Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. 294, 2003
D. Deming and S. Seager, eds.

Ultra-high Photometric Precision and the Search for Extrasolar Planets

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Abstract. Employing the transit method and the technique of ensemble differential photometry with the newly refurbished 1.3 m telescope on Kitt Peak we will search dense stellar fields to detect extrasolar planets. For a single exposure of a few minutes we will achieve a photometric precision, $\sigma \sim 500$ μmag (0.0005^m) for the brighter stars ($V, R \sim 12^m$) and $\sigma \sim$ 10 millimag (0.01^m) for the fainter stars ($V, R \sim 19^m$). This level of precision will allow us to detect jupiter-sized planets for all stars imaged, but also neptune-sized planets transiting the brighter stars. Our approach enables the detection of extrasolar planets around faint, distant stars ($d <\sim$ kpc). Thus, we will be able to provide statistics on the distribution of jupiter-sized planets outside the solar neighborhood over a wide range of metallicity and age, which is currently unaccessible to spectroscopic radial velocity studies and also to wide-field imaging telescopes.

1. Introduction

To date $\sim$ 100 extrasolar planets have been discovered, all via the radial velocity method. The radial velocity method involves high-precision spectroscopic studies of minute changes in a star's radial velocity, which require a large number of photons. Thus, it can only find planets around relatively bright stars ($V <\sim 11$). Consequently, not being able to detect planets around faint, distant stars, the method can not be currently employed to investigate the distribution of planets outside the solar neighborhood. Similarly, employment of the transit or photometric method with wide-field imaging telescopes of small aperture ($<< 1$ m) can detect only planets around bright relatively nearby stars.

In order to detect planets around distant stars ($d <\sim$ kpc) via the transit method, faint stars must be measured with high photometric precision. As we show below, ultra-high photometric precision ($\sigma < 0.001^m$) can be achieved if the technique of ensemble differential photometry is employed on a meter class imaging telescope. Using this method and this technique with the 1.3 m on Kitt Peak will allow us to investigate the distribution of jupiter-sized planets outside the solar neighborhood and to detect neptune-sized planets around the brighter stars.

2. The Transit Method

If an extrasolar planet passes in front of its parent star, it will cause an apparent reduction in brightness, I, of the star. This decrease in stellar brightness, ΔI, to the first order is given simply by the ratio of the cross-sectional areas of the planetary and stellar disks:

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

where R_p and R_s are the radii of the planet and star respectively. The detailed shape of the transit curve, $\Delta I(time)$, is determined by five factors: Planetary radius, stellar radius, stellar mass, orbital inclination and limb darkening. Normally one assumes the stellar mass and radius as well as the limb darkening are known. In such a case the best fit to the transit curve yields the planetary radius and orbital inclination. Equation 1 makes clear that the success of the transit or photometric method for the detection of extrasolar planets depends crucially on the precision with which we measure ΔI. The greater the precision the smaller the planets we can detect for a given star.

From Equation 1 the transit depth or the differential magnitude, Δm, between the stellar brightness, I, without the planet and the stellar brightness, $I - \Delta I$, with the planet in front of it, is given by:

$$\Delta m = -2.5 \log_{10} \left(\frac{I - \Delta I}{I} \right) = -2.5 \log_{10} \left(1 - \frac{R_p^2}{R_s^2} \right) \tag{2}$$

This equation tells us that the transit depth of a neptune-sized planet in front of for example a late F star is: $\Delta m \sim 0.001^m$. Thus, a photometric precision, σ, for a single measurement of at least 1 millimag is required to detect such an object.

3. Ultra-high Photometric Precision

The above makes clear that a photometric precision of $\sigma < 0.001^m$ is required to detect neptune-sized bodies around a late F star. We refer to this range of precision as ultra-high photometric precision. The maximum precision, σ, achievable in a single measurement is derived from the Poisson distribution (Howell 1993):

$$\sigma = \frac{1.0857}{\sqrt{N}} \tag{3}$$

where N is the number of photons collected. Some astronomers believe that it is not possible in practice to obtain this maximum theoretical precision. However,

