Photometric Detection of Extrasolar Planets by the Transit Method

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Abstract. The transit method for the detection of extrasolar planets is based on the detection of stellar brightness variations, which result from the transit of a planet across a star's disk. This method is also known as the 'photometric' or 'occultation' method. The transit method is the only method that may lead to the detection of earth-class planets with current technical means. For some stellar systems, detections of planets in the earth-to-Neptune size range may even be possible with ground based 1m class telescopes. Strategies to improve detection probabilities are the observation of large numbers of stars, observation of stars with inclinations close to 90 degrees - especially binary eclipsing stars - and the use of matching filter algorithms to extract sub-noise transit signals. Pertubations in the times of eclipses of extrasolar planets may be used to determine on the prescence of additional planets around the same central star. An overview of current earth-based, as well as planned space based observing programs is given. The transit method may also allow observations of atmospheric features in extrasolar planets, which may be indicative of exobiologic processes.

1. Introduction

The detection of extrasolar planets is one of the most important, yet difficult observational problems in astronomy today. Enormous progress has been made in the last few years, although some detections of giant planets from measurements of Doppler Shifts of the central star are currently disputed. For the foreseeable future this method is, however, limited to the detection of planets with about 10 M_{earth} at a distance of 1 AU (Black, 1996; Borucki and Koch, 1984). Earth class planets, which are defined as planets with 0.5-10 M_{earth} (Borucki et al, 1997), are beyond its reach. Among the methods currently pursued to detect extrasolar planets, the transit method may be the only one to find earth class planets in the near future. The original idea - to detect a star's brightness drop as it is transited by one of its planets - is mentioned in passing by Struve (1952). The first detailed development of the method was done by Rosenblatt (1971), who proposed a network of telescopes to monitor stars for brightness variations and the characteristic color-changes that occur during the transit of a planet. Major later refinements were contributed by Borucki and Summers (1984), and by Hale and Doyle (1994). The transit method is also known as the 'occultation method'. This term is however misleading, as the transit of a planet in front of a much larger star does not constitute an 'occultation'. The term 'photometric method' has also been used. However, this term is very generic, and also describes methods which are *not* based on the detection of planetary transits - for example methods employing the timing of eclipsing binary minima (Doyle et al, 1997).

The detection of earth class planets is especially important, as these are the only ones thought to be able to support life in the universe, if their distance from the central star puts them into the habitable zone (Doyle, 1996, and references therein). Planets smaller then these would not maintain plate tectonic movements (which are essential for the maintenance of an atmosphere) for sufficient time that life can develop, whereas planets too large would have retained their H-He atmospheres and developed into gas-giants. The only other method currently being employed for the detection of earth-class planets attempts to observe gravitational lensing events caused by the planets' passing in front of distant background stars. The major drawback of this method is that gravitational lensing events are unique and no follow-up of a detection will be possible. This is exactly the opposite with the transit method, as transits, once observed, should re-appear with the orbital period of the planet, allowing in-depth studies of known planets with improved future equipment. Lastly, it should be noted, that the transit method is not limited to certain spectral classes (except stars which are not photometrically stable), and can also be applied to binary or multiple stellar system. Of course, the method also has drawbacks, stemming from the high photometric precision needed, and from the obvious fact that a planet needs to cross the line-of-sight between observer and star to cause an observable transit.

2. Description of the Transit Method

The aim of the transit method is to measure the brightness drop of a star, which results from the transit of one of its planets across its disk (Fig. 1). Observation of such a brightness variation can immediately reveal several parameters about the system. In this discussion, the term 'brightness' means the flux that is received from a star.

