that the metallicity of the proto-planetary disk would have a bearing on whether anything can form. As the timescales for planet nucleus formation is predicted to be extremely short, possibly in the order of a few hundred years (Boss 2000), it follows that the viscosity of the disk would be important for this process to occur most efficiently. For both disk instability and core accretion, if the material in the protoplanetary disk is more efficient at sticking together, it follows that the probability of planet formation increases. Perhaps the presence of heavy elements in the protoplanetary disk helps the material to stick together. Hence, if the metallicity of the disk is higher, the clumps that make up a planetary core will have a shorter timescale of formation. This would have the added bonus of stellar encounters having a smaller effect on destroying hopeful planets, increasing their universal frequency and the resultant metallicity trend that is observed.

1.2.2 Orbital Eccentricity

Further to the metallicity trend, the known extrasolar planet sample seems to show that as their orbital semi-major axis increases, the spread of eccentricity of the planetary orbit also increases. Fig. 1.4 shows this trend for planets discovered with the Lick, Keck and AAT planet search programs, as taken from a link to the California-Carnegie planet search team[1] on the Extrasolar Planets Encyclopedia webpage[2]. This trend provides a clue as to the dynamical history of these systems, and shows again that ESP systems are greatly different from our own Solar System.

Indeed, the median eccentricity of the currently known systems is 0.28, larger than the maximum eccentricity known in the Solar System with Pluto having ϵ=0.248 (Tremaine & Zakamska 2004). The eccentricity of a system can be altered via several possible mechanisms. Dynamical instabilities can develop in the final stages of planetary formation, due to migrational processes or the increase of mass

[1] http://exoplanets.org/team.html
[2] http://www.obspm.fr/encycl/encycl.html

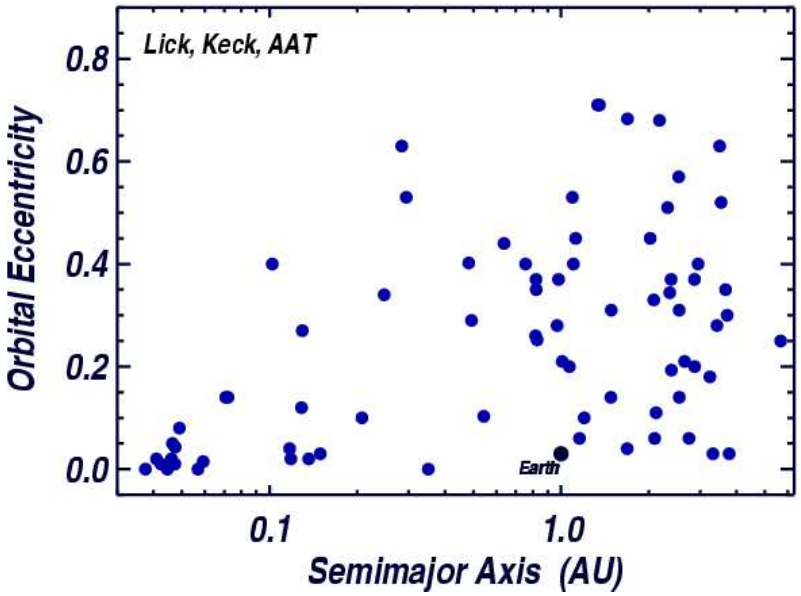

Figure 1.4: The observed trend of extrasolar planet orbital semi-major axis and orbital eccentricity for Lick, Keck and AAT detections. The spread of eccentricity increases with semi-major axis. This shows that the ESP's currently being discovered differ greatly from our own Solar System, and perhaps provides information about their dynamical histories and formation environments.

as planetary core accretion occurs. This process usually leads to the ejection of a planet or the significant increase of a planetary eccentricity (Lin & Ida 1997). Furthermore, interactions or resonant interactions between planets can cause this effect (Ford et al. 2001).

Another possibility is that the planets are affected in their early lives by a nearby passing star. As stars are formed inside the moderately dense cores of open clusters, it is possible this occurs relatively frequently (Hurley & Shara 2002). However, this does not seem to have occured in our own Solar System and the real reason for the eccentricity trend is still under debate.

1.3 Methods of Planetary Detection

1.3.1 Radial Velocity

When considering the detections of these new bodies, it is important to discuss the relative merits and downfalls of the detection methods used, in order to better understand how observational and technological selection effects can affect the results and conclusions when studying the whole planet sample.

The method used to detect the vast majority of these new planets (at least at the current time) is that known as the radial velocity (RV) method. This involves studying spectroscopically with great accuracy the radial velocity (velocity along the line of sight) of the target star, and observing how it changes with time. Using a simple application of the conservation of angular momentum, the target star will undergo a reflex motion if an orbiting planet is associated with it, measurable in that star's radial velocity variations with time. The period of modulation is equal to the orbital period of the unseen planet. It follows that the amplitude of modulation is directly proportional to the orbital semi-major axis and mass of the planet, with the known (or assumed) mass of the primary.

Generally speaking, the amplitude of the Doppler signature is ~1-100 m/s^{-1}. With a current sensitivity of ~3 m/s^{-1} (comparable to a brisk walk), RV searches are capable of detecting planets with masses significantly lower than that of Jupiter. As derived from equating centripetal and gravitational forces, and by incorporating Keplers' third law (which relates orbital period to semi-major axis), the amplitude of the radial velocity variation for any star is given by:

$$V_R = 28\frac{M_P \sin i}{P^{1/3} M_S^{2/3}} \tag{1.1}$$

where V_R is the amplitude of the Doppler variation (in m/sec), M_P is the mass of the primary (in solar units), i is the inclination of the planetary orbit, P is the period of the variation (in years) and M_S is the mass of the secondary (in Jupiter masses), in our case a planet. This Doppler 'wobble' is seen via high resolution spectroscopy, the result is that the stellar absorption lines are periodically red and blue-shifted phased with the period of the companion. After a couple of orbits, the observations allow us to calculate an accurate period and an estimate of the mass of the unseen companion. An example radial velocity curve for a planet with zero orbital eccentricity is shown in Fig. 1.1.

It is clear that extremely accurate wavelength knowledge must be had of the spectral lines with which to compare the observations. Generally, a precision calibrated iodine absorption cell is used to acheive this. The absorption produced

by the iodine gas in this cell imprints a dense network of narrow lines on the spectra with which the observed stellar lines are compared. One example of a successful search which uses this technique and has led to the discovery of several planets is the Anglo-Australian Planet Search (Tinney et al. 2001)[3].

Despite the successes, the Doppler method has its disadvantages. First, there is no knowledge of the orbital inclination of the target system. The mass derived from the RV technique is only an estimate, $m(\sin i)$, where m is the mass of the companion and i is the orbital inclination. Therefore, the derived masses can only be accurate if the planetary orbit is sufficiently inclined to be viewed edge-on. If it is face-on the derived mass is wildely inaccurate and some planets may be discounted in the future due to this effect. Further to this, with current technology it is not possible to search for planets associated with stars that are fainter than V$\sim$10, even with large aperture telescopes.

