Transiting Planets
Proceedings IAU Symposium No. 253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308026185

Ground-Based Photometric Searches for Transiting Planets

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Abstract. This paper reviews the basic technical characteristics of the ground-based photometric searches for transiting planets, and discusses a possible observational selection effect. I suggest that additional photometric observations of the already observed fields might discover new transiting planets with periods around 4–6 days. The set of known transiting planets supports the intriguing correlation between the planetary mass and the orbital period suggested already in 2005.

1. Introduction

The first known transiting planet, HD 209458b (Charbonneau *et al.* 2000; Henry *et al.* 2000), was discovered as a extra-solar planet by the radial-velocity (RV) technique (Mazeh *et al.* 2000; Henry *et al.* 2000). This planet attracted much interest because the observations of the transit in different wavelengths opened up a wide window through which we could study for the first time some planetary features of an extra-solar planet. This includes measuring the planetary mass and radius, studying the planetary envelope (Charbonneau *et al.* 2002; Vidal-Majar *et al.* 2003; 2003) and even deriving the planetary direction of motion relative to the rotation of its parent star (Queloz *et al.* 2000).

Since then two additional interesting transiting planets were found by ground-based observations *after* their discovery as planets by the RV technique. HD 149026 (Sato el al. 2005) with its relatively small radius is one of the very few planets that probably have a metallic, rocky core, and GJ 436 (Butler *et al.* 2004; Maness *et al.* 2007; Gillon *et al.* 2007) is the only transiting planet known with a Neptunian mass and radius.

Although these three systems contributed substantially to our knowledge of extra-solar planets, the bulk of the information we acquired about planetary radii and masses comes from the transiting planets that were discovered by systematic ground-based photometric searches. For these planets, the order of detection is reversed — we first detect transiting planet candidates by photometry and only then confirm their planetary nature by RV follow-up observations.

The photometric search for transiting planets has two types of drawbacks. The first type is associated with the fact that the detectability of transiting planets is limited to only those planets whose orbits cross the disc of their parent stars, as seen from our line of sight. For a given stellar radius, R_*, planetary radius, r_p, and semi-major axis a, the fraction of planets with circular orbits and random orientations that transit their parent stars is

$$\text{Prob(transit)} = \frac{R_* + r_p}{a}. \qquad (1.1)$$

Therefore, the fraction of transiting planets is about 10% at most, even for the hot-Jupiters with periods of the order of 3 days. The fraction goes down to 1% for planets around solar-type stars with periods of about 100 days, limiting the search for transiting planets to short-period planets only.

Fortunately, the short-period planets pose quite a few intriguing open questions, including migration and stopping mechanism, tidal interaction and heating by the insolation of the close-by star. Moreover, the short-period planets compose a substantial part of the known population of the extra-solar planets, as can be seen from Figure 1, which presents an histogram of the known planets found by the RV technique. One can see that the observed frequency rises when going from 10 to 100 days, indicating that the longer the period the more planets we are about to find by RV observations (the drop of frequency for periods longer than 100 days is due to RV selection effects.) In addition, the histogram shows one pronounced peak consisting of planets with periods at about 3 days. This peak is probably caused by the migration mechanism, which apparently prefers to shrink the planet orbits into periods of about 3 days. These planets are the main candidates for being transiting planets. The photometric search, therefore, enables us to study in details this intriguing subset of extra-solar planets.

One other type of drawback of the photometric search for transiting planets is associated with the discovery technique. First, because of the relatively low frequency of the short-period planets and the low percentage of planets that transit their parent stars, one needs to observe many hundreds of solar-type stars in order to discover a transiting planet. In addition, in any field on the sky the solar-type stars are diluted by many early-type main-sequence stars and by giant stars, which cannot possibly show detectable transits. So, on the average, one has to follow of the order of 10,000 stars in order to find one transiting planet.