The depth of the brightness drop, ΔL, and the star's brightness $L_\star$, are approximately related to the radii of the planet and star by:

$$\frac{\Delta L}{L_\star} \approx \left(\frac{R_{pl}}{R_\star}\right)^2 \tag{1}$$

This equation assumes a uniform surface brightness of the transited star. The exact shape of the brightness drop depends on the size ratio of planet and central star, the latitude of the transit across the central star, and the star's limb-darkening. The calculation of the lightcurves of these transits can be performed similar to the lightcurves of eclipsing binary systems; however, since usually $R_{pl} \ll R_\star$, this can be simplified greatly, without a significant loss of precision (Deeg, in prep.). For a central transit across a star with a limb darkening coefficient of 0.6, the maximum of the brightness drop is 25% larger then given in equation (1). Since the limb-darkening of a star is dependent on

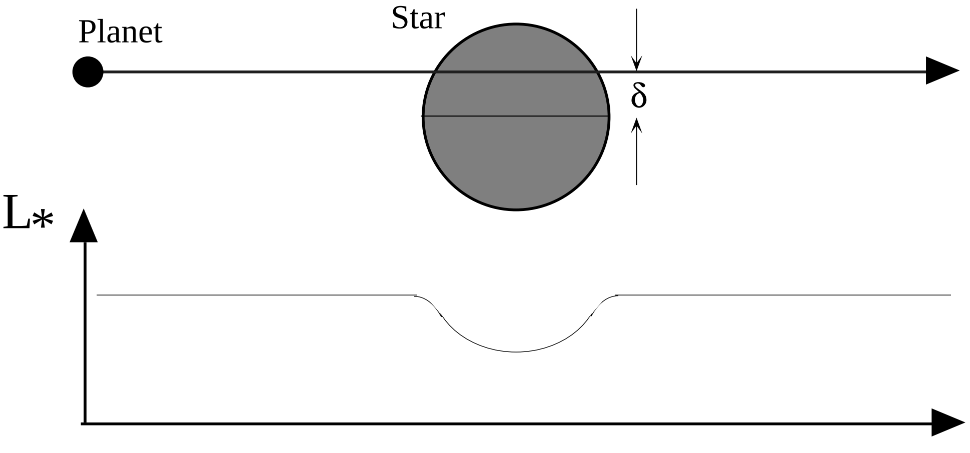

Figure 1. Schematics of the brightness variation caused by a planet transiting its central star. δ is the latitude of the transit on the stellar disk; $L_\star$ is the brightness of the star

the wavelength, a planetary transit event will also cause a characteristic, albeit small, color-change (Borucki and Koch, 1984).

The duration of the transit, t_{tr}, is given by:

$$t_{tr} = \frac{T_{pl}}{\pi}\left(\frac{R_\star \cos(\delta) + R_{pl}}{a_{pl}}\right), \tag{2}$$

where δ is the latitude of the transit on the stellar disk, a_{pl} is the major halfaxis of the planetary orbit, and T_{pl} is the orbital period.

T_{pl} can be determined trivially if several transits, at time intervals T_{pl}, are observed. One may note here, that minor variations of T_{pl} in subsequent transits may allow the determination of orbital perturbations from the presence of additional, non-transiting planets. In actual observing programs, the observation of several transits is desirable, as the repeatability is a key feature for the verification of observed brightness drops as planetary transits. If the radius of the central star is known; e.g. from spectroscopic classification, then the planet's radius can be determined from equation (1). With further knowledge of T_{pl} and the central star's mass, the orbital halfaxis a_{pl} can be derived from Kepler's third law. From the duration of the transit, t_{tr}, an estimate of the latitude δ of the transit can then be done with equation (2). This information can be used to derive the inclination of the orbital plane of the planet, which is given by:

$$\cos i = \frac{R_{star} \sin \delta}{a_{pl}} \tag{3}$$

For an explanation of the geometry, see Fig 2. For the case $\delta = 90°$, equation (3) also leads to the minimum inclination where transits can occur; it is $i_{min} = \cos^{-1}(\frac{R_{star}}{a_{pl}})$. We neglect here the radius of the planet (which will make i_{min} somewhat smaller). In reality i_{min} is somewhat larger, since brightness