The radial velocity detection method is therefore naturally biased towards detecting close-in more massive planets, as these will have the largest detectable signals. This is the reason why the Hot Jupiter (HJ) planets described earlier were discovered first, and is simply a result of the method and not indicative that these types of planet are more common than any other. As the temporal baseline of observations increases with time, and technologies become more sensitive to picking up smaller amplitude radial velocities, it follows that longer period and lower mass planets will be uncovered. Indeed, Santos et al. (2004) has very recently accounced the discovery of a planet with only $14M_{\oplus}$ due to this reason. The first extrasolar Jupiter (a planet with $1M_J$ and $\alpha\sim5.2$AU) should be identified in the next couple of years.

1.3.2 Transit Photometry

Another search method that was hinted at earlier involves observing the transits of planets, done via accurate photometry capable of discerning the temporary drop in brightness as a planet passes in front of its host star. This is the method used to produce the results for this thesis, and it shall be described in detail here, along with its advantages and disadvantages. The details of how this method was applied in this work shall be described in section 1.6. This method was first suggested for planet detection use by Struve (1952) and was later quantified by Rosenblatt (1971) and Borucki & Summers (1984).

Transits allow the accurate determination of a number of important planetary system characteristics, some of which are impossible to find from RV studies. A very accurate orbital period calculation is found, along with an estimate for the inclination, and transits provide the only method that can measure directly the planetary radius. When coupled with radial velocity observations, the transit-

[3] http://www.aao.gov.au/local/www/cgt/planet/aat.html

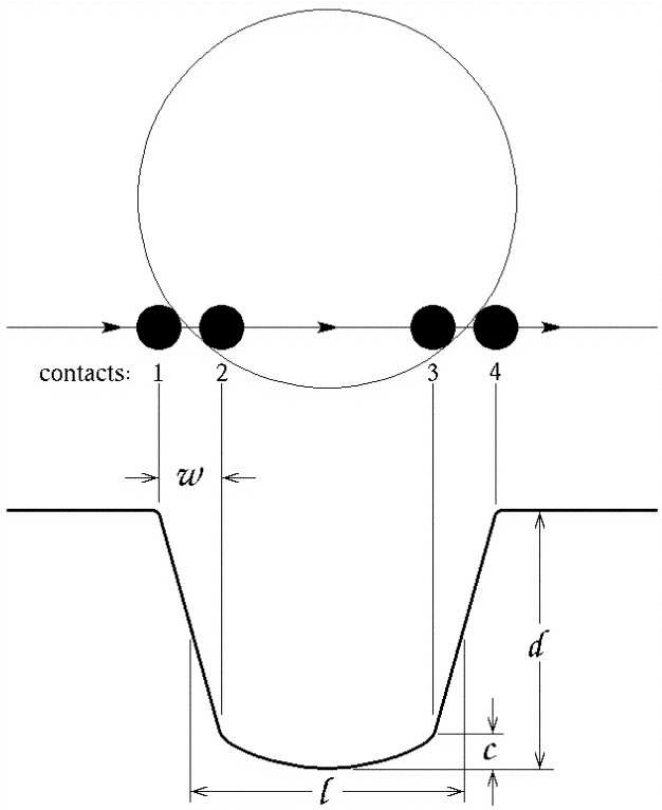

Figure 1.5: A schematic transit of a planet, showing the main stages of the event, and the corresponding observable signature; taken from Brown et al. (2001). d indicates the depth of the transit, and is typically 0.01-0.02 mag in amplitude. w defines the time interval when the planet is just crossing onto the disk, and leaves a sloped photometric signal. l is the total duration and c is a measure of the in-transit phase, the rounded shape caused by the stellar limb-darkening.

derived knowledge of the orbital inclination allow a measure of the planetary mass to be determined with small errorbars. With both the radius and mass, the density can be found. Hence, such transit-determined parameters are important for theoretical studies of extrasolar planet formation and evolution.

Using this method to search particularly for close-in extrasolar giant planets (specifically the Hot Jupiter planets) has provided some success in recent times. It is clear that as a transit is caused by a chance alignment, many stars must be searched before a successful detection can be made. The probability of a transit occuring is inversely proportional to the planetary semi-major axis. Thus it is much easier to see planets with short orbital periods and HJ planets are perfect candidates for detection. Many ground-based and planned space-based transit searches are underway at the present time, and results are being announced at fairly regular intervals. A literature review and description of selected current searches is provided in section 1.4..

Fig. 1.5 shows the typical observable signature of a planetary transit. The four numbered points indicate the limits where the planet passes onto the stellar disk

and hence can be photometrically detected, with points 2 and 3 corresponding to the portion of the event when the planet is completely superimposed on the stellar disk. Points 1-2 and 3-4 indicate the ingress and egress phases of the transit respectively, which cause a sloped photometric signal as the planet gradually passes onto the bright disk. The transit is typically flat-bottomed, caused by the fact that the planet is significantly smaller in radius than the star, and can show a slightly rounded effect caused by the stellar limb-darkening which can be seen on Fig. 1.5. An analytic form for this shape was derived by Sackett (1999).

Therefore, given appropriate orbital inclination with a period of a few days (typical of the HJ planets known in the Solar Neighbourhood from RV searches), a planet of Jupiter's radius will cause a periodic 1-2% (0.01-0.02 mag) dimming for a couple of hours duration in a solar-type main sequence star. This leads to a specific box-shaped and flat-bottomed photometric signature which can be easily detected on bright stars with photometry taken with only modest equipment. With larger instruments, these signatures can be detected on much more distant and faint targets than can be acheived with radial velocity methods. Further to this, with large instruments and bright stars the presence of planetary satellites and rings can be determined with small uncertainty.

However, planets are not the only objects which can cause the appearance of such a signature. Binary stars can mimic this, especially if the companion star is grazing. These can sometimes be identified by the presence of a secondary eclipse (since a planet is dark and therefore will not display such a feature) or by the physical shape of the transit (grazing binaries are generally much more V-shaped). A further worry, especially when searching for terrestrial-radius planets with this method, is the phenomenon of blends, which a bright star has a faint eclipsing binary positioned by chance directly behind it. The net effect is that the photometric signal of the binary produces a spurious transit-like signature on the bright foreground star. Discerning the actual nature of the transiting body is a subject that is currently being pursued by many researchers (ie Sirko & Paczyński 2003; Tingley 2004).

