Transit Photometry as an Exoplanet Discovery Method

Hans J. Deeg and Roi Alonso

Abstract Photometry with the transit method has arguably been the most successful exoplanet discovery method to date. A short overview about the rise of that method to its present status is given. The method's strength is the rich set of parameters that can be obtained from transiting planets, in particular in combination with radial velocity observations; the basic principles of these parameters are given. The method has however also drawbacks, which are the low probability that transits appear in randomly oriented planet systems, and the presence of astrophysical phenomena that may mimic transits and give rise to false detection positives. In the second part we outline the main factors that determine the design of transit surveys, such as the size of the survey sample, the temporal coverage, the detection precision, the sample brightness and the methods to extract transit events from observed light curves. Lastly, an overview over past, current and future transit surveys is given. For these surveys we indicate their basic instrument configuration and their planet catch, including the ranges of planet sizes and stellar magnitudes that were encountered. Current and future transit detection experiments concentrate primarily on bright or special targets, and we expect that the transit method remains a principal driver of exoplanet science, through new discoveries to be made and through the development of new generations of instruments.

Introduction

Since the discovery of the first transiting exoplanet, HD 209458b (Henry et al. 2000; Charbonneau et al. 2000), the transit method has become the most successful detec-

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tion method, surpassing the combined detection counts of all other methods (see Fig. 1) and giving rise to the most thoroughly characterized exoplanets at present.

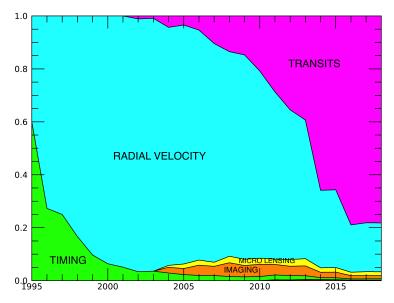


Fig. 1 The fractions by which various detection methods contributed to the accumulated sample of known planets is shown, for years since 1995. At the end of 1995, only five planets were known, three from pulsar timing and two from radial velocities. Between 1996 and 2013, the sample of known planets was dominated by those discovered with radial velocities, while in 2018, 78% of all known planets had been discovered by transits. Based on data from the NASA Exoplanet Archive in Feb. 2018, and using its classification by discovery methods. 'Timing' includes planets found by pulsar timing, eclipse timing, or transit timing. Other detection methods (astrometry, orbital brightness variation) generate only a very small contribution that is barely visible at the bottom of the graph, for years following 2010.

The detection of planetary transits is among the oldest planet detection methods; together with the radial velocity (RV) method it was proposed in 1952 in a brief paper by Otto Struve. The early years of exoplanet discoveries were however dominated by planets found by RVs, and prior to the 1999 discovery of transits on HD 209458, the transit method was not considered overly promising by the community at large. For example, a 1996 (Elachi et al.) NASA Road Map for the Exploration of Neighboring Planetary Systems (ExNPS) revises in some detail the potential of RV, astrometry and microlensing detections, with a recommended focusing onto space interferometry, while transits were considered only cursory. Consequently, activities to advance transit detections were rather limited; most notable are early proposals for a spaced based transit-search by Borucki, Koch and collaborators (Borucki et al. 1985; Koch et al. 1996; Borucki et al. 1997) and the TEP project, a search for transiting planets around the eclipsing binary CM Draconis that had started in 1994 (Deeg et al. 1998; Doyle et al. 2000). The discovery of the first transiting planets,

with some of them like HD 209458b already known from RV detections, quickly led to intense activity to more deeply characterize them, mainly from multi-color photometry (e.g. Jha et al. 2000; Deeg et al. 2001) or from spectroscopy during transits (e.g. Queloz et al. 2000; Charbonneau et al. 2002; Snellen 2004); to provide the community with efficient transit fitting routines (e.g. Mandel and Agol 2002; for more see below), or to extract the most useful set of physical parameters from transit lightcurves (Seager and Mallén-Ornelas 2003).

The first detections of transits also provided a strong motivation towards the setup of dedicated transit searches, which soon led to the first planet discoveries by that method, namely OGLE-TR-56b (Konacki et al. 2003) and further planets by the OGLE-III survey, followed by TrES-1 (Alonso et al. 2004a), which was the first transit-discovery on a bright host star. Transits were therefore established as a valid method to find new planets.

Central to the method's acceptance was also the fact that planets discovered by transits across bright host stars permit the extraction of a wealth of information from further observations. Transiting planets orbiting bright host-stars, such as HD 209458b, HD 189733 (Bouchy et al. 2005), WASP-33b (Christian et al. 2006; Collier Cameron et al. 2010), or the terrestrial planet 55 Cnc e (McArthur et al. 2004; Winn et al. 2011) are presently the planets about which we have the most detailed knowledge. Besides RV observations for the mass and orbit determinations, further characterization may advance with the following techniques: transit photometry with increased precision or in different wavelengths; transit photometry to derive transit timing variations (TTVs); spectroscopic observations during transits (transmission spectroscopy; line-profile tomography of exoplanet transits; Rossiter-McLauglin effect). Furthermore, the presence of transits – strictly speaking primary transits of a planet in front of its central star – usually implies the presence of secondary eclipses or occultations, when a planet disappears behind its central star. These eclipses, as well as phase curves of a planet's brightness in dependence of its orbital position, might be observable as well.