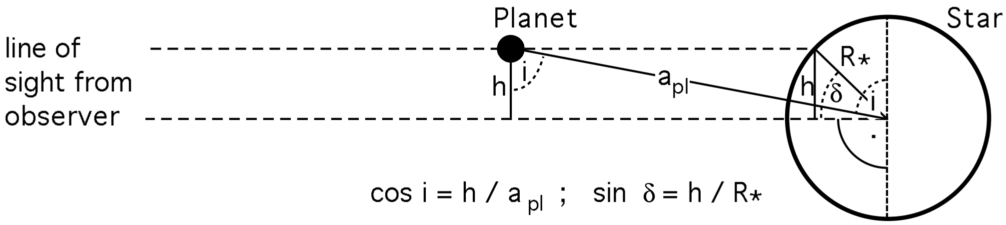

Figure 2. The geometry of a planetary transit, showing the relation between the latitude of the transit across the central star, δ, and the inclination of the planetary orbit, i. The 'impact parameter' h is the shortest projected distance between the planet and the star's center. The observer is at a semi-infinite distance.

variations from transits across latitudes close to ±90° are not measurable, due to the limb-darkening, and are of a very short duration. Also note, that i_{min} for planets *close* to the central star is *lower* then for planets farther away.

Equations (1) and (3) also show the major limitations of the transit method: they are the very small brightness variations, and the need of orbital inclinations very close to 90°. These requirements are discussed in the next two sections:

2.1. Photometric Precision

The diameter-ratio of the solar system's inner planets to the sun is about 1:100. For an external observer, who tries to detect transits of solar system planets, the intensity variations would be:

$$Earth - Sun : \frac{\Delta L}{L} = 8.4 \cdot 10^{-5}$$

$$Mars - Sun : \frac{\Delta L}{L} = 3 \cdot 10^{-5}$$

$$Jupiter - Sun : \frac{\Delta L}{L} = 1.1 \cdot 10^{-2}$$

The photometric stability of the sun on timescales of a few hours to one day (the typical duration of a transit) is $\frac{\Delta L}{L} \approx 10^{-5}$, and therefore presents no problem. The limit of earth bound observations on these time scales is however $\frac{\Delta L}{L} \approx 8 \cdot 10^{-4}$ (Gilliland, 1993). Brightness variations from starspots can be larger, but can be differentiated from planetary transits due to their different timescale, bound to the rotation of the star. Although the transit of Jupiter-sized planets would be easily observable, space-based observations are needed to detect transits of terrestrial planets across solar-type stars. One alternative is observations of transits across *smaller* stars - this is the approach taken by the ground-based observations of the TEP network - the program star is a binary of two M4 stars with a total surface area of ≈ 12% of the sun. Rosenblatt (1971) and Borucki and Summers (1984) also discuss the changes of stellar colors during a transit. This color change, if defined as the change in the flux ratio in two passbands (Borucki and Summers give 0.5 and 0.8 μm), is about 5 times lower then the values for $\frac{\Delta L}{L}$ given above.

2.2. Detectability Limits from Orbital Inclination

For someone observing the solar system from a distance far away, the Earth's orbit needs to have an inclination of more then 89.73° to cause observable transits. The probability to observe transits for randomly oriented system is given by (Borucki and Summers, 1984):

$$p = R_{\star}/a_{pl} = \cos i_{min} \tag{4}$$

If this observer has *no* information about the orientation of the sun (and the solar system), the probability that s/he will detect planetary transits across the sun are:

$$Venus - Sun : 0.65\%$$

$$Earth - Sun : 0.47\%$$

$$Jupiter - Sun : 0.041\%$$

The relative probability to detect a transit of Jupiter is even lower, if one considers that Jupiter transits can occur only once every 11.7 years. This makes their discovery in short observing spans about 100 times less likely than that for terrestrial planets.