It is clear that knowledge of the mass of the companion must be made before a planetary classification can be announced. With faint stars, this may not be possible. An interesting prospect for non-RV followup work is to study the change in the host stars' colour during the transit. As the planet does not add enough photons to be detectable, it does not add to the overall colour of the system. The edge of a star is generally redder than the centre, due to limb-darkening, and it therefore follows that as the planet passes onto and off the disk (points 1 and 3 in Fig. 1.5), the colour of the system as a whole gets slightly bluer. As the planet is superimposed totally onto the disk, the colour gets slightly redder. This is shown in Fig. 1.6. Binary stars do not show this double-horned effect, and only a planet can do so (ie Tingley 2004). Therefore, if a transit is observed on a

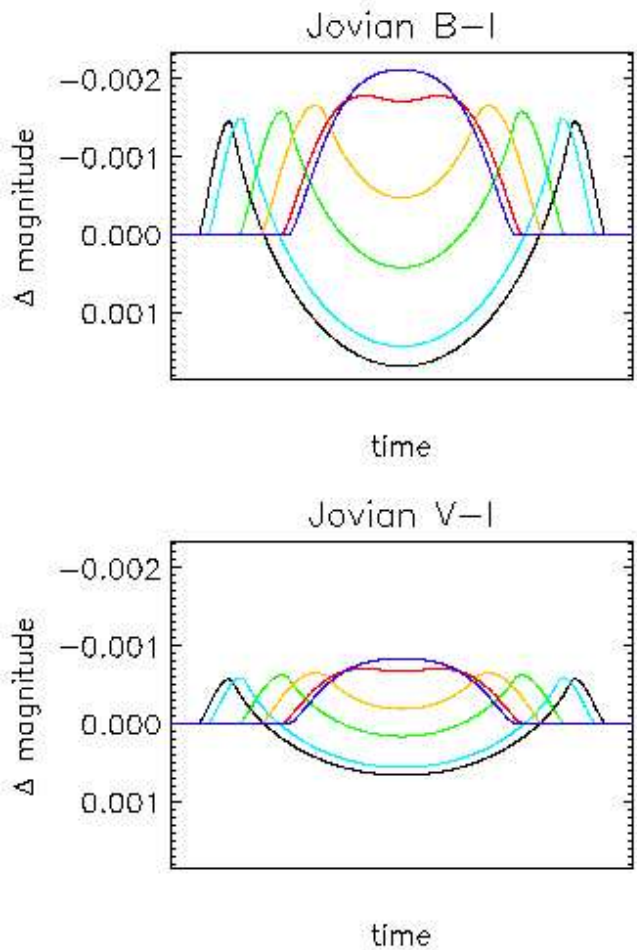

Figure 1.6: The variation of host star colour during a planetary transit, for a Jupiter-like companion. The different coloured lines indicate different orbital inclinations, with black indicating a centrally-crossing planet, and blue indicating an extreme grazing system. The system colour as a whole can be seen (in Δ mag units) to undergo a specific trend, in that the star becomes bluer at the transit ingress and egress phase, and the becomes redder during the main transit itself. This is caused by the limb-darkening of the star, and can be used to infer the planetary nature of the transiting object, if RV followups are not possible and given sufficient photometric accuracy (ie: Tingley 2004).

star that is too faint for RV followup work to confirm the mass, the nature of the transiting body can be inferred from colour observation both outside and inside transit, if photometry of sufficient accuracy can be obtained. This phenomenon could provide a powerful tool when working on the nature of transiting objects observed in distant star clusters and otherwise inaccessible parts of the Galaxy.

The availability of medium to large aperture telescopes using long contiguous observing windows has allowed many transit candidates to be discovered over the last few years with large-scale surveys. HD209458b was the first planet to be observed with the transit method (Charbonneau et al. 2000; Henry et al. 2000), being first discovered using radial velocity techniques (Mazeh et al. 2000). The

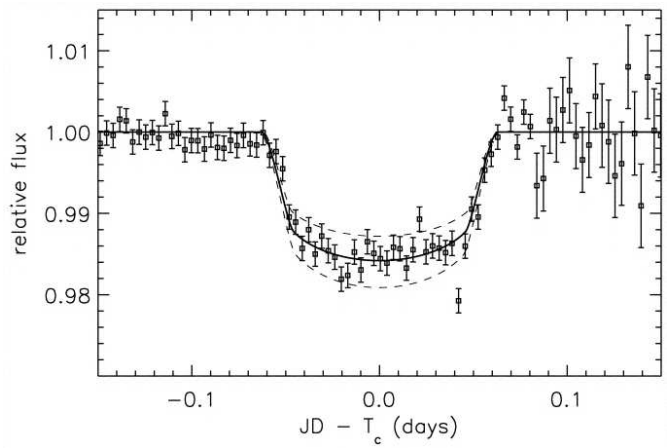

Figure 1.7: The transit of HD209458b, the first planet to be detected via the transit method (Charbonneau et al. 2000; Henry et al. 2000), being previously discovered with radial velocity techniques (Mazeh et al. 2000). The increased scatter after the transit is caused by increased airmass. The specific shape as described in the text and seen in Fig. 1.5 is clearly seen.

first planet to be seen to transit, and identified with only a 10cm aperture, observations of HD209458 showed with great effect how these objects can be discovered in association with bright stars and with only very modest equipment. This places them well within the regime where amateur astronomers could add significant scientific results to the general community at large.

The transiting HD209458b was later followed up by Brown et al. (2001) using HST/STIS, which achieved the incredible photometric precision of 0.1 mmag with a corresponding temporal resolution of 80s. Using this dataset the planetary and stellar radii were estimated to be R_p=1.35±0.06R_{Jup}. With the RV-derived knowledge of the planetary mass (M_p=0.69±0.05M_{Jup}), an estimate was made for the density (0.35 g/cm^{-3}). As well as this, the dataset produced robust limits on the null detection of satellites and rings. It is therefore clear that transits present an excellent opportunity to understand a planetary system with greater accuracy than can be derived via other detection methods.

Using the 1.3m Warsaw telescope in Chile, the OGLEIII group have become very prolific transit-finders. They originally discovered 46 transiting systems towards the Galactic Bulge (Udalski et al. 2002). These systems could however comprise planets, brown dwarfs, stellar companions or blends, as described earlier, and hence are the subject of vigorous followup programs to determine their likely nature. A total of 137 candidates have currently been presented (Udalski et al. 2003). From these candidates, OGLE-TR-56b became the first planet discovered using the transit method (Konacki et al. 2003), confirmed with radial velocity data that measured the planetary mass (Torres et al. 2003, 2004), along with followup work by Sasselov (2003); Burrows et al. (2004) and coworkers. The estimates for the main parameters are M_p=1.45±0.23M_{Jup} and R_p=1.23±0.16R_{Jup}. These

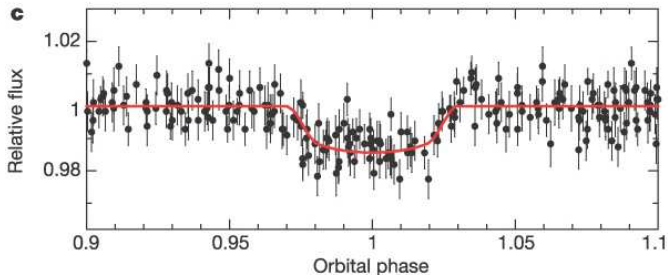

Figure 1.8: The transit of OGLE-TR-56b, the first planet to be discovered purely by the transit method (Konacki et al. 2003). The responsible object has a mass of 1.45±0.23 M_{Jup} and a radius 1.23±0.16 R_{Jup} (Torres et al. 2004).

values produce a density (1.0 g/cm^{-3}), which is significantly higher than that of HD209458b.