Second, the expected transit depth is of the order of only one percent and its phase duration is short, of the order of a few hours for a period of 3 days. Therefore, we need many accurate measurements in order to discover the transit. Moreover, variability induced by stellar activity together with observational errors can easily mask the transit minute modulation. Third, many eclipsing binaries, some of which are blended with one more star in the obtained image of the field, disguise as transiting planets. Only RV

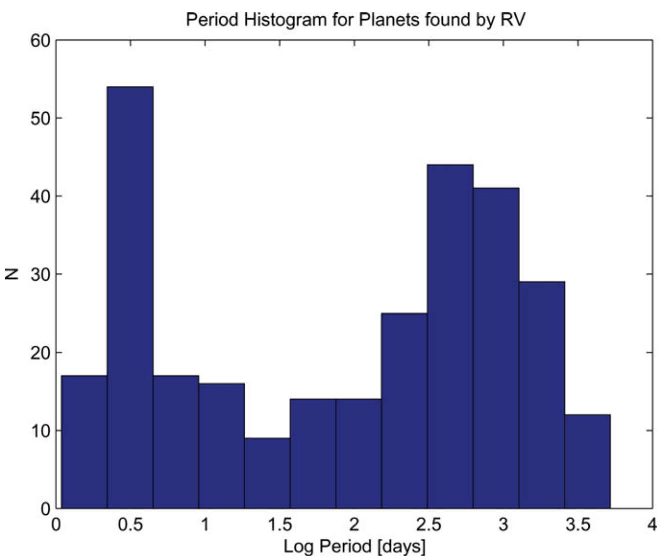

Figure 1. The period distribution of the planets found by RV observations.

https://doi.org/10.1017/S1743921308026185 Published online by Cambridge University Press

observations can lift their mask and discover their true nature. Therefore, the photometric searches depend heavily of RV follow-up observations.

Despite all the drawbacks of the photometric approach, it proved to be very efficient in finding transiting planets. This is so because newly available CCD technology enables us to perform efficient photometric surveys. The size of the new CCDs, some with 4K×4K pixels, enables us to follow the brightness of tens or even hundreds of thousands stars per exposure, the efficiency of the CCDs allows photometric measurements with a cadence of the order of a few minutes, and the precision of the new devices could reach a few millimag for a measurement of a stellar brightness.

However, it seems that the advanced technology of the new CCDs is not enough. The very first years of the photometric systematic searches that followed the discovery of HD 209458b in 2000 yielded much less transiting planets than expected (e.g., Horne, 2003), except the outstanding success of the OGLE team (e.g., Udalski *et al.* 2002a,b; 2003; 2004; 2005; Pont *et al.* 2007a; 2008). Apparently, the proper analysis of the data might also have a role in the success of the photometric search (e.g., Pont *et al.* 2006; 2007b). After some algorithms to search for the transits (e.g., BLS —- Kovács 2002) and to clean the data (e.g., SysRem (Tamuz *et al.* 2005) and TFA (Bakos *et al.* 2005)) were developed, and when new specifically build small telescopes became available for routine observations, the yield of the photometric searches became substantial.

This paper reviews the technical details of present and planned systematic photometric searches (Section 2) and points to a possible selection effect hindering the detection of transiting planets with periods in the range of 4–6 days (Section 3). Finally, Section 4 reviews the accumulated evidence for the intriguing correlation between the mass and the period of the short-period planets.

2. Present and future photometric systematic searches

This section reviews some basic features of present and planned systematic photometric searches for transiting planets, in order to give the grand picture of this endeavor. Making every effort to bring the correct figures relevant to each project, the review is based on correspondance I have had with members of each team.

A short summary is given in Table 1, which lists the name of the project, diameter of the telescope(s) used, size of individual field of view (FoV) observed (in square-degrees), number of CCD pixels used per field, number of telescopes operated by the project, number of fields observed so far, averaged number of measurements acquired so far per field and an estimate of the total number of stars observed so far to a precision of 1% per measurement. Finally, the last column brings the number of planets discovered so far by the project. The number of transiting planets published is given first and then, in parenthesis, the number of planets announced, as of May 2008.