In our solar system, the orbital plane of the Earth is inclined 7.6° to the equator of the sun. To evaluate, if time on transit observations of the sun is well spent, the external observer may therefore attempt to measure the solar inclination, as the inclinations of planetary orbits are expected to be within 10° of the inclination of the central star (Hale and Doyle, 1994). The difficulties in deriving stellar inclinations, especially the large uncertainties for inclinations near 90°, have prevented the use of this measure in the planned space based surveys, which will observe large numbers of stars. A special case, where inclinations are known with great precision, are eclipsing binary stars.

2.3. Transits across Eclipsing Binary Stars

Eclipsing binary stars provide us with a special opportunity to employ the transit method, as was first suggested by Schneider and Chevreton (1990). Here we consider the case, that a planet orbits both components of a close binary. By definition, the inclination of the plane of the binary components is close to 90°, and can be measured precisely from an analysis of the binary's lightcurve. Furthermore, a planetary system is expected to have precessionally dampened into the plane of the binary components during its formation (Schneider, 1994a). For suitable eclipsing binary systems, the probability that planets will cause observable transits is close to 100% (Schneider and Doyle, 1995). A further advantage of the observation of binary stars is the unique, quasi-periodic transit signals they would produce. Since the star is double, there will normally be two transits, whose exact shape depends on the phase of the binary system at the time of the planetary transit. Such a signal is well suited to cross-correlation of model transit curves against the observed data, to allow the detection of sub-noise signals (Jenkins, Doyle and Cullers, 1996).

2.4. Detection of O_2 or O_3 in a Planet's Atmosphere

The presence of O_2 and O_3 in a planet's atmosphere would be an indicator for the presence of life (Léger, Pirre and Marceau, 1994), since biologic reactions are needed to sustain the out-of-equilibrium chemical reactions that are producing these components. Schneider (1994b) suggests, that spectroscopic observations of these components - while a planet is in transit - are possible by a 2.4 m telescope with integration times on the order of 10^3 seconds. The same is not possible for planets which are *not* transiting their parent star, as their observed fluxes would only be reflected light, and unrealistic integration times (10^{6-9} secs) would be needed. Planets discovered by the transit method therefore allow diagnostics for the presence of life that are not possible for non-transiting planets.

3. Current and Future Observing Projects

In this section, an overview is given of observational projects based on the transit method. The ground-based TEP network attempts to find planetary transits across an especially well suited eclipsing binary star. Photometric observations of large numbers of stars are the goal of the two space-based projects, COROT and Kepler.

3.1. The TEP network

The TEP (Transits of Extrasolar Planets) network has been observing the eclipsing binary CM Draconis with a network of telescopes in the US, Spain, France, Russia, Greece and Korea since 1994. CM Dra, an eclipsing binary consisting of two M4 stars, is unique in its small size (R_*=0.25, 0.23 $R_\odot$), its low temperature, its nearly edge-on inclination of 89.8 degrees, and its proximity of 16.9pc. These properties are advantageous for the detection of planetary transits for several reasons: In systems of low luminosities and temperatures, it is expected that terrestrial planets will form much closer to the central star (Schneider and Doyle 1995, and references therein) and have periods on the order of weeks, giving a high probability of observing transits in observing runs of moderate length. Second, planetary transits across CM Dra (total surface area: 12% of the sun) would cause brightness drops an order of magnitude larger than the transits of similar planets across stars of solar size. Transit signals of planets with 2.5 earth radii (halfway in area between Earth and Neptune), for example, would produce a drop in brightness of about 0.6%, a precision in photometry that TEP has achieved in observations with 1-meter class telescopes. For the detection of smaller planets (an earth-sized planet would cause a drop of 0.09%), whose signals are hidden in the noise, matched filter cross-correlation techniques (Jenkins et al. 1996) are being employed.

