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The STARBASE Network of Telescopes and the Detection of Extrasolar Planets

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Abstract. A network of longitudinally spaced imaging telescopes is described. Due to the limitations of the radial velocity method extrasolar planets have only been found around bright stars (less than 10 mag). Employment of the network and the photometric method to detect extrasolar planets will lead to the discovery of extrasolar planets at much fainter magnitudes (less than 19 mag).

1. Introduction

In the past few decades, significant advances have been made in our understanding of how stars and planetary systems are formed. In the last few years both extrasolar planets and brown dwarfs, whose masses are between those of planets and stars ($10^{-3}M_{sun} < M < 0.1M_{sun}$) have been found. Most stars (60 to 95%) are not single stars like the sun, but are found in binary systems. The theory of binary star formation is too rudimentary to make conclusions about possible associated planetary systems. However, our theoretical understanding leads to the profound conclusion that planetary systems should be found around virtually every single star. This connection is so strong that if planetary systems around single stars are not found it means that the basic tenets of the theory of star formation need to be revisited. Thus, the existence of planetary systems represents a test of the theory.

A number of different techniques to detect extrasolar planets are currently being employed or in the planning stages. They are: astrometry, spectroscopy (two approaches - radial velocity and line identification), photometry, the monitoring of pulsar periods, and high spatial resolution imaging (both optical and infrared). All extrasolar planets discovered to date ($\sim$ 55) have been found with the radial velocity method.

The radial velocity approach involves the measurement of the back and forth motion of the parent star in the radial (line of sight) direction due to the gravitational attraction of the planet on the parent star. It yields only minimum masses and orbital information. In order to determine the chances of extraterrestrial life however, we need to know the physical properties of an

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extrasolar planet - radius, density, surface gravity, temperature, etc. With a network of robotic imaging telescopes, Western Kentucky University (WKU) and Planetary Science Institute (PSI) astronomers will work to detect extrasolar planets using a different approach - the photometric method, which can lead to the determination of the above mentioned physical quantities.

2. The Photometric (Transit) Method

The photometric or transit method involves the measurement of the decrease in stellar brightness due to the transit of a planet in front of the parent star. The decrease, ΔI, in brightness, I, of the star is given simply by the ratio of the cross-sectional areas of the planetary, R_p^2 , and stellar disks, R_s^2:

$$\frac{\Delta I}{I} = \frac{R_p^2}{R_s^2} \tag{1}$$

The shape of the transit curve, that is $\Delta I(time)$, is determined by five quantities: Planetary radius, stellar radius, stellar mass, orbital inclination and limb darkening. Normally one can assume that the stellar quantities (radius, mass and limb darkening) - are relatively well known. The unknown quantities of planetary radius and orbital inclination are then derived from the best fit to the transit curve.

3. History of Extrasolar Planet Searches

The basic idea that a planet transiting a parent star could be a cause of a decrease in the brightness of a star goes back to at least the middle of the nineteenth century (Lardner 1858). Last century Sturve (1952) revived this idea and it was studied by Huang (1963). But it was first Rosenblatt (1971) who developed a viable approach. He suggested a system of three wide-field, widely-spaced, robotically-controlled, photometric telescopes. Our approach (some thirty years later) is basically a realization of the Rosenblatt method. It was kept alive by Borucki and Summers (1984) and others in the intervening years.

It was however Mayor and Queloz (1995) using the radial velocity approach who first succeeded in detecting planets around ordinary stars. They found most unexpectedly a probable Jupiter-mass planet in a 4.2 day orbital period around the G2V star 51 Pegasi. The distance of the planet from the parent star is only .05 AU, far closer than Mercury is from the sun (.39 AU). Rosenblatt expected to find only $\sim$ 1 planet/year. However, the presence of large planets ("hot Jupiters") in short period orbits means that the likelihood of detecting planets is significantly higher.

Because the radial velocity method can only derive minimum masses from observations, it was not completely clear that the tens of probable Jupiter-mass bodies discovered where actually planets until 1999. Employing the photometric method Henry et al. (2000) and Charbonneau et al. (2000) found a transiting planet. Charbonneau derived the radius, mass, density, surface gravity, and orbital inclination for the planet orbiting the parent star HD209458, which had been previously discovered by astronomers using the radial velocity method.