The upper part of the table reviews the presently active projects. It includes five small-telescope projects, which use telescopes with diameters of the order of 10 cm: WASP N&S (e.g., Pollacco *et al.* 2006), XO (McCullough *et al.* 2005), HATnet (Bakos *et al.* 2002; 2004), and TrES (e.g., Alonso *et al.* 2004). The table lists WASP N (north) and WASP S (south) in two separate lines, although they are two parts of the same project. Note that the two parts of the WASP project are covering together about 20,000 square-degrees already, which is about half of the whole sky.

The upper part of the table also lists OGLE (Udalski *et al.* 2002) and ANU Lupus (Weldrake *et al.* 2007), two projects that use 1-m class telescopes for some of their observing nights, and therefore their field of view is of the order of half a square-degree. This should be compared with the large FoV of the small telescopes, which are of the

Table 1. The present and future systematic photometric searches for transiting planets.

	Tel. (cm)	FoV (Sq. deg)	Pixel (#)	Tel. (#)	FoV (#)	Meas. (#)	Stars Observed (#)	mag range (V)	Planets discovered (#)
WASP N	11.1	61	4M	8	200	6,000	1,000,000	13	3+5
WASP S	11.1	61	4M	8	120	10,000	500,000	13	2
XO	10.	51	2M	2	90	3,000	250,000	12	3+2
HATnet	11	100	16M	6.5	50	5,000	500,000	12	7
TrES	10	36	4M	3	19	8,000	50,000	14	4
OGLE	130	0.36	64M	1	20	1000	500,000	16	7
ANU Lupus	100	0.66	60M	1	1	3000	15,000	17	1
HAT S	11	100	16M	24					
BEST	19.5	9.6	4M	1					
BEST II	25	2.9	16M	1					
LAIWO	100	1	64M	1					
ANU skymapper	130	5.7	270M	1					
Pan-STARRS	180	7	1400M	1					

order of hundred times larger. Note also that the 1-m class telescopes detection range is V=16–17 mag, 40–100 fainter than the transits found by the small telescopes.

The second part of the table lists the planned projects, which include one project with small telescopes — HAT S, which will have extremely large observing power; two projects with intermediate telescopes, BEST and BEST II (Kabath *et al.* 2007), with telescopes slightly larger than the small ones; two projects with 1-m class telescopes — LAIWO (Afonso *et al.* 2006) and ANU skymappers (Bayliss & Sackett 2007); and finally the ambitious project — Pan-STARRS (e.g., Afonso & Henning 2007) with a 2-m class telescope.

The small telescopes were built and are operated for detecting transiting planets only, while the larger telescopes were and are used for other projects too. As a consequence, the small telescope observing time is devoted almost completely to the search for transiting planets. Together with their large FoV, this will lead to the coverage of the whole sky in the very near future. We therefore anticipate that the small-telescope projects probably will go back to the already observed fields and add many more observations. As will be suggested in the next section, additional observations might lead to the discovery of more transiting planets.

3. A possible selection effect of the ground-based small-telescope searches

This section discusses the set of transiting planets discovered by the ground-based small-telescope projects and considers a possible selection effect acting against discovering planets with long periods (see discussion by Gaudi *et al.* 2005). A suggestion that such a selection effect is in action might be found in Figure 2, which shows the orbital period of the transiting planets discovered by the small telescopes as a function of their estimated distance from the Sun. Although the distances of the individual stars are not very well known, we assume that the general trend that appears in the figure is correct. Assuming that the distribution of planets in the Solar neighbourhood is constant, the dependence seen in Figure 2 can be attributed only to observational selection effects.

