How Amateurs Can Contribute to the Field of Transiting Exoplanets

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Abstract In 1999 on two evenings in September, the first tell-tale dips of a transiting extrasolar planet passing in front of its star were detected with a 10-centimeter telescope that was set up in a parking lot beside a wooden shed. Although these observations were obtained by professional astronomers, their setup—a modest aperture telescope in an unassuming location—