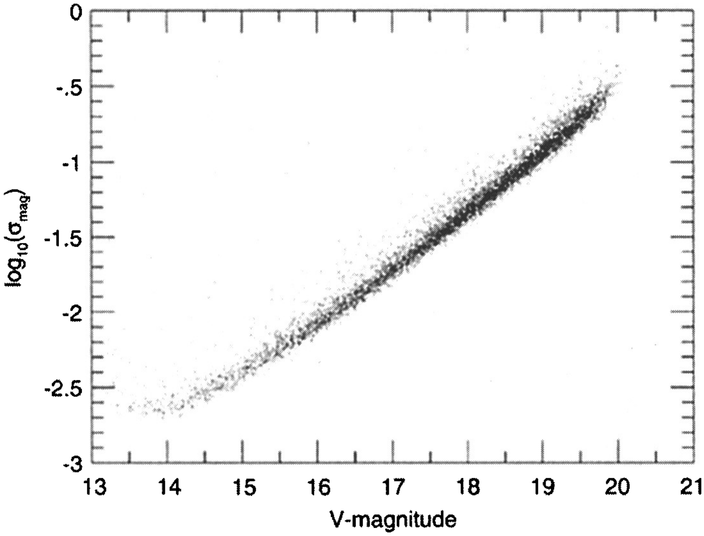

Figure 1. The log of the calculated uncertainty in each star's light curve vs. V magnitude of the star. The data comes from one of the CCDs of the KPNO 0.9 m mosaic camera. The best precisions are 0.0019^{m} (V$\sim$ 14.2 – 14.8). The variable stars are easy to pick out as they lay above the main concentration of the plot. The best theoretical precision for this CCD and telescope combination is 0.002^{m}.

Now that Henry and Charbonneau have successfully applied the transit method, the PSI and WKU will employ it to discover previously unknown extrasolar planets.

4. Photometric Precision

According to Equation (1) a transit of a Jupiter-like planet in front of a sun-like star produces a 1% (0.01 mag) decrease in the stellar brightness. Ground-based stellar photometry can easily achieve this precision. Therefore, such a transit is detectable using ground-based telescopes. In fact, PSI and WKU will undertake a program of photometrically monitoring field stars in search of these amplitude variations, as described in the following sections. We will show below that we expect to achieve an order of magnitude higher precision ($\sim$ .1%, 0.001 mag) with the 1.3 m telescope at the Kitt Peak National Observatory (KPNO) for our brighter stars ($V \sim 14$ mag).

Figure 1 presents the photometric precision of observations from Everett & Howell (2001). The observations were made at KPNO on the NOAO .9 m telescope using the wide-field MOSAIC CCD Camera on 16-20 March 2000. They determined their photometric precision by calculating the standard deviation, σ, of each star's light curve over the five nights of observations. In Figure 1, $\log_{10}\sigma$ is plotted vs. the mean V magnitude of the light curve. Each point in

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the figure represents the standard deviation from the light curve mean based on all their single 3-minute integrations over the five nights of observations. No light curve averaging has been done.

For the brightest stars in Figure 1 (V$\sim$ 14.2 – 14.8) a precision of 0.0019 mag (0.17%) is achieved. This agrees well with the best precision (0.002 mag) that is theoretically possible (from Poisson statistics) for this telescope, exposure time and CCD detector. Everett and Howell achieved this through application of differential ensemble photometric techniques as pioneered by Howell et al. (1988).

The attainment of the theoretical limit of photometric precision means that all sources of systematic errors have been eliminated. This is achieved through careful application of differential photometry. Specifically, careful data reduction, use of high-quality hardware, good observing techniques, and proper error assignment to each data point (not an approximate value assigned to some mean datum) essentially eliminates instrumental errors and random effects. Now that we have demonstrated we can obtain the limit of theoretical precision as given by Poisson statistics, we consider the 1.3 m telescope located at KPNO, which we will refer to as the RCT.

For a 2-minute integration using the RCT, saturation will occur at $V \sim 14.3$ mag. Compared to the mosaic data (Figure 1) the much deeper CCD well depths of the RCT will allow not only a higher precision but also a larger overall dynamic range in which Jupiter-sized planets can be detected. For the RCT this range is 5 magnitudes as opposed to only 2.5 magnitudes for the mosaic. This larger magnitude range greatly increases the total number of stars we can search for transits (McGruder et al. 2000).

5. Types of Detectable Planets

Now that we understand the precision we can obtain in CCD photometric measurements we turn to the question of what types of planets can we detect with this precision. We will show that not only Jupiter-size (both hot and cold), but also Neptune-size and even earth-size planets can be detected via the transit method.

In Figure 2 the relationship between main sequence spectral type and relative transit depth, $\Delta I/I$ (as given by equation 1) for different planetary radii is shown. We consider four planetary radii - hot Jupiter ($1.3R_J$), cold Jupiter (R_J), Neptune ($.34R_J$) and Earth ($.09R_J$). We have chosen to use $1.3R_J$ for hot Jupiters because this value agrees with the only radius of a hot Jupiter that has been measured (Charbonneau et al. 2000). However, theory (Guillot et al. 1996) indicates that R for hot Jupiters can go up to just shy of $3R_J$. Thus, our predictions may be conservative.