The obvious assumption would be that the selection effect observed in Figure 2 is due to the fact that the photon noise, which is one of the major factors of the observational

https://doi.org/10.1017/S1743921308026185 Published online by Cambridge University Press

noise for small telescopes, is larger for more distant, and therefore fainter, systems. For the more distant transiting planets we need more observations to occur within the transit in order to detect the small periodic drop of the stellar brightness. On the other hand, it is more difficult to discover transits with longer periods because of two effects. First, the number of individual transits actually observed for a given observational time span is inversely proportional to the length of the period. Second, the phase of the transit, f, which can be written for a circular orbit as

$$f = \frac{R_*}{\pi a}, \tag{3.1}$$

is shorter for longer periods. Therefore, for a given number of observational points, the number of points within the transit is a decreasing function of the period. Both effects make transiting planets with longer periods more difficult to discover, and therefore their detection threshold brighter.

This can also be seen in Figure 3, which shows the orbital periods of the detected transiting planets as a function of the magnitude of their parent stars. The very clear dependence supports the assumption about the selection effect.

One possible prediction that might be drawn from the suggested selection effect is that the small-telescope projects might find additional transiting planets if they go back to the fields already observed and increase substantially the number of observation per star. The additional observations might fill up, for example, the parameter space in Figure 3 with period range between 2 and 5 days for stars fainter than 12 mag.

4. The mass-period relation for the very short-period planets

Mazeh *et al.* (2005) already noticed a correlation between the mass of the transiting planets and their period (see also Gaudi *et al.* 2005). As that suggestion was based on only six transiting planets known at that time, it is of some interest to revisit the mass-period diagram and see if the correlation still holds. To do that we plotted in Figure 4 the

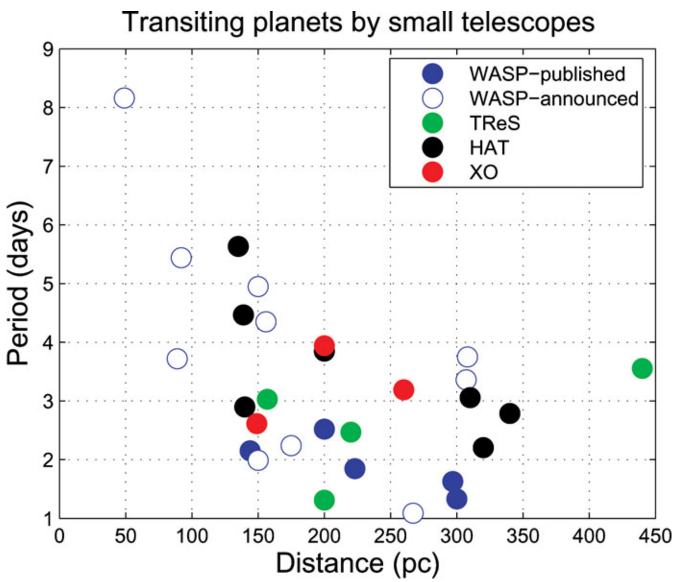

Figure 2. The orbital period of the transiting planets discovered by small telescopes as a function of their distance from the Sun.

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derived masses of the known transiting planets as a function of their orbital periods. The figure shows all transiting planets discovered by photometry, including the ones detected by OGLE. One can see clearly that the correlation still holds.

The astrophysics behind this correlation is not clear. One could argue that if a planet gets too close to its parent star, the stellar insolation tends to evaporate the planetary atmosphere. Therefore, only planets with large enough masses and therefore large surface gravities can survive at short distances from their parent stars. However, this argument only explains why there are no planets with small masses *and* short periods, but cannot explain why there are almost no planets with large masses *and* long periods.