Very recently, two new transiting planets have been identified by Bouchy et al. (2004): OGLE-TR-113b and OGLE-TR-132b. Of these, OGLE-TR-113b was independently verified by Konacki et al. (2004). Both of these new discoveries have very short orbital periods (∼1.2d), much shorter than the apparent 3d cutoff seen from radial velocity Hot Jupiter discoveries, either indicating the presence of a new class of close-in 'Very Hot Jupiters', or revealing a selection effect. Either way, these objects present interesting targets for theoretical work. Further to these detections, Pont et al. (2004) has announced the confirmation of a 0.53±0.11 M_{Jup} planet causing the OGLE transit candidate OGLE-TR-111, previously published in Udalski et al. (2003). Also, Alonso et al. (2004) has announced the discovery of a further transiting 0.75±0.07M_{Jup} planet associated with a relatively bright (V=11.79) K0V star. Clearly, the transit method is becoming extremely successful at detecting extrasolar planets.

Further information on the status and prospects of current selected transit searches has been published by Horne (2003), and an extensive list of both ground-based and space-based searches is available on the Extrasolar Planet Encyclopedia[4]. A description of highly-cited ground and space-based transit searches is given in section 1.4.

[4]http://www.obspm.fr/encycl/encycl.html

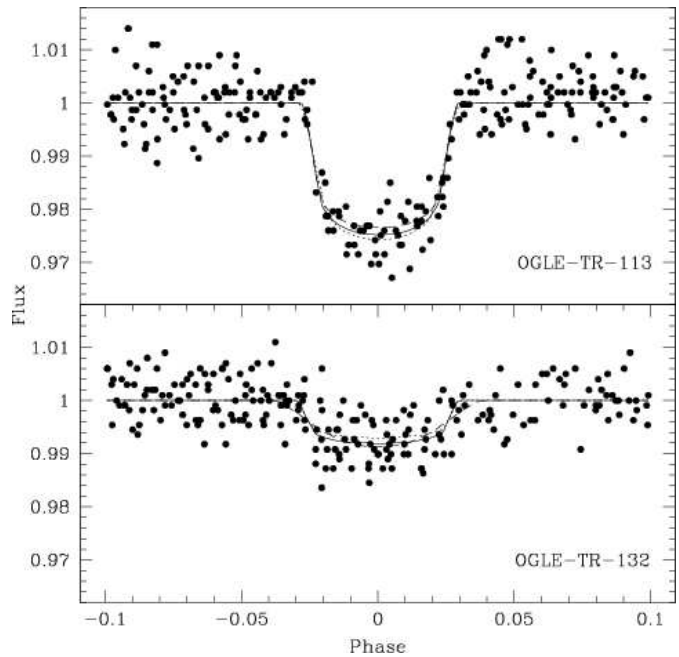

Figure 1.9: These two transits were catagorised as planets via radial velocity techniques after first being discovered by their transits (Bouchy et al. 2004).

Observable Transit Parameters

In order to determine the frequency of detectable HJ transits in any given dataset, an estimate must be made of the numerical probability of a transit occuring for any given star. As previously described, the probability of a transit occuring decreases as the planet-star distance increases. If a search is to be undertaken, it is important to quantify this probability as a function of orbital period.

A transit can only occur if the orbital plane is inclined at a suitably critical viewing angle. This inclination i must therefore satisfy:

$$\alpha \cos i = R_* + R_p \tag{1.2}$$

where α is the planetary semi-major axis, i is the orbital inclination, R_* is the stellar radius, and R_p is the radius of the orbiting planet, as described in Sackett (1999). However, cos i can take on any random number from 0 to 1, so to derive a transit probability Pr_{trans} for a large sample of targets, this must be taken into account:

$$Pr_{tran} = \frac{\int_0^{(R_*-R_p)/a} d(\cos i)}{\int_0^1 d(\cos i)} = \frac{R_* - R_p}{\alpha} \sim 0.87(\frac{R_*}{\alpha}) \tag{1.3}$$

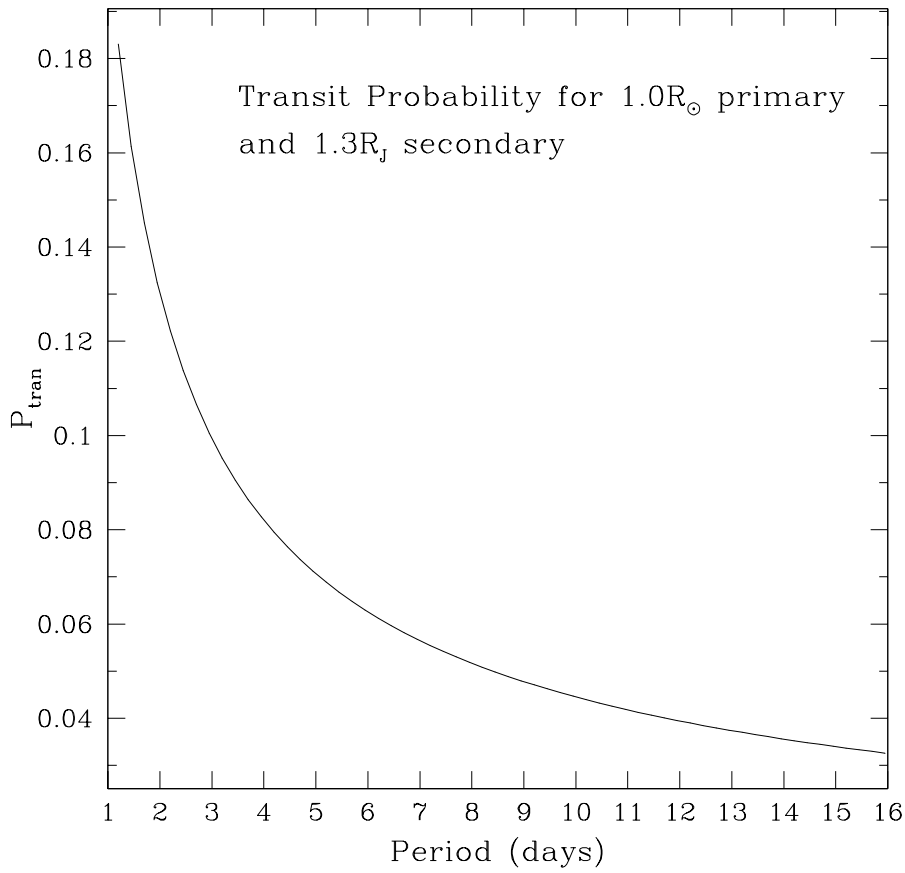

Figure 1.10: The geometrical transit probability as a function of orbital period (P=1-16d), for a star of solar radius and a planet of 1.3 R_J, as derived from Equation 1.3.