Given the modest instrumental requirements to perform such transit searches on bright star samples - both HD209458b's transits and the planet TReS-1 were found with a telescope of only 10cm diameter - the first years of the 21st century saw numerous teams attempting to start their own transit surveys. Also, for the two spacebased surveys that were launched a few years later, CoRoT and Kepler, it is unlikely that they would have received the necessary approvals without the prior groundbased discovery of transiting planets. The enthusiasm for transit search projects at that time is well represented by a paper by Horne (2003) which lists 23 transit surveys that were being prepared or already operating. Its title 'Hot Jupiters Galore' also typifies the expectation that significant numbers of transiting exoplanets will be found in the near future: Summing all 23 surveys, Horne predicted a rate of 191 planet detections per month. In reality, advances were much slower, with none of these surveys reaching the predicted productivity. By the end of 2007, before the first discoveries from the CoRoT space mission (Barge et al. 2008; Alonso et al. 2008), only 27 planets had been found through transit searches. This slower advance can be traced to two issues that revealed themselves only during the course of the

first surveys: The amount of survey time required under real conditions was higher than expected, and the presence of red noises decreased sensitivity to transit-like events (see later in this chapter). Once these issues got understood and accounted for, some of these ground-based surveys became very productive, and both WASP and HAT/HATS have detected over 100 planets to date. The next major advances based on the transit method arrived with the launch of the space missions CoRoT in 2006 and Kepler in 2009. These led to the discoveries of transiting terrestrial-sized planets (CoRoT-7b by Léger et al. 2009, Kepler-10b by Batalha et al. 2011); to planets in the temperate regime (CoRoT-9b, Deeg et al. 2010); to transiting multi-planet systems (Lissauer et al. 2011) and to a huge amount of transiting planets that permit a deeper analysis of planet abundances in a very large part of the radius - period (or Teff) parameter space. In the following, an introduction is given on the methodology of the transit detection and its surveys, as well as an overview about the principal projects that implement these surveys.

Fundamentals of the transit method

A schematic view of a transit event is given in Figure 2, where the bottom part represents the observed flux of the system. As the planet passes in front of the star, its flux diminishes by a fractional denoted as ΔF . Under the assumptions of negligible flux from the planet and of spherical shapes of the star and planet, ΔF is given by the ratio of the areas of the planet and the star:

$$\Delta F \approx \left(\frac{R_p}{R_s}\right)^2 = k^2 \tag{1}$$

where R_p is the radius of the planet, R_s the radius of the star, and k is the radius ratio. The total duration of the transit event is represented as t_T , and the time of totality, in which the entire planet disk is in front of the stellar disk (the time between *second* and *third* contacts, using eclipse terminology) is given by t_F , during which the light curve is relatively flat. Using basic geometry, the work by Seager and Mallén-Ornelas (2003) derived analytic expressions that relate these observables to the orbital parameters. In particular, the impact parameter b, defined as the minimal projected distance to the center of the stellar disc during the transit, can be expressed as:

$$b \equiv \frac{a}{R_s} \cos i = \left\{ \frac{(1-k)^2 - \left[\sin^2(t_F \pi/P) / \sin^2(t_T \pi/P)\right] (1+k)^2}{\cos^2(t_F \pi/P) / \cos^2(t_T \pi/P)} \right\}^{1/2}$$
(2)

where a is the orbital semimajor axis, i the orbital inclination, and P the orbital period. A commonly used quantity that can be obtained from photometric data alone is the so-called scale of the system, or the ratio between the semimajor axis and the radius of the star:

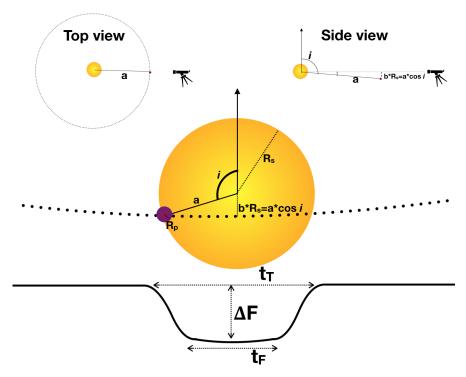


Fig. 2 Outline of the transit of an exoplanet, with the main quantities used to describe the orbital configuration, from the observables given in the lower solid curve (the observed light curve), to the model representations from the observer's point of view (central panel) or other view points (top panels). See the text for details.

$$\frac{a}{R_s} = \frac{1}{\tan(t_T \pi/P)} \sqrt{(1+k)^2 - b^2}$$
 (3)

which, using Kepler laws of motion and making the reasonable approximations of the mass of the planet being much smaller than the mass of its host star, and a spherical shape for the star, can be transformed into a measurement of the mean stellar density:

$$\rho_s = \frac{3\pi}{GP^2} \left(\frac{a}{R_s}\right)^3 \tag{4}$$

This measurement and its comparison with the stellar density estimated by other means (through spectroscopy, mass-radius relations, or asteroseismology) has often been used as a way to prioritise the best transit candidates from a survey (Seager and Mallén-Ornelas 2003; Tingley et al. 2011; Kipping et al. 2014). In the previous equations we have assumed circular orbits for simplicity; a derivation of equivalent

equations including the eccentricity terms can be found in Tingley et al. (2011, with a correction in Eq. 15 of Parviainen et al. 2013).