5. Discussion

The ground-based systematic photometric searches for transiting planets have proven themselves to be observational projects with high yield. With relatively small investment of resources they are producing a flux of transiting extra-solar planets. To estimate the efficiency of the photometric searches, it might be of interest to compare the number of planets discovered by photometry with the number of planets discovered by RV technique (Gaudi *et al.* 2005). This is done in Figure 5, where the number of planets discovered by photometry *divided* by the number of planets detected by RV observations is plotted in period bins of one day. In the first bin, which presents the ratio of planets found in the range of [0.5, 1.5] days, this ratio is 3, which indicates that the photometric search is more effective than the RV technique. However, this ratio drops dramatically for longer periods. As can be seen in the figure, this ratio is about 0.5 for periods longer than 2 days.

We do expect this ratio to fall off for longer periods because of the geometrical effect (see Equation 1.1). However, it seems as if the drop is sharper than expected. To see that this is the case the figure shows two possible simple-minded analytic models of the

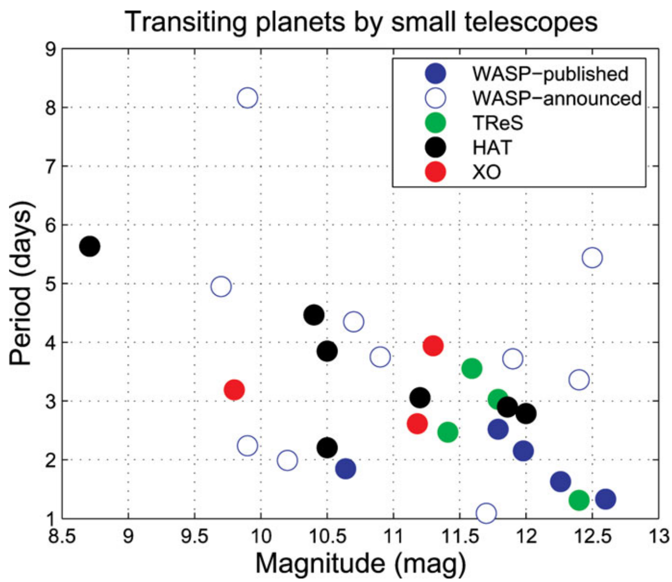

Figure 3. The orbital period of the transiting planets discovered by small telescopes as a function of the their parent star brightness.

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expected ratio between the photometric discovered planets and the ones detected by RV observations, one with $P^{-1/3}$ and the other with $P^{-2/3}$ dependence. The latter presents the geometrical effect of the transiting planets only, while the former tries to take into account the selection effect of the RV technique too, which is also less effective for longer periods. To calculate the expected number of RV detections we need a much more detailed study, which takes into account the mass-period distribution of the population of the planets as a whole (Gaudi *et al.* 2005), beyond this short review. If we naively assume that the RV detection efficiency is proportional to the RV amplitude, which goes like $P^{-1/3}$, then we may deduce that the expected ratio of detection should vary like $P^{-1/3}$ too. We therefore expect the actual ratio of the two sets of planets to be somewhere between the two dashed lines in the figure. The figure suggests that the actual ratio is much smaller than expected for periods of 3–6 days. This is consistent with the suggested selection effect discussed in the previous section. We expect this ratio to substantially improve with more photometric observations per star.

As the photometric searches become more and more efficient, more RV resources are needed to identify the true transiting planets. As these resources (e.g., Bouchy *et al.* 2006) are rather limited, the bottleneck of the ground-based photometric searches might soon be the RV follow-up observations (e.g., Pont *et al.* 2008). The problem is enhanced by the fact that the small-telescope projects choose their exposure time so that their detection will be most effective for stars of about 12–13 mag. This causes the transiting planets discovered by photometric search to be relatively faint, and therefore more difficult to follow by RV observations.

One way to overcome this problem is to set a follow-up program consisting of a few stages. In the first stage the candidates would be observed by a relatively low-resolution spectrograph (e.g., Latham 1992) to weed out obvious false candidates. Most of the short-period binaries and the blends would be detected and rejected in this early stage of the follow-up program. Only the good candidates would then be observed with high-resolution spectrographs to prove the planetary nature of the unseen companions and to derive their masses. Such a mode of operation is already being performed in a few ground-based systematic searches (e.g., Bakos *et al.* 2007).