This relationship is true when the limit of detection is defined as when the outer edge of the planetary disk just grazes the edge of the stellar disk, and hence the factor of 0.87 is derived from an assumed planetary radius of $1.3R_J$ ($0.13R_*$). Using this relationship, the transit probability of a planet of $1.3R_J$ orbiting a solar radius primary plotted as a function of orbital period (P=1→16d) is presented in Fig. 1.10. It is clear that the transit probability drops dramatically as period increases: at 2d orbital period the probability is 13.0%, whereas at 8d, the probability drops to 5.2%.

The two main observable characteristics of a transit are the depth and duration, shown as d and l in Fig. 1.5. First, we must consider the relationship between length of transit (hours) and stellar parameters, as presented in Gilliland et al. (2000):

$$\tau_{tran} = 1.412 M_*^{-1/3} R_* P_{orb}^{1/3} \tag{1.4}$$

where M_* and R_* are the stellar mass and radius in solar units and P_{orb} is the orbital period of the planet in days, derived from Kepler's third law. This relationship includes a $\pi/4$ reduction in transit duration, and hence is the expected duration for a planet which crosses the 'average' chord length of the stellar disk. A centrally-crossing transit has a duration 1.27 times longer and a grazing transit has a duration 0.66 times shorter than the values obtained from this relationship. Hence, a transit that is oriented so that the planet just fits inside the stellar disk has a duration 0.52 times the value if it was centrally-crossing. These values shall be shown schematically in the transit expectation section of Chapter 5.

The transit depth (in %) can be determined from a simple ratio of the planetary and stellar radii, as derived by considering the maximum fractional change in the observed flux:

$$Dep \sim \left(\frac{R_p}{R_*}\right)^2, \tag{1.5}$$

where R_p is the radius of the planet. This quantity is important for modelling transits and in determining the expected transit recoverability in the dataset.

It is therefore clear that transits present an important tool with which to study extrasolar planets. This method does, however, have its caveats. Planets with longer orbital periods ($\sim$16d) are not as likely to be detected, due to the transit probability decrease. Further, even for planets with short periods this method can only work when the orbital inclination is at the correct critical angle, with only $\sim$10% of the planets being suitable oriented. Despite this, the method remains viable, as the recent results have shown. This method opens up for exploration stars that are too faint and distant for radial velocity study, and given the sheer numbers of targets available for analysis this method will undoubtedly lead to the discovery of scores more planets in the very near future. It is very likely that the transit method will eventually produce more discoveries than any other method currently available to researchers.

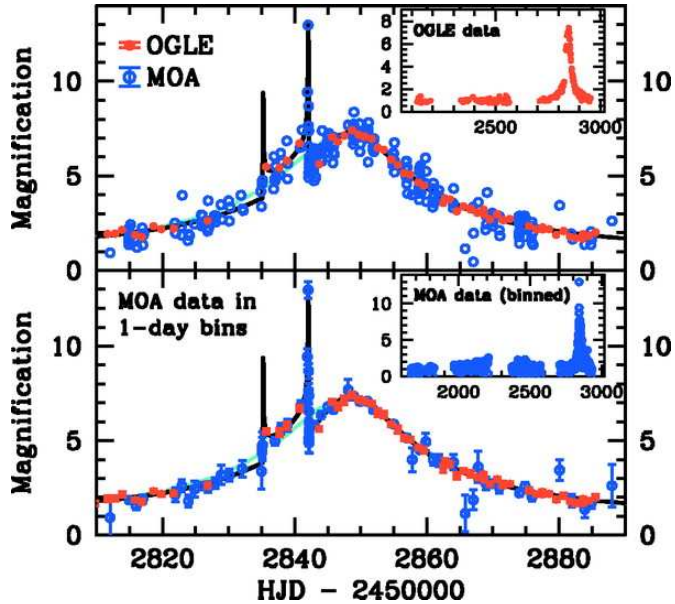

Figure 1.11: The microlensing discovery of the OGLE 2003-BLG-235 planetary system (Bond et al. 2004). The planet is given away by spikes in the microlensing lightcurve signature, and this is best attributed to a planet of mass $\sim$1.5M$_{Jup}$ with an orbital radius of $\sim$3AU.

1.3.3 Microlensing

In addition to radial velocity and transits, microlensing presents a third method which has been used to detect ESPs. Currently microlensing has been used to detect only one planet (Bond et al. 2004). The principle of microlensing is that the light of a background source (a star) is altered by the gravitational field of a foreground source (another star) as the foreground source moves between the observer and the background source. The background star grows brighter during the microlensing as the light from either side of the lens is bent, producing multiple images. These multiple images are typically $\sim$1 milliarcsecond apart, and hence unresolvable from the ground. The photometric signature of a microlensing event is hence a gradual increase and decrease in brightness as the foreground star moves relative to the background star, taking on the order of days to complete. Most importantly for planetary detection via microlensing is the magnification by a planet-bearing star. Clearly, this depends on an extremely critical alignment of the two stars, and many targets must be examined in order for one to be seen.

If a planet (or binary object) is associated with the lensing star, a further effect is seen as the microlensing progresses. A brief magnification disturbance (caustic) gives the appearance of a spike on the lightcurve on one side of the main microlense peak. Analysis of this disturbance gives information about the mass ratio of the binary lensed object. Fig. 1.11 shows just such a disturbance. The microlense signature of this object (OGLE 2003-BLG-235) is best described as having a mass ratio of 0.0039^{+11}_{-07}, and hence the lensing star seems to have a companion that is

very likely planetary in nature. The best fit to these data indicates a planet with mass $\sim$1.5M$_{Jup}$ with an orbital radius of $\sim$3AU (Bond et al. 2004), under certain assumptions about the primary lensing object.

Interestingly, there is one datapoint in this detection that lies below the model by 3.6σ. Such an outlier is not unusual due to the photometric error distributions in crowded fields. Nevertheless if this single point did represent a real lightcurve deviation it could be explained by the presence of a moon in orbit of the planet. Such speculation (Bond et al. 2004) is fuelled by the ability of microlensing to detect objects of extremely small mass at relatively large radial distances from their parent stars.