While the previous expressions allow quick estimates of the major parameters of an observed transit, more sophisticated derivations using the formalisms of Mandel and Agol (2002) or Giménez (2006) are commonly used for their more precise derivation. This is in part due to a subtle effect visible in Figure 2: the limb-darkening of the star, that manifests itself as a non-uniform brightness of the stellar disk. The limb-darkening of the star makes it challenging to determine the moments of *second* and *contact* of the transit, and to precisely measure ΔF . For more detailed introductions into the parameters that can be measured from transits, we refer to Winn (2010) and Haswell (2010).

Detection probability

The geometric probability to observe a planet in transit is given by (Winn 2010):

$$p_{tra} = \left(\frac{R_s \pm R_p}{a}\right) \left(\frac{1 + e\sin\omega}{1 - e^2}\right) \tag{5}$$

where the + sign is used to include grazing transits, and the - sign refers to the probability of full transits, that have *second* and *third* contacts. For a typical hot Jupiter with a semimajor axis of 0.05 AU this is on the order of 10%, while for a Earth at 1 AU it goes down to 0.5%. This geometric obstacle is the main handicap of the transit method, since the majority of existing planet systems will not display transits.

False Positives

A transit-shaped event in a light curve is not always caused by a transiting planet, as there are a number of astrophysical configurations that can lead to similar signatures. These are the so-called false positives in transit searches, which have been a nuisance of transit surveys since their beginning. One example of a false positive would be a stellar eclipsing binary in an apparent sky position that is so close to a brighter single star that the light of both objects falls within the same photometric aperture of a detector: the deep eclipses of the eclipsing binary are diluted due to the flux of the brighter star, and a shallower eclipse is observed in the light curve, with a very similar shape to a transiting planet. More complete descriptions of the types of false positives that affect transit searches, and their expected frequencies, can be found in Brown (2003); Alonso et al. (2004b); Almenara et al. (2009); Santerne et al. (2013).

To detect false positives and to confirm the planetary nature of a list of candidates provided by a transit survey, a series of follow-up observations are required

(e.g. Latham 2003; Alonso et al. 2004b; Latham 2007, 2008; Deeg et al. 2009; Moutou et al. 2013; Günther et al. 2017b), which apply to both ground-based or space-based surveys. Traditionally, the *confirmation* that a transit signal is caused by a planet takes place when its mass is measured with high precision RV measurements. In some cases, particularly with planets orbiting faint host stars, or for the confirmation of the smallest planets, the achievable RV precision is insufficient to measure the planet's mass. As these cases are of high interest, for example, planets with similar sizes as the Earth orbiting inside the habitable zone of its host star, statistical techniques have been developed to estimate the probability of the observed signals being due to planets relative to every other source of false positive we know of. In this case, the planets are known as validated. Current validation procedures use the fact that astrophysical false positives scenarios have very low probabilities when several transiting signals are seen on the same star (Lissauer et al. 2012), or they use all the available information (observables and knowledge of the galactic population and stellar evolution) to compare the probabilities of a signal due to a transiting planet vs. anything else. A few examples of validation studies are Torres et al. (2011); Morton (2012); Lissauer et al. (2014); Rowe et al. (2014); Díaz et al. (2014); Torres et al. (2015); Morton et al. (2016); Torres et al. (2017), some of which use one of the current state-of-the-art validation procedures: BLENDER, VESPA, and PASTIS.

Finally, some false positives may be due to artifacts of the red noise or other instrumental effects, even in the most precise surveys to date (e.g. Coughlin et al. 2014). In a few cases planets that were previously validated have been disproved after an independent analysis (Cabrera et al. 2017; Shporer et al. 2017), which should generate some caution about the use of results from validations, which are statistical by design.

Transit Surveys: factors affecting their design

The task of surveying a stellar sample for the presence of transiting planets must overcome the inherent inefficiencies of the transit method: The planets need to be aligned correctly (see previous section) and the observations must be made when transits occur. The expected abundances of the desired planet catch must be taken into account and their transits need to be detectable with sufficient photometric precision. Furthermore, transit-like events (false positives) may arise from other astrophysical as well as instrumental sources and means to identify them need to be provided. The success of a transit-detection experiment must take these factors into account, which are discussed in the following.

Sample size The probability p_{tr} for transits to occur in a given random-oriented system is between a few percent for Hot Jupiters and less than 0.1% for cool giant planets. In order to achieve a reasonable probability that N transiting system will be found in a given stellar field, the number of surveyed stars (that is, stars for which

light curves with sufficient precision for transit detection are obtained) should be at least $N_{\rm survey} \approx N/(p_{\rm tra}\ f)$, where f is the fractional abundance of the detectable planet population in the stellar sample. For surveys of Hot Jupiters, with $f \approx 1\%$ of main-sequence (MS) stars (Wright et al. 2012; Mayor et al. 2011), this leads to minimum samples of 2000 MS stars to expect a single transit discovery. Given that most stars in the bright samples of small-telescope surveys are not on the MS, sample sizes of 5000 - 10000 targets are however more appropriate. Survey fields that provide sufficient numbers of suitable stars, by brightness and by desired stellar type, need therefore be defined. The size of the sample is then given by the size of the field of view (fov) and by the spatial density of suitable target stars, which depends on the precision of the detector (primarily depending on the telescope aperture) and on the location of the stellar fields. Also, in most surveys, sample size is increased through successive observations of different fields.