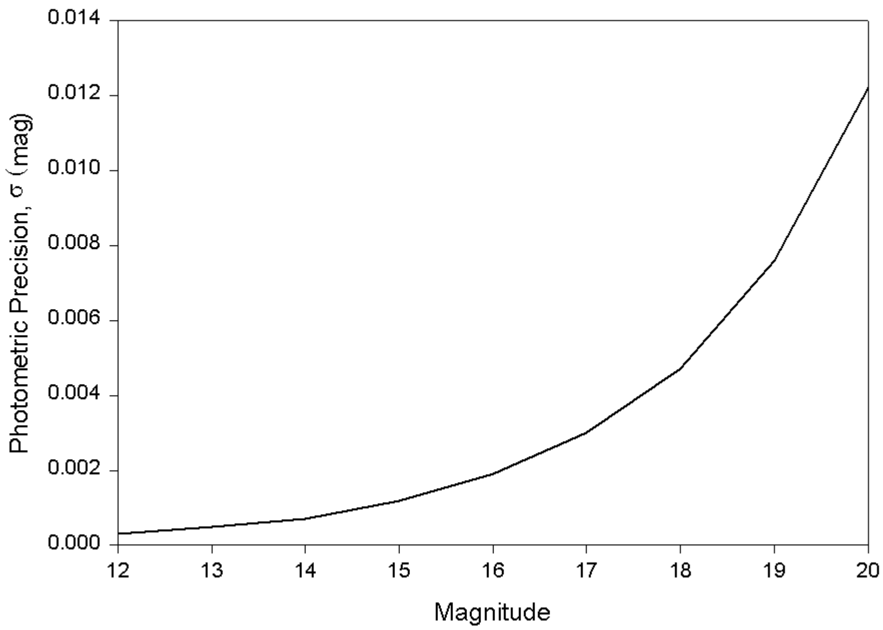

Figure 1. Expected photometric precision (for a single measurement) vs. V or R magnitude for the KPNO 1.3 m telescope (RCT). Integration time is 180 s and seeing is 1".

Everett and Howell (2001) have proven conclusively that careful application of the technique of ensemble differential photometry (Howell et al. 1988) leads to precisions that agree precisely with the above equation for the brighter stars. Thus, ultra-high precision photometry is possible.

What is the optimal telescope required to achieve ultra-high photometric precision? The optimal telescope has an aperture $\sim 1 - 2$ m (McGruder et al. 2003). We will employ the 1.3 m telescope at the Kitt Peak National Observatory (KPNO) for our planet search via the transit method.

3.1. Photometric Precision with the 1.3 m Telescope (RCT)

The 1.3 m on KPNO is called the RCT - "Robotically Controlled Telescope". Western Kentucky University along with the Planetary Science Institute will devote 40-50% of the observing time to the search for extrasolar planets via the photometric method and the data collected will also be used for variable star research too.

We have a SITe 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 10' X 10' field of view with 0.3 arcsec/pixel to provide well-sampled PSFs. The telescope will be fully operational in 2003.

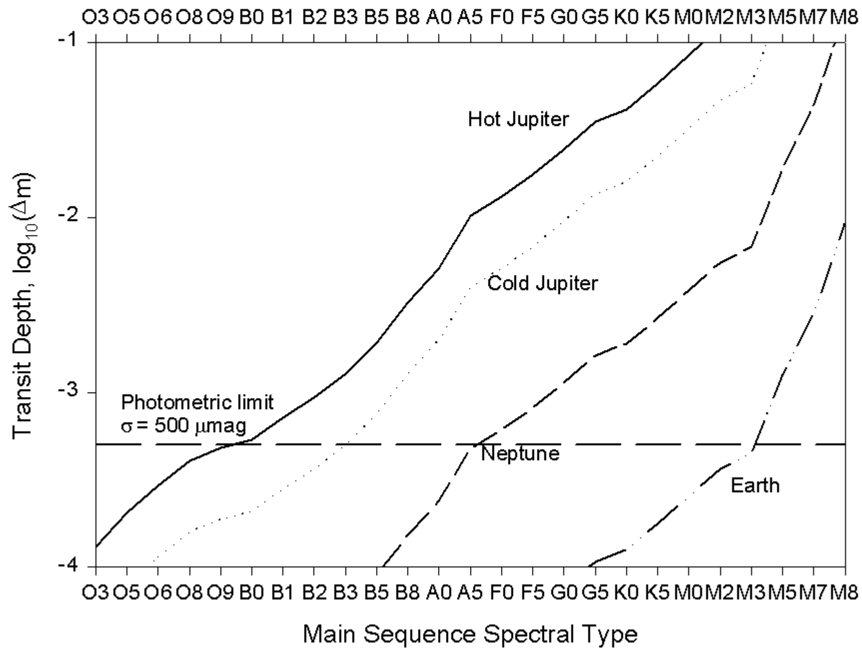

Figure 2. Transit depth vs. main sequence spectral type: the horizontal line is the approximate photometric limit (precision for a single RCT measurement) for bright stars (V or $R \sim 12^m$).

Figure 1 shows the photometric precision for a single measurement we expect to obtain with the 1.3 m RCT. It was computed from the theoretical work in (Howell, 1993) and Merline & Howell (1995), which has been confirmed in observations (see Everett and Howell 2001). The large CCD well depths of the RCT will allow not only high precision but also a large overall dynamic range (over 6 magnitudes) in which jupiter-sized planets can be detected. This large magnitude range means that the total number of stars we can search for transits is large too.

4. Detectable Planets

What types of planets can we detect with the 1.3 m RCT using ultra-high precision photometry? Figure 2 answers this question. It's curves were computed from Equation 2. 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.

Figure 2 makes clear that jupiter-sized planets can be detected over a much wider range of spectral class than is currently possible with the radial velocity method. They can be found for B and A stars as well as early F. In addition Figure 1 makes clear that neptune-sized and earth-sized planets can be detected too. 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 M stars, although higher photometric precisions can be achieved through time-averaging. And there are two caveats: Firstly, there may be relatively few late type M stars found down to the limiting magnitude of our search ($\sim 19^m$). Secondly, these stars exhibit intrinsic photometric variability and we must learn to differentiate between their stellar variability and that caused by a planetary transit.

Finally, we note that with the RCT we will observe more than $30,000$ stars/year measured with $\sigma \leq 0.01^m$.

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Discussing the posters