The advantage of this method is that planets with wide orbits and those of extremely low mass can be detected. However, microlensing has an extremely small success rate, as the planet and star must be exactly aligned for the caustic spike to be detectable. Further, the temporal resolution must be high enough for it to be seen. Nevertheless, $\sim$2000 microlenses have been observed since 1993, and OGLE 2003-BLG-235 is the first planet to be found this way. Unfortunately, current technology does not allow any followup of planets found via microlensing. It is simply a chance alignment that reveals them for a very short period of time, and they will never be detectable again.

1.4 Current Transit Searches

As previously described, transits present an effective method with which to find extrasolar planets. Many searches are currently planned and underway, with results being announced at fairly regular intervals. In order to better introduce the work of this thesis it is necessary to place it in context with some of these current searches.

The general way in which to look for transiting planets is to monitor a specific region of the sky for a long contiguous observing window with a wide field of view. As followup work with radial velocities is much easier for bright stars, small aperture telescopes are perfectly suited to this task. This simple application has been chosen by several ongoing searches. As previously mentioned, the most successful search at the present time is the OGLEIII campaign (Udalski et al. 2002, 2003). Using a 1.3m telescope, rich Milky Way starfields in Carina (Galactic disk) have been observed. At the current time, there are 137 transit candidates, which are the targets of followup work to determine their likely nature.

Using small wide-field telescopes on large swaths of the sky are also being used by other groups. Hidas et al. (2003) (UNSW planet search) are currently using a 0.5m telescope with a $2^\circ \times 3^\circ$ field at Siding Spring Observatory. They are observing many different Milky Way fields and a few intriguing candidates have

been found to the present time (Hidas, private communication). Using this same technique is the STARE group, only they employ a 9cm telescope with a 6.1° square field. Located on Tenerife, this group recently announced the discovery of a transiting planet (Alonso et al. 2004) with data supplemented by two other identical optical systems situated at different parts of the world; PSST in Arizona and SLEUTH in California. Utilizing all three sites gives a much longer contiguous observing window, reducing the gaps in the data caused by daylight and cloud.

Some groups are searching for transits in specific open star clusters. The PISCES collaboration (Mochejska et al. 2002a, 2004, 2002b) is targeting specific, old, metal-rich clusters. Open clusters present a laboratory in which to study the preferential formation of Hot Jupiter planets. All the stars in a given cluster are the same age, and hence if sufficient numbers of planetary detections can be made, a study can commence on how the mass of the star affects planetary formation . Also, sampling clusters of different ages allows insight into the timescales necessary for HJ formation and migration. As far as open clusters are concerned, variable stars have been identified in NGC 2158 (Mochejska et al. 2004), but no transit candidates have yet been found. Three possible candidates have been found in the old open cluster NGC6791 (Bruntt et al. 2003), along with 42 variable stars.

An all-sky transit search has been proposed by Deeg et al. (2004) and is about to start operation. This project (The Permanent All Sky Survey, PASS) has the primary goal of detecting all transiting HJ giant planets in the entire sky, complete for stellar systems V$\sim$5.5-10.5. A further goal is to undertake permanent all-sky tracking of variable stars with high temporal resolution.

Placing a dedicated transit telescope in space would give it a significant advantage over other ground-based searches. The detrimental effects of the Earth's atmosphere will be removed, as well as eliminating gaps in the time series caused by bad weather and daylight. The KEPLER mission (Borucki et al. 2003), scheduled for launch in 2007 has the capability of revolutionising the field of planet transit detection. The expected results of this mission are impressive, 640 planets if most have radii $\sim$2.2$R_\oplus$, based on their transits, and about 870 giant planets with periods less than one week by studying the modulation of the system light as they orbit. Based purely on transits, 135 HJ planets should be detected. Clearly the near future holds many important scientific discoveries.

1.5 Globular Clusters as Laboratories of Planet Formation

None of the transit searches described in section 1.4 deal purely with globular clusters. These objects present us with a perfect opportunity for planet transit detection, being large in apparent size and containing many thousands of stars available for analysis within a single field of view. This thesis deals with the first dedicated ground-based transit search of a globular cluster. A short introduction to these objects is given here, along with the relative merits of using them as targets for planet research. This shall lead into a description of the thesis target, 47 Tucanae.

A globular cluster is a spherically symmetric compact cluster of stars, containing anywhere from several tens of thousands to over a million stars that are all thought to share a common origin. Located outside the main disk of the Galaxy, these clusters populate the Galactic Halo. The concentration of stars increases greatly towards the cluster core, where the stellar density becomes as high as 10^5 stars/pc^3 (Davies & Sigurdsson 2001) (for 47 Tuc). They are among the oldest of all astronomical objects and with this extreme age, comes low metallicity. There is, however, a significant spread of metallicity among the members of the Milky Way globular cluster population (Armandroff 1989), which displays a bimodal metallicity distribution.

The more metal rich clusters tend to be situated closer to the Galactic core, whereas the more metal poor clusters are spread more throughout the Galactic Halo. This is highly suggestive of extended globular formation in the early history of the Galaxy. A total of 150 globulars have been identified in our Galactic Halo, and many more have been found in association with neighbouring galaxies. Harris (1996) presents a comprehensive catalogue of the observable characteristics of a large Galactic globular cluster sample. The most important cluster parameter that shall be referred to in this thesis is the cluster tidal radius. This is the radius from the core at which the gravitational force felt by a given cluster star is balanced by the gravitational force of the Galaxy as a whole. This defines the limit to the radial extent of the cluster. For 47 Tuc, the tidal radius is at 45.9 arcminutes (Leon et al. 2000).

The age of any given globular is usually determined by measuring the mass of the stars that lie at the cluster main sequence turnoff (MSTO) (Bergbusch & Vandenberg 1992). As the cluster gets older, the stars that lie at the MSTO become less massive, as the more massive stars evolve off onto the Red Giant Branch (RGB). These parts of the cluster Colour Magnitude Diagram (CMD) are illustrated in Fig. 2.12 of the next chapter. A good estimate can be made of cluster age by comparing the position of the MSTO with theoretical isochrones for that cluster metallicity and different ages. The model that best fits the observed

Figure 1.12: A colour image of 47 Tucanae, the main thesis target. This image displays a $52' \times 52'$ field of view, the actual field used for the transit search obtained and produced from data taken during the course of this project. The spherical shape and radial extent of this typical globular cluster can be seen.

luminosity function is the one that generally holds the 'correct' age.

Distances can be determined by a number of different methods. Firstly, the brightness of the cluster Horizontal Branch (HB) can be measured. This part of the cluster population is dominated by low mass stars that have lost mass during the red giant phase. They all have the same absolute magnitudes (M_V) and hence are horizontal when seen on the cluster colour magnitude diagram. By measuring the apparent magnitude, the distance can be determined using the absolute magnitude value of the stars in the HB. The HB is typically populated by RR Lyrae stars. These are pulsating variable stars with typical periods of less than a day. As they have the same absolute magnitude they can be used as distance indicators out to $\sim$200kpc. The use of RR Lyraes as distance indicators shall be presented in the variable star Chapter of this thesis, Chapter 4.