Temporal coverage At any given moment, the probability for the observation of a transit of a correctly aligned system is $p \approx t_T/P$, where t_T is the duration of a transit and P the orbital period. This probability goes from 5-8% for Ultra-short periodic planets over 2-3% for typical Hot Jupiter systems to 0.15% for an Earth-Sun alike. For an estimation of the number of transits for a given sample at a given time, we need to multiply this probability and the probability for correct alignment with the abundance of detectable planets. To determine a planet's period, of course at least two transits need to be observed. The requirement to observe three transit-like events that are periodic has however been habitual in ground-based observations, which are prone to produce transit-like events from meteorologic and other non-astronomic causes. Furthermore, for an increased S/N of transit detections, especially towards the detection of smaller planets, as well as towards a more precise derivation of physical parameters, the rule is 'the more transits, the better'. Continuous observational coverage is the most time-efficient way to achieve the observation of a minimum number transits (e.g. $N_{\text{tr,min}} > 3$) for a given system. However, only space missions are able to observe nearly continuously over timescale of weeks, which is the only way to ascertain that transiting planets above some size threshold and below some maximum period are being detected with near-certainty. Ground-based surveys, with their interruptions from the day/night cycle and from meteorological incidences, can only seek reasonable probabilities (but no certainty) to catch a desired number of transits from a given planet. The principal factor that determines the number of observed transits in a given discontinuous light curve is a planet's orbital phase (at some reference time, such as the begin of observations) or its epoch (the time when one of its transits occurs); both are of course unknown prior to a planet's discovery. An example of the effect of phase on the number of observed transits in discontinuous data is shown in Fig. 3. As a rough rule, in order to achieve reasonable detection probabilities (e.g. > 70%) for typical Hot Jupiters (P = 3 - 4d) with a requirement of 3 observed transits, surveys should cover a stellar field for at least 300h.

Transit detection precision A basic version of the S/N of a single transit is given by the ratio

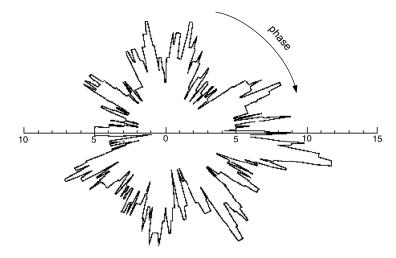


Fig. 3 The expected number of transits by a a test-planet with a period of 5 days that would have been observed in a ground-based lightcurve covering 617 hrs (= 25.7 d). The clockwise direction is the planet's phase at some time of reference and the radial distance gives the number of transits that would have been observed at each phase. Achieving that the large majority of the potential phases would produce at least 3 transits required an observational coverage that was much longer than 3 times the orbital period. Adapted from Deeg et al. (1998).

$$(S/N)_{tr} \approx \Delta F/\sigma_{lc}$$
, (6)

where ΔF is the fractional flux-loss during a transit and σ_{lc} is the fractional noise of the light curve on the timescale of the transit-duration T_T . This noise is composed of various sources, most notably photon noise from the target and the surrounding sky background, Cosmic Ray hits, CCD read noise and flat-fielding or jitter noises (which arise from variations of the positions or shapes of stellar point spread functions on detectors whose sensitivity is not uniform). For ground-based surveys, we also have to add variations from atmospheric transparency and scintillation noise. Fig. 4 shows the scatter over 1 hour time-scales from the most precise space-based survey, Kepler, and from NGTS, one of the leading ground-based ones.

Early estimates for planet detection yields assumed commonly a white-noise scaling from the point-to-point scatter of an observed light curve to the usually much longer duration of a transit. In practice, red or correlated noises degrade the precision of nearly all photometric time-series over longer time-scales, as was first shown by Pont et al. (2006), based on data from the OGLE-III transit survey. Only the space-based data from the Kepler mission uphold a white-noise scaling from their acquisition cycle of 30 minutes to a transit-like duration of 6 hrs (Jenkins et al. 2010a; see Gilliland et al. 2011 for more details on Kepler's noise properties). The CoRoT mission, in contrary to Kepler on a low Earth orbit, produced light curves that on time-scales of 2h were already about twice as noisy as would be the result

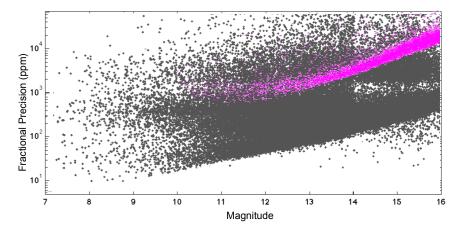


Fig. 4 Comparison of precision of between Kepler (grey points) and NGTS (violet points). Given is the lightcurves' rms scatter on a 1h time-scale. The magnitudes for NGTS are in the I-band; for Kepler they are in its own system. The Kepler noises are from long-cadence (0.5h cycle time) curves of Q1 targets (Jenkins et al. 2010a) and scaled by $\sqrt{1/2}$ towards the 1h time-scale. The NGTS data are from 695 hours of monitoring with a 12 s cadence, rebinned to exposure times of 1 h, from Wheatley et al. (2017). The difference between NGTS and Kepler precision would be reduced by a factor of $\sqrt{950/200} \approx 2.2$ if the different aperture sizes are taken into account. The precision for the brightest NGTS targets is limited by scintillation noise, which is independent of the targets' brightness.

of a white-noise scaling from their acquisition cycle of 8.5 minutes (Aigrain et al. 2009). At least as strongly affected are ground-based surveys, with the principal culprit being the nightly airmass variation, which is on a similar time-scale as the duration of most transits. Correlated noises have been the principal source for the early overestimations of detection yields. In the case of SuperWASP, recognizing their influence led to a revision of detection yields and to an increase in temporal coverage early in its operational phase (Smith et al. 2006). For surveys that attempt to detect shallow transits, brightness variations due to the sample stars' activity might also be of concern. The demonstration that this variability does not prevent the detection of terrestrial planets of solar-like stars (Jenkins 2002) was an important advance during the development of the Kepler mission. Aigrain et al. (2004) found then that K stars are the most promising targets for transit surveys, while the surveys' performance drops significantly for stars earlier than G and younger than 2.0 Gyr. For a quantitative discussion of the factors that influence the yield of transit surveys, we refer to Beatty and Gaudi (2008).