The TEP project has obtained through 1996 a lightcurve of CM Dra containing 560 hrs of observations, in 17000 data points (Doyle et al., 1996; Deeg et al., 1997a,b). These observations contain about 20 brightness variations which are not incompatible with a planetary transit, and whose confirmation is the goal of ongoing observations. Further information about the TEP network can be found in http://www.iac.es/proyect/tep/tephome.html.

3.2. COROT

COROT is a 'small mission' project of the French space agency CNES. It is scheduled for launch at the end of 2001. As its name (= COnvection and ROTation) implies, it is primarily designed for the study of the interiors of solar-type stars through the photometric detection of stellar oscillations; a secondary mission is the detection of extrasolar planets (Deleul et al, 1997). The satellite contains a telescope with a 25cm aperture, whose light is split by semi-transparent mirrors into two colors. For each color, there is a CCD camera which contains two sets of CCDs: one is optimized for the astroseismologic studies, and the other one for the detection of planetary transits. Each covers a field of 1.5 x 3 arcmin. COROT's polar orbit will allow uninterrupted observations of 5 months duration on fields near 0° declination; twice a year it needs to be pointed into the roughly opposite direction to avoid pointing too close to the sun. The field selection criteria will be dominated by the astroseismological studies, and the field-of-view for the exoplanet detection is constrained to an adjacent field within a few degrees. The noise level with an integration time of 30 minutes will be about 10^{-4} for photometry of stars with magnitude $V = 12$. There will be a few hundred stars with $V \leq 12$ in the field of view. However, the noise level to reach earth-sized planets is expected to be obtained for a few 10s of stars only; causing a low probability of discovering transits of earth-sized planets in the habitable zone. The detection probabilities increase significantly for planets that are slightly larger, or closer to their central star. Several detections of planets with 2 earth radii can be expected, if only 5% of all main-sequence stellar systems have these. Further information about COROT can be found at http://lasm0b.astrsp-mrs.fr/www/corot01.html.

3.3. The Kepler Proposal

This mission has been proposed by NASA-Ames for the 'Discovery Program'. It is a telescope of 1m diameter on a heliocentric orbit, dedicated to the discovery of planetary transits (Borucki et al., 1997). The telescope would contain an array of 21 CCDs, with a 12° field of view, and remain pointed at *one* field in the Cygnus constellation for the 4 year mission lifetime. In this field, about 80000 main sequence stars are present, on which photometry with a precision of $2 \cdot 10^{-5}$ (at 5 hrs integration time) can be performed. The parameters of this system are adequate to obtain a reliable mass function of planetary systems, including earth-class planets. If our solar system is typical, the discovery of about 500 earth-sized planets and 25 outer-orbit Jupiter-type planets is expected. About 1000 inner orbit giants (like 51 Pegasus) may also be detected by their reflected light (if they exist around 2% of all MS stars). Unfortunately, the Kepler proposal is currently not selected for realization by NASA. The Kepler web site is at http://www.kepler.arc.nasa.gov

4. Summary

The transit method is the only way to detect extrasolar earth-like planets with current technical means. The photometric stability needed to detect the transits of earth-sized planets across solar type stars is a few times 10^{-5} on timescales of a half day. The probability of detecting transits of terrestrial planets in a randomly oriented planetary system is about 1%. This requires either the observation of large numbers of stars, or the observation of eclipsing binary systems with inclinations very close to 90°, where planetary orbits can be assumed to cross the line-of-sight. This second approach is currently being followed up by the ground-based TEP network. Observations of large numbers of stars are being pursued by the planned space-based missions. The COROT mission, sceduled for launch in 2001, is expected to assess the existence of large terrestrial planets, but lacks sensitivity to detect earth-sized planets in the habitable zone. We will likely need to wait until more sensitive instruments, like the proposed Kepler mission, are flown, to know the frequency and size distribution of earth-like planets. Once transiting planets are found, in-transit spectroscopic observations of key atmospheric features are feasible. These objectives are vital to the estimation of the frequency of life in the universe, and the transit method may be the key to achieve them.

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