A further method of distance determination (and one also utilised in this thesis) is to use contact eclipsing binaries. Described fully in the variable star chapter, this method uses a relationship between absolute magnitude and binary period, unreddened colour, and system metallicity (Rucinski 1993). Clearly globular clusters present us with a laboratory in which to test theories of stellar evolution and

due to their relative closeness to us, can be observed in great detail.

The stars inside a globular are all the same age, hence the same metallicity, and the stellar mass is the only factor which defines the fact that stars are seen at different evolutionary stages. Consequently the stars that still lie on the cluster main sequence (and hence of suitable radius for a transit search) are of low mass (Bergbusch & Vandenberg 1992). With low mass comes a smaller radius, and hence the detectability of a planet transit is somewhat higher for these lower mass stars than in a general stellar sample, in view of the transit depth calculations from Equation 1.5.

As described earlier, planets are seemingly associated with stars of higher metallicity (Gonzalez 1997; Laughlin 2000; Santos et al. 2001; Fischer & Valenti 2003a). Globular clusters are intrinsically low in metal content, and as such present a further test to this metallicity dependence. By considering the metallicity distribution of planet-bearing host-stars, a further estimate of the expected number of planets detectable in these clusters can be made. These expectations are outlined in the 'Planetary Transits in 47 Tucanae' results section, Chapter 6.

Further to the metallicity, globular clusters allow a test to be made of how stellar crowding affects planet formation. The presence of OB stars in the early evolution of a crowded star-cluster can inhibit planet formation. The UV radiation from these stars 'eats' away at protoplanetary disks and stops planet formation before it can even begin (Armitage 2000). This however requires that the massive stars are located very close to the proto-planetary disk bearing stars. Via mass segregation, the more massive stars will preferentially be located towards the core of any given forming cluster. With more distant low mass stars in the outer regions of clusters, these factors, combined with the seemingly extremely rapid planet formation process (Boss 2000), suggest that planets can still form in the cluster environment. Also, this OB radiation effect can be minimised if the formation of high and low mass stars does not occur at the same time. While the OB star effect on planet formation is surely important in the cores of forming clusters, it may not have as big as impact in the outer regions.

Bonnell et al. (2001) undertook a further investigation into the effect of stellar crowding on planet formation. The conclusion was that the disruption of Hot Jupiter planets is unlikely to occur owing to encounters in a stellar cluster, due to the long timescales involved. Planets with long orbital period can, however, be ejected from their parent system. In the core of a cluster with densities $>10^4$ star pc^{-3}, even those planetary systems with semi-major axes of 0.1 AU are likely to be disrupted and only those systems with semi-major axes <0.01 AU are likely to survive. Lower densities typical of the halo of the cluster will leave wider systems (<10 au semi-major axis) intact. Further to this, Davies & Sigurdsson (2001) show that planets with semi-major axes >0.3AU are very likely to survive in the

cluster environment.

In this regard, a null detection of Hot Jupiters in a globular cluster would very likely suggest that the giant planets did not form in the first place. In the cluster halo, stellar encounters are not important for disrupting planet systems, with correspondingly low relaxation times and the planets should survive to the present day, assuming they formed at all. Bonnell et al. (2001) state that planetary systems with very small semi-major axes (<1 au) are generally unaffected by stellar encounters in globular clusters unless the cluster density was extremely large ($>10^5$) for the majority of the cluster's lifetime (10^9 yr).

An estimate can be made of the timescales of planetary survivability if Hot Jupiter planets are found in globular clusters. Clearly, they must have survived for the age of the cluster if they remain to be detected with wide field photometric surveys. This has important consequences for planetary migration theory. It is an open question whether HJ migration halts at some specific radial distance from the star, or whether the planet is finally absorbed by the star after a certain length of time (Basri 2004). This question should be answered when a statistically large sample is probed by current transit and radial velocity searches. If planets are found in globulars, this places a lower limit on the timescales necessary for planet accretion onto its host star, at least in that environment.

A further question is whether planets preferrentially form in association with stars of a certain mass. As the stars in a globular are all the same age, if planets are found their presence can be tied to other properties such as mass of their host stars. High mass stars are generally thought to be associated with more high mass planets, due to the high mass protoplanetary disks having a higher accretion rate. It follows that low mass planets are more likely to be found in association with low mass stars (Alibert et al. 2004; Butler et al. 2004). Another way to address this question without the added complication of the low metallicity inherent to globulars is to search for transits in selected open clusters (Mochejska et al. 2002a,b, 2004).

By considering these factors, globular clusters present an interesting laboratory in which to search for transiting planets. Both a successful detection and a significant null result would offer important astrophysical insights into the formation and evolution of Hot Jupiter planets in a crowded, low-metallicity stellar environment. Indeed, one globular cluster transit search has already been undertaken (Gilliland et al. 2000), the results of which could have large ramifications for planetary formation theories. The search presented in this thesis is complementary to that search, and by combining both results, important insights can be gained into planet formation in these clusters.

1.5.1 47 Tucanae

As globular clusters go, only a handful are sufficiently close and bright enough to allow photometric analysis at the level needed for Hot Jupiter planet detection. The Southern Hemisphere contains the two brightest globular clusters in the sky, ω Centauri and 47 Tucanae. In order to best address the question of HJ planet frequency in globulars, the cluster 47 Tucanae was chosen. In terms of metallicity, 47 Tuc is metal-rich as far as globular clusters go ([Fe/H]=-0.76) (Harris 1996), although very metal poor compared to the Solar Neighbourhood. As metallicity is clearly important for planet formation, 47 Tuc presents an excellent opportunity, and is the main target to be analysed in the course of this work, as is now explained.

A long contiguous observing window is needed to maximize the probability of a detection. As such, a target had to be chosen that has an excellent observability from Siding Spring Observatory, where the observations were made. In its respective season, 47 Tuc is observable for the whole of the night. With more data points covering the duration of the transit, the significance of the detection increases, and hence the need to observe cluster for as long as possible. Distance from the moon during its monthly wanderings is also important. As moonlight drowns out faint stars, the further away from the moon's path the target is, the better.

Lying at a large Galactic latitude (b=$-44.89°$, Harris (1996)), 47 Tuc does not have a significant amount of foreground contamination from the Galactic disk. The reddening is estimated to be E(B-V)=0.04 (Harris 1996). It is, however, located some seven degrees North West of the Small Magellanic Cloud (SMC), and as such the field contains significant background contamination from this object. A variability study of 47 Tuc will therefore have the added bonus of containing variable objects located in the outer regions of the SMC.