Algorithms to dampen red noises and other systematic effects have been developed to either 'clean' directly a lightcurve from their influences or as part of a detection algorithm, thereby increasing its sensitivity for transit-like features. Examples are the pre-whitening employed in the Kepler pipeline (Jenkins et al. 2010b), the cleaning of Corot lightcurves (Guterman et al. 2015) or the widely used SYSREM (Tamuz et al. 2005) and TFA (Kovács et al. 2005) algorithms.

Brightness of the sample: Rejection of false positives and characterisation of the planet catch As mentioned, a large number of transit surveys was initiated in the first years of the 21st century, after the discovery of the first transiting planets. These early efforts were aimed about equally at deep surveys of small fields using larger (1m and more) telescopes and at shallow surveys with small instruments having fields of view. The surveys with larger telescopes, including early projects with Hubble Space Telescope (Gilliland et al. 2000, on the 47 Tucanae globular cluster, and the SWEEPS survey by Sahu et al. 2006), were met however with limited success, with the most productive one becoming the OGLE-III (Udalski 2003) survey using a dedicated 1m telescope. Besides the difficulties to get access to the required large facilities to perform a deep survey over a sufficiently long time, a major drawback of such surveys is the faintness of the sample. RV verifications or further observational refinements of their transit detections are either impossible, or if possible at all, they likely require the largest existing telescope facilities.

For example, from the SWEEPS survey that targeted the Sagittarius I window of the Galactic bulge with the Hubble Space Telescope, Sahu et al. (2006) report the detection of transits on 16 targets. Their faintness of V=18.8 to 26.2 as well as crowding permitted however only for two of them (SWEEPS-04 and 11) a confirmation as planets, based on RVs taken with the 8m VLT. All other SWEEPS detections have remained in candidate status until the present. We also note the comparatively small impact (relative to brighter targets) of the very large number of planets on the fainter end of the Kepler mission's sample (Rowe et al. 2014 with 815 planets, Morton et al. 2016 with 1284 planets). These planets count only with probabilistic validations, and their principal usefulness are statistical studies on planet abundances across their known parameters (radius, period, central star type, planet multiplicity). The brightness of a target sample is therefore a very valuable parameter towards the science return of a transit survey!

The most common follow-up observations of transit detections are RV measurements, which do not only prove (or disprove) a planet's existence beyond reasonable doubt, but also greatly improve our knowledge about them, providing masses, orbital eccentricity and occasionally, also the detection of further non-transiting planets in the same system. In practise, from the RV follow-up of numerous candidates for the Kepler, K2 and CoRoT missions, we found that a magnitude of ≈ 14.5 is a soft limit for their routinary follow-up. This is due to that brightness being near the limit for RV measurements at several relatively well-accessible mid-sized telescopes with appropriate instrumentation (e.g. the FIES instrument on the 2.5m Nordic Optical Telescope, or the HARPS instruments on the 3.6m Telescopio Nazionale Galileo (TNG) and on the ESO 3.6m telescope).

On transiting systems of bright central stars, a host of further possibilities to examine these systems opens up - such as observation of the Rossiter Mc-Laughlin effect, transit spectroscopy, secondary eclipse measurements or the detection of phase curves (see the Handbook's Section on Exoplanet Characterization). For this reason – increased knowledge about the discovered systems – both of the upcoming space-based transit surveys, TESS and PLATO, will focus on samples that are brighter than those of Kepler and CoRoT, while ground-based surveys continue with their

efforts to find transiting planets principally on bright, or on special types of target stars.

Transit detection in light curves

Efficient recognition of transit-like features in light curves is a central part of any transit detection experiment. This task is usually performed in two steps. In the first one, detection statistical values that describe the likelihood of a light curve to contain a transit-like event are assigned. These might also be expressed as a function of a candidate planet's size, period and further parameters. In the second step, these statistical values are evaluated and those candidates that deserve closer investigation are extracted. We reproduce here a description of this step in the Kepler pipeline, from Jenkins et al. (2010b): "Light curves whose maximum folded detection statistic exceeds 7.1 σ are designated Threshold Crossing Events (TCEs) and subjected to a suite of diagnostic tests in Data Validation (DV) to fit a planetary model to the data and to establish or break confidence in the planetary nature of the transit-like events". The threshold value for the extraction of candidates needs to be chosen with care, as it must provide a balance between the number of false positives – which increases to unmanageable levels if the threshold is too low – and the risk to miss detections of true planets if the threshold is too high.