So far no extrasolar planets have been found around stars with $R_s \geq 1.2R_{sun}$. This is a limitation of the radial velocity method. Figure 2 makes clear that the transit method can detect "hot Jupiters" revolving around stars up to $R_s \approx 4R_{sun}$ (spectral type: B).

To date no extrasolar Neptune-sized planets have been discovered. This is because the radial velocity method cannot detect planets with $M \leq M_{Neptune}$. However, from Figure 2 it is apparent that the transit method is capable of de-

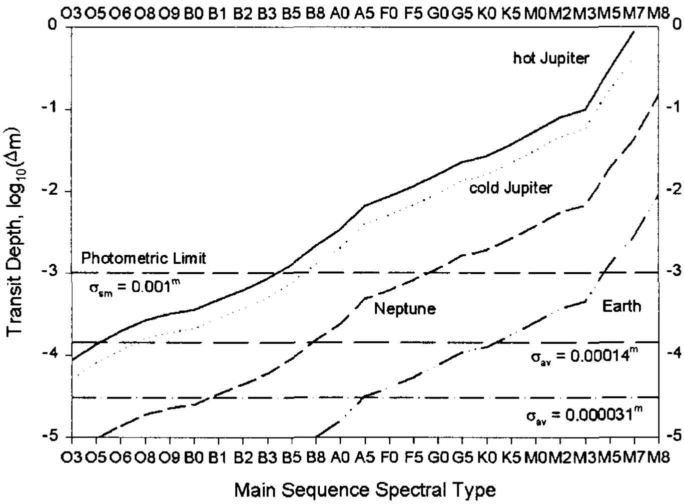

Figure 2. Transit Depth vs. Main Sequence Spectral Type. Three photometric limits (horizontal lines) are shown - precision for a single RCT measurement ($\sigma_{sm} = 0.001^{\rm m}$), an average over all measurements made in a single transit window ($\sigma_{av} = 0.00014^{\rm m}$) and an average over all transit windows during an entire observing season ($\sigma_{av} = 0.000031^{\rm m}$).

tecting Neptune-sized planets revolving around stars with $R_s \leq 1.1R_{sun}$ (spectral types: G, K and M). Thus, since Neptune is the smallest of the gas giants of the solar system, the photometric approach can detect all types of the solar system gas giants.

Most importantly Figure 2 makes clear that earth-sized planets can be detected via the photometric method. In fact, apart from the microlensing approach the transit method is the only ground-based method capable of detecting earth-sized planets. However, for single measurements this is only true for $R_s \leq\sim 0.3R_{sun}$ (late type M stars). And there are two caveats: Firstly, there may be relatively few late type M stars found down to the limiting magnitude of our search (19 mag). Secondly, these stars exhibit intrinsic photometric variability and we must learn to differentiate between their stellar variability and that caused by a planetary transit.

5.1. Time Averaging and Planet Detection

The types of planets that can be detected with the photometric method depends upon the precision achieved. Time averaging allows one to obtain significantly higher precisions. Consequently, smaller planets or planets at earlier spectral types can be detected. This higher precision is achieved however at the loss of time resolution. We will consider two extreme cases.

First we consider averaging all of the points of a single transit curve. This means no time resolution at all. That is, the actual transit curve cannot be determined, only whether a transit exists or not. Thus, the planetary radius derived will not be very accurate. We consider an RCT exposure time of 2 minutes with a readout time of 1.5 minutes. Thus, the sampling time is 3.5 minutes. A "hot Jupiter" requires about 3 hours to transit. Thus, 51 measurements take place in the 3 hours. The precision achieved is .001/(51)1/2 = $.00014^m$. Figure 2 also shows this photometric limit, 140 mmags. One sees that earth-size planets may be detected around K stars; Neptune-size planets around B and hot Jupiters can be seen even at later type O stars. It will be necessary to compare the results of many periods for a confirmation.

We consider a second extreme case. Averaging over an entire observing season with continuous telescopic observations (via a worldwide network of telescopes). This scenario would mean that there would be no information on the transit curve only on detection of the planet. If we take the observing period to be three months (90 days), a 51 Pegasi like planet with a period of 4.2 days, and again as above a transit duration of 3 hour and a RCT sampling time of 3.5 minutes, then there are 21 transits in the observing period or 1071 observations in the transit widows. Averaging gives a precision of: .001/(1071)1/2 = $.00003^m$. Figure 2 also contains this photometric limit, 30.6 mmags. We see that with this precision Jupiters (both hot and cold) can be detected around all main sequence spectral types. Neptune-size planets up to early B and earth-size planets can be seen even at A type stars. The necessary confirmation must be achieved by comparing the results over a number of years.

The photometric prerequisite of attaining these extremely high precisions is the elimination of systemic errors, which we have showed above, is possible.