The distance to the target must also be considered. It follows that the closer a cluster is to us, the brighter the suitable main sequence stars will be, and hence the higher the chance of obtaining photometry of suitable quality. Also, a closer cluster will present a physically larger extent on the sky, making the best use of wide-field detectors. Considering these factors, 47 Tucanae is a perfect target. It lies at an estimated distance of 4kpc (Harris 1996; Kaluzny et al. 1998; Percival et al. 2002), and hence has a MSTO at V=17 (Hesser et al. 1987). With small-to medium-aperture telescopes, it is possible to readily obtain suitable photometric accuracy for a transit search with short exposure times. These short exposure times are important, as the temporal resolution of the dataset must be maximized as much as possible since a transit generally only lasts for 2 hours or so (Charbonneau et al. 2000).

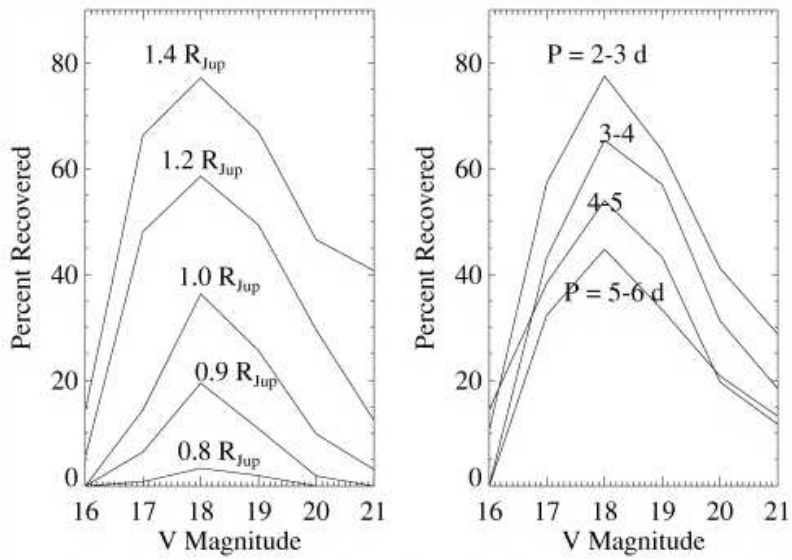

Figure 1.13: The expected planet recoverability in the HST 47 Tuc transit search, taken from Gilliland et al. (2000). This plot shows the ability of the HST dataset to display visible transits, and highlights the significance of this null detection. The left panel shows the recoverability of planets of various radii, whereas the right panel shows the recoverability of a planet of $1.2R_J$, both as a function of apparent brightness of the host star.

Due to its closeness to us and the fact that 47 Tuc is a massive cluster, this target presents the perfect opportunity to sample many thousands of main sequence stars in an area of the sky small enough to fit on most wide-field detectors. Hence the whole of the visible extent of the cluster can be sampled in a single exposure. Just how many planets this cluster can possibly contain shall be described in detail in Chapter 6.

1.5.2 The HST 47 Tuc Transit Search

In 2000, the Hubble Space Telescope (HST) observed 47 Tucanae for a total of 8.3 days in order to search specifically for transiting Hot Jupiter planets. Placed in the 'scientifically risky' category, that work hoped to gain an insight into HJ frequency in the cluster. Comprising the first-ever transit search in a globular cluster, the result was one that could have large ramifications for planet studies.

The HST was pointed at a field directly on the core of the cluster, hence increasing the number of stars to sample and also the expected number of planets. The dataset comprised time-series lightcurves for 34,090 cluster main sequence stars. Fig. 1.13 shows the expected recoverability of transits involving planets of different radii, as well as the recoverabilty of a $1.2R_J$ planet at different orbital periods, as a function of V magnitude in that dataset. Distributed among this dataset should be $\sim$17 detectable HJ planets, a number resulting from Monte Carlo simulations, if the formation rate of HJs is the same in the core of 47 Tuc as

it is in the Solar neighbourhood. A full analysis revealed ~75 variable stars, but no planetary transit candidates. This provides a null detection with extremely high statistical significance, indicating that planet formation is inhibited in the core of the cluster. This could be caused by the crowding, the low metallicity, or a combination of these or other factors.

By observing the core region of the cluster the numbers of stars analysed can be maximized, and this field was chosen for this reason, especially as the HST only provides a small field of view. An extension to this project is needed to help uncover the reasons why the planets are more rare in this cluster than in the Solar Neighbourhood, and to remove crowding (or verify it) as a viable reason for a null detection. As the crowding is highest in the core, it follows that by performing a wide-field ground-based search of the cluster that is most sensitive to the uncrowded outer halo of the cluster, where planets are more likely to exist, the question of Hot Jupiter formation in the cluster environment can be further addressed.

If planets are found in the outer regions of the cluster, this would argue that the crowding is responsible for the Gilliland et al. (2000) null result. However, if no planets are found, then this would suggest that system metallicity is the dominant factor inhibiting planet formation in 47 Tuc as a whole. If metallicity is found to be the key to planetary formation in the cluster, this would have important consequences on the metallicity scale needed for HJ formation, limiting the places in which these planets can form. This would show that system metallicity has to be higher than ≈-0.76 dex for planets to have a significantly higher probability of forming.

1.6 Main Thesis Aims and General Overview

This thesis aims to provide observational constraints on the formation and survivability of Hot Jupiter planets in globular clusters, in particular 47 Tucanae. By observing, from the ground, a wide field centered on the cluster, this thesis complements the work of Gilliland et al. (2000) and determines whether system crowding or metallicity is the dominant factor controlling planet formation in the cluster environment. As the Gilliland et al. (2000) results showed, the formation of such planets is significantly inhibited in the cluster core. As described above, the core is perhaps the worst place in which to look, considering the huge stellar crowding $>10^5$ star pc^{-3} (Davies & Sigurdsson 2001) present there (the choice was dictated by the small field of view of the HST).

This work addresses the question by measuring the Hot Jupiter frequency in the cluster halo, and comparing it to the core result. This requires a long contiguous observing window and suitable photometric accuracy for a large enough

ensemble of stars in order to place statistical significance on the results. Contained within this thesis is a complete description of the work undertaken along with the resulting astrophysical interpretation.

The next chapter (Chapter 2) deals with a description of the observations carried out for this project, along with a description of the data reduction and telescope details. This will allow discussion of the relative merits of this particular optical system and dataset for meeting the thesis aims. Chapter 3 will describe how the photometry was derived, along with a description of a periodogram used to search the data for variable stars. Chapter 4 presents the catalogue of variable stars identified as a by-product of the transit search. One hundred variables were identified, 69 of which are new discoveries. This sample allowed interesting results to be uncovered which shall be presented in full. Chapter 5 presents an extensive discussion of the transit-finding algorithm developed and tested to search the data for transit-like events. Chapter 6 presents transit results, and Chapter 7 combines all the results into the main astrophysical interpretation. The main conclusion, summary and description of future work are presented in Chapter 7. Finding Charts for all variable stars discovered in the 47 Tuc field are presented in Appendix A.