As representative transit detection methods and algorithms we mention here the early work on matched-filter detection algorithms by Jenkins et al. (1996), which provided the basics for the transit detection of the early TEP observing project as well as for the Kepler mission; the widely used box least-squares (BLS) algorithm (Kovács et al. 2002) with derivatives (e.g. Collier Cameron et al. 2006) or algorithms using wavelets (e.g. Régulo et al. 2007).

For the second step of a detection procedure, the evaluation of a transit candidate as a planet-like event, usually a more detailed modelling (or fitting) of the light curve of the presumed transit is performed. The Mandel and Agol (2002) algorithm or the analytical eclipsing formulae by Giménez (2006) are widely used basic transit modellers that have also been integrated into several transit fitting packages.

Transit surveys: past, current and future projects

The Extrasolar Planets Encyclopedia (http://www.exoplanet.eu/research/) lists currently web-sites of 39 planet search projects that indicate 'transits' as a principal observing method. These projects include finished ones, currently operating ones, projects that are in various preparation stages, as well as projects or proposals that have never moved beyond some design phase. It includes also some projects that aren't dedicated to the discovery, but to the follow-up of transiting planets, such as ESA's CHEOPS space mission. In Table 1 and in the following notes we provide

 Table 1
 Selected transit surveys

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m ₀₅ , m ₅₀ , m ₉₅ (Vmag)		140 150 158	11.4, 11.8, 13.7	9.8, 11.1, 12.1	10.0, 11.8, 13.6	12.1, 13.5, 14.6	9.8, 11.5, 12.9	7.6,10.0, 11.5	15.5		19.3 4	11.9, 14.9, 15.8	11.8, 14.6, 15.9	11.1, 13.3, 15.7						
$R_{05},R_{56},R_{95} \\ (R_{jup})$		1.08, 1.25, 1.61	1.10, 1.21, 1.71	0.97, 1.20, 2.07	0.82, 1.27, 1.79	0.87, 1.25, 1.75	0.85, 1.24, 1.71	1.11, 1.53, 1.91	1.33		0.97	0.3, 1.05, 1.47	0.083, 0.189, 0.633	0.097, 0.202, 1.05						
$N_{ m planet}$		∞	s	∞	1 64 1	36	146 1	19	1		2	35	2300	176						
$fov_{ m instr} ({ m deg}^2)$	sk			300		<i>L</i> 9	480		96	×.					2300	2232				
fov _{sngle} (deg²) fov _{instr} (deg²)	Ground-based surveys	0.34	36	49	64	17	09	929	8	Space-based surveys	0.003	3.5 / 1.7 1	107/102 6	94 / 95 6	576	1100				
config		5	Gr	Single telescope of 1000mmØ	3 sites, each with one telescope of 100mm@	Single site (3 sites in 2012-14) with common mount for 2 cams.	2 sites , one (FLWO) with 5 cams and one (Mauna Kea) with 2 cams, all individually mounted with 110mmø	3 sites, each with 2 mounts that each hold 4 cameras with 180mm0, covering adjacent fields in 2x2 pattern	2 sites, each with single-mount array of 8 cams of 111 mm 0 covering adjacent fields	2 sites, each with single camera of 42mmØ	Single site with 12 telescopes of 200mm Θ on independent mounts	ds	Hubble Space telescope (2.5mØ) with ACS cam.	Space telescope of 270mmØ	Space telescope of 950mmØ	Same as Kepler	4 cams of 105mmØ each covering adjacent areas	24 cams of 100mmØ in 4 groups, with 6 co-aligned cams	in each group. Partial overlap of all 24 units. 2 further 'fast cams' with color filter and short evele time	
years		2001-2009	2003-2010	2003-2014	since 2003	since 2009	since 2004	since 2005	since 2016		2006	2007-2012	2008-2013	2014-2018	launch 2018	launch 2026				
Name		OGLE	TrES	OX	HATnet	HATSouth	WASP	KELT	NGTS		SWEEPS	CoRoT	Kepler	K2	TESS	PLATO				

 1 Includes 3 planets common to HAT and WASP 2 Orginial $f\!o\nu$ and after March 2009, due to failed DPU.

3 I band magnitudes

⁴ Average of the two confirmed planets

 5 Kepler Bandpass magnitudes 6 for values before /after July 2016 (K2), due to detector failures

an overview over a selection of well-known transit detection surveys. The columns of Table 1 have the following meaning:

years: Indicates the years of operation.

config: Instrument configuration, with the aperture diameters of individual optical units (cam = camera).

fov_{single}: The sky area in deg² covered by a single optical unit of the detection experiment.

fov_{instr}: The sky area in deg² that is covered simultaneously be the experiment at a single site in its usual operating mode. Only given if there are multiple optical units at a site.

 N_{pl} : Count of planet detections in February 2018, based on the number of planets carrying an instrument's designation in the name. Planets labeled with other designations, such as HD or GJ numbers, are missed.

 R_{05} , R_{50} , R_{95} : 5th, 50th (median) and 95th percentiles of the radii of the detected planets. If $N_{nl} \le 20$, the smallest and largest planets are given.

m₀₅, m₅₀, m₉₅: Similar to the previous, but indicating the V-mag brightness of the detected systems.

Planet counts, radii and magnitudes are from the Encyclopedia of Extrasolar Planets and from the NASA Exoplanet Explorer. Below, some notes are provided for the transit surveys listed in Table 1.