6. Probability of Planet Detection

The number of stars, n, with an observable planetary transit at any given instant is (Giampapa 1995):

$$n = \frac{f_p N}{\pi} \left(\frac{R_s}{a} \right)^2 \tag{2}$$

where R_s is the stellar radius, f_p the fraction of stars with at least one planet, N the number of stars in the sample, and a is the orbital radius of a planet. Equation 2 assumes circular planetary orbits. We will use it to estimate the probability of planet detection.

Approximately 3% of solar type stars have giant planets within .1 AU (Cumming et al. 1999). Perhaps 60% of the stars in a field are solar type (late F down to M). Thus about 18 in every 1000 stars will be solar type with a planet.

Clearly, a successful photometric detection is only possible if the planet is in the line of sight (Borucki & Summers 1984). Given that a star possesses a planet, then the probability that the planet produces an observable transit is proportional to the radius of the star and inversely proportional to the radius of the planet's orbit (Koch & Borucki 1996). For a randomly oriented sample of target systems, the probability of a transit is only 0.47% for a Jupiter-size planet in a Jupiter-like orbit. But "hot Jupiters" have a relatively high probability ($\sim$5%, $R_s/a = R_{sun}/.1$ = 0.05) of producing a transit because they are very close to their parent stars. Thus, about 1 in a 1000 stars will have an observable transit.

Now given that a star possesses an observable transit, what is the probability at any given instant of actually seeing the planet in transit? This probability is simply the ratio of transit duration to the orbital period. For a circular orbit this is: $R_s/\pi a$. For a sun-like star this probability is: 0.016. It follows that we have to observe about 100,000 stars at any given instant just to find 1-2 stars with planets that are transiting.

We conclude that in order to find an appreciable number of planets we need to observe a large number of stars *continuously.*

7. The STARBASE Network

The above section makes it clear that we need to observe star fields continuously in order to maximize the number of planetary detections. Obviously, a single telescope cannot observe continuously because stars cannot be seen in the daytime. What is required is a network of longitudinally-spaced, robotically-controlled, imaging telescopes. WKU is in the process of creating such a network. It is called the STARBASE (Students Training for Achievement in Research Based on Analytical Space-Science Experiences) network because students will observe and analyze the data under professional supervision. Initially, the network will consist of three telescopes, which we describe below.

WKU possesses the largest (.6 m), research-grade optical telescope in Kentucky, and one of the largest local facilities of any state or private institution of higher education in the southeast. We already use this facility for student training and research experiences at WKU, and it will serve as the starting point for expanded access by the STARBASE network.

The telescope is located (longitude: 86°36'42.2" W, latitude: 36°55'10.9" N) at a dark-sky site on a rural hilltop about 12 miles southwest of WKU and Bowling Green, a small city with over 45,000 inhabitants. It is a Cassegrain telescope with an $f/11$ focal ratio. Group 128 in Waltham, MA, built it in 1975. The telescope is equatorially mounted and housed in a permanent structure, with an Ash Dome. The primary scientific instrument is an Axiom K-2 thermoelectrically cooled CCD camera, with a field of view of 5' by 7' and a set of BVRI filters. The telescope was refurbished and automated as the initial node of the STARBASE Network by Astronomical Consulting and Equipment, Inc. (ACE).

The most important telescope in the network is the 1.3 m telescope located at the KPNO. In an open competition held last year, NSF and NOAO requested bids for ownership and use of the 1.3 m telescope on KPNO. WKU as the lead institution along with its partners - PSI, Boston University, South Carolina State University, and Lawrence Livermore National Laboratory submitted a proposal. In December 1999 WKU was informed of the success of our peer-reviewed proposal to assume responsibility for the operation of this telescope.

NASA and NSF commissioned this telescope in the 1960's. It was to be the first remote-controlled telescope (and therefore called the RCT) using phone lines for control and data transfer from Tucson. Initially the purpose was to develop techniques for controlling orbiting space telescopes and later it was employed as an attempt to enhance the productivity of moderate aperture telescopes (Maran 1967). We have contracted with EOS Technologies to refurbish and fully robotize this instrument. We still call it the RCT, whereby the letters now stand for "robotically controlled telescope".

We have already purchased a SIT2 2048 X 2048 CCD with pixel well depths of 363,000 electrons, a read noise of 5 electrons, and a quantum efficiency of 80% between 400 and 700 nm. We will be able to image a 20' X 20' field of view with 0.6 arcsec/pixel to provide well-sampled PSFs. The telescope is slated for engineering and camera tests in early 2001, initial science observations and "at telescope" preliminary data reduction in fall 2001, with full operations occurring in early 2002.

Finally, WKU plans to place a robotic telescope (at least .6 m aperture) at the Wise Observatory in Israel. The site (34° 45'48" E, 30° 35'45" N, 875 m altitude, UT+2:00) is about 200 km south of Tel Aviv, located on a high plateau in the central part of the Negev desert, 5 km west of Mitzpe Ramon, a town of 6000.

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