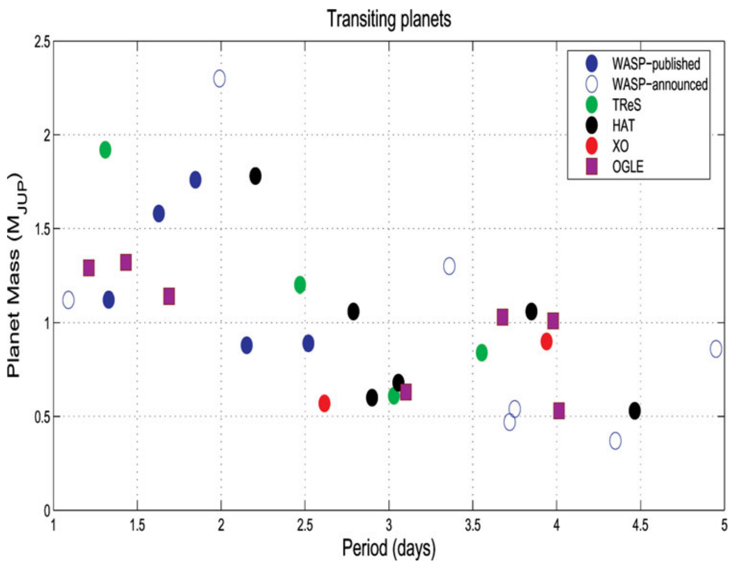

Figure 4. The mass of the transiting planets as a function of their orbital period.

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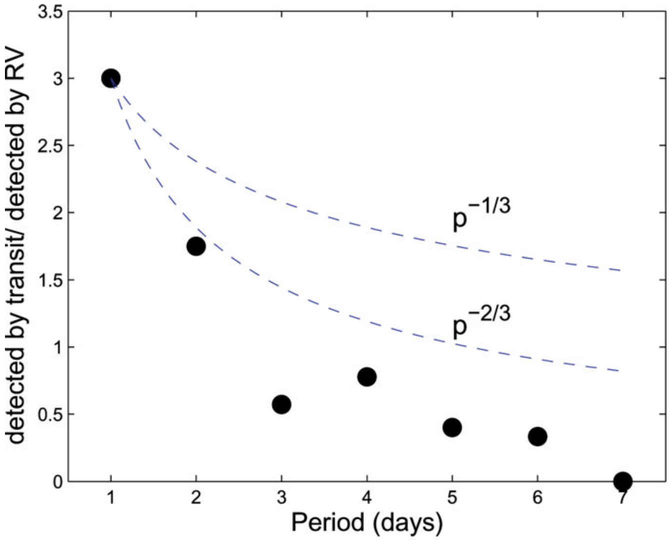

Figure 5. The ratio of transiting planets discovered by photometry to the ones discovered by the RV technique.

Finally, this review concentrated on the ground-based searches only. However, two large systematic space-borne searches are on their way. CoRoT has already been working for more than a year (see Baglin *et al.* in this volume) and producing superb lightcurves of newly discovered planets (e.g., Alonso *et al.* 2008; Aigrain *et al.* 2008; Moutou *et al.* 2008), and Kepler is about to be launched in less than a year (Borucki *et al.* 2008). We expect that with their superb precision these two satellites will find more transiting planets in the range of Neptune and even super-Earth size.

Acknowledgements

I heartily thank C. Alonso, G. Bakos, A. Cameron, P. Kabath, P. McCullough, F. O'Donovan, P. Sackett and A. Udalski who were kind enough to answer my questions about the technical details of their projects. I thank F. Pont for being patient with the manuscript of the paper and O. Tamuz for critical reading of the manuscript. This work was supported by the Israeli Science Foundation. I am indebted to the Radcliffe institute for advanced studies at Harvard, where the last version of the paper was prepared.

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