OGLE-III The Optical Gravitational Lensing Experiment has been implemented in four phases, with the fourth one operational at present. OGLE is dedicated to the detection of substellar objects from microlensing, except for its third phase (OGLE-III, Udalski 2003), when the observing procedure of the 1m OGLE telescope at Las Campanas Observatory was modified to enable the detection of transits. OGLE-TR-56 was the first planet discovered in a transit search, with a posterior verification from RV follow-up (Konacki et al. 2003).

TrES The 'Trans-Atlantic Exoplanet Survey' was the first project with instruments that were specifically designed and dedicated for transit surveying. Its first telescope, originally named STARE, was used in the 1999 discovery of the transits of HD 209458b during tests at the High Altitude Observatory at Boulder. In 2001, it was relocated to Teide Observatory, Tenerife, where a systematic transit search began. Since 2003, the project operated under the TrES name, after the merger with two other projects using similar instrumentation, namely PSST at Lowell Observatory and the Sleuth Project at Palomar Observatory (O'Donovan 2008). The principal success of TrES was the detection of the first transiting planets orbiting bright stars (TrES 1, Alonso et al. 2004a; TrES 2 O'Donovan et al. 2006) by a dedicated survey. TrES was discontinued in 2010.

XO This survey started in 2003 at a single site, with a second phase observing from three sites from 2012-2014. The CCDs are read in time-delayed integration (TDI): pixels are read continuously while stars move along columns on the detector, owing

to a slewing motion of the telescope. This setup enlarges the effective field of view and results in stripes of 7° x 43° that are acquired during each single exposure.

HAT This denominator (Hungarian-made Automated Telescope) encompasses two surveys: For one, since 2003 HATnet operates seven CCD cameras with 110mm apertures on individual mounts, with five of them at Fred Lawrence Whipple Observatory at Mount Hopkins in Arizona and two at Mauna Kea Observatory in Hawaii. For another, HATSouth (Bakos et al. 2013) is a network across three sites in the southern hemisphere that is able to track stars continuously over longer time-spans. Since 2009, it operates at the Las Campanas Observatory (Chile), at the High Energy Stereoscopic System site (Namibia), and at the Siding Spring Observatory (Australia). Each of these sites contains two mounts, with each of them holding four Takahashi astrographs with individual apertures of 180 mm. The HAT consortium is also advancing the HATPI Project of an all-sky camera consisting of 63 optical units on a single mount.

WASP (Wide Angle Search for Planets, see Pollacco et al. 2006 for an instrument description; Smith et al. 2014 for a review). This consortium operates two instruments: SuperWASP-North, since 2004 at Roque de los Muchachos Observatory on the Canary Island of La Palma, and WASP-South, since 2006 at the South African Astronomical Observatory. A predecessor instrument, WASP0, was operated during the year 2000 on La Palma. SuperWASP-North is an array of 8 cameras covering 480 degrees of sky with each exposure; WASP-South is a close copy of it. WASP is currently the ground based search that has detected the most planets, among them several (such as WASP-3b, 12b, 43b) that stand out for their excellent suitability for deeper characterization work, due to their short orbital period and/or large size.

Kelt The 'Kilodegree Extremely Little Telescope' has to date been the most successful survey using very wide field detectors (with a *fov* of 26° x 26°) with commercial photographic optics of short focal length. Kelt-North operates since 2005 from Winer Observatory, Arizona, and KELT-South since 2009 from Sutherland, South Africa. Both instruments use a CCD camera with an 80mm/f1.8 Mamya lens.

NGTS The Next-Generation Transit Survey (Wheatley et al. 2013, 2017) is operated by a consortium of seven institutions from Chile, Germany, Switzerland, and the United Kingdom. After testing in La Palma and at Geneva Observatory, operations started in 2016 at ESO's Paranal Observatory. NGTS employs an automated array of twelve 20-centimeter f/2.8 telescopes on independent mounts, sensitive to orange to near-infrared wavelengths (600 - 900 nm). It is a successor project to WASP that achieves significantly better photometric precision (Fig 5), but with a focus on late type stars. Its first planet discovery has been the most massive planet known to transit an M-dwarf (Bayliss et al. 2017). Simulations for a 4-year survey predict the discovery of about 240 planets, among them about 20 planets of 4 $R_{\rm Earth}$ or less (Günther et al. 2017a).

CoRoT Named after 'Convection Rotation and Transits', this was the first space mission dedicated to exoplanets. Launched in December 2006 by the French space

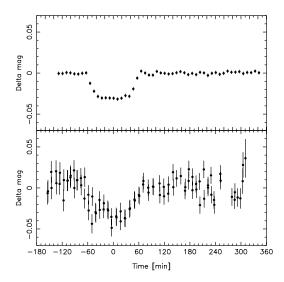


Fig. 5 Single transit observations of the hot Jupiter WASP-4b with one NGTS telescope unit (top) and WASP (bottom). From Wheatley et al. (2017), reproduced with permission.

agency CNES and partners into a low polar orbit for a survey lasting initially 4 years, it surveyed 163 665 targets distributed over 26 stellar fields in two opposite regions in the galactic plane, with survey coverages lasting between 21 and 152 days (Deleuil et al. 2018). In May 2009, its first data processing unit failed and CoRoT's *fov* was reduced to half, while the failure of the other unit in Nov. 2012 caused the end of the mission. Its most emblematic discovery was CoroT-7b, the first transiting terrestrial planet (Léger et al. 2009)

Kepler This NASA mission was launched in 2009 into an Earth trailing orbit, for a mission of 4 years to survey a single field of 170,000 stars, principally for the presence of Earth-sized planets. Kepler has discovered the majority of currently known exoplanets, with discoveries that have revolutionized the field of exoplanets. In contrary to the planets found by any other transit survey, only a small fraction (3%) of Kepler planets are Jupiter-sized ($\geq 0.9R_{jup}$), while the vast majority are Earth or Super-Earth sized ones. Science operations under the 'Kepler' denomination ended in May 2013 when two of the spacecraft's reaction wheels failed and its pointing become unreliable.

K2 In March 2014, the Kepler spacecraft was returned into service under the K2 name. Its observing mode was adapted to the reduced number of reaction wheels, surveying fields near the ecliptic plane for about 80 days each (Howell et al. 2014). Planets found by K2 have a rather similar size-distribution to Kepler, albeit with a somewhat larger fraction of Giant planets (8% are larger than $0.9R_{jup}$). K2 is expected to end around Oct. 2018, when the spacecraft runs out of fuel.

TESS The 'Transiting Exoplanets Survey Satellite' by NASA aims to scan about 85% of the entire sky for transits across relatively bright stars (Ricker et al. 2015). Most areas will be covered by pointings lasting 28 days. The spacecraft harbors 4 wide-field telescopes that cover jointly a stripe of the sky of 24° by 96°. TESS is expected for launch in spring 2018 into an elliptical orbit with a 13.7-day period in a 2:1 resonance with the Moons orbit, for a mission of 2 years.

PLATO This ESA mission, named after 'PLAnetary Transits and Oscillation of stars', is expected to be launched in 2026 into an orbit around the L2 point, to perform during at least 4 years a survey of several large sky-areas (Rauer et al. 2014). The missions core sample are 15 000 stars of $8 \le m_V \le 11$ while a secondary 'statistical' sample includes 245 000 targets up to $m_V \approx 16$. PLATO will have four groups of detectors, each with six cameras that all point to the same *fov*. Between the groups there is a partial overlap due to which areas near the center of the common *fov* will be covered by all 24 cameras while outer zones will be covered by 6 or 12 cameras only. Two additional fast cameras with rapid cycle-times and color-filters will survey the brightest stars of 4 - 8 m_V .

Surveys for planets of low-mass stars

Several surveys, which are not listed in Table 1, have been designed specifically for the detection of planets around low mass stars, and in particular, M-stars. Given the difficulties to detect planets in the habitable zone of solar-like stars, planet-searches around such stars provide an alternative path for the detection of potentially habitable planets (e.g. Scalo et al. 2007). Their small size permits that terrestrial planets produce transits that are deep enough to be observable from moderate ground-based instruments. Also, the habitable zone around these stars corresponds to orbital periods of a few days to weeks, making habitable planets' transits shorter, more frequent, and hence easier to detect than for solar-type stars. Disadvantages of low-mass stars as targets are however a flux variability that is exhibited by most of them, and the sparsity of such stars with sufficient apparent brightness. As a consequence, these detection projects are not performed as wide-field surveys, but as searches that point to selected target stars, which are covered sequentially. As such, these projects cover relatively few targets and have only a small planet catch, but may provide discoveries of large impact towards our knowledge of potentially habitable planets.

MEarth This project operates since 2008 eight 40 cm telecopes at Mount Hopkins, Arizona, and since 2014 a similar setup at Cerro Tololo, Chile (Berta et al. 2012). MEarth has discovered several small planets, among them LHS1140b, a planet of $1.4\,R_{\rm Earth}$ in the habitable zone of an M dwarf at a distance of 10.5 parsec (Dittmann et al. 2017).

TRAPPIST / SPECULOOS The 'TRAnsiting Planets and PlanetesImals Small Telescope' survey consists of two 60 cm robotic telescopes, one operting since 2010

at ESO's La Silla Observatory, Chile, and one since 2016 at Oukaimden Observatory, Marocco. It has the dual objective of transit detection and the study of comets and other small bodies in the Solar System (Jehin et al. 2014). Its outstanding discovery has been the TRAPPIST-1 system of seven planets, with some of them in the habitable zone, around an ultra-cool M8 dwarf at a distance of 12 parsec (Gillon et al. 2017). TRAPPIST is also a prototype of the SPECULOOS (Search for habitable Planets EClipsing ULtra-cOOl Stars) project, whose first phase will consist of four 1m robotic telescopes at ESO's Paranal Observatory.

Conclusion

In the year 2003, K. Horne predicted the success of transit surveys in a paper entitled 'Hot Jupiters Galore'. It took longer than expected to get to that point, and required the understanding and resolution of several subtle issues affecting these surveys, but today the paper's title has become reality and the discovery of transiting planets is common place. This applies not only to Hot Jupiters but also to planets across the entire size regime and has been a consequence of the continued refinement of observing techniques and of the development of new instruments, both ground and space based.

At the time of writing, the transit method is expected to remain the largest contributor towards the discovery of new planets and planet systems, with several ambitious ground and space-based searches under way. Planet systems found in transit searches will also continue to provide the motivation for the continued development of instruments and observing techniques, which take advantage of the opportunities for deeper insights that transiting systems offer. In that sense, systems found by transit surveys will continue as a basic nutritient of the field of exoplanet science.

For further reading about transits as a tool to detect and characterize exoplanets, we refer to the reviews by Winn (2010) and by Cameron (2016) and to a book dedicated to transiting exoplanets by Haswell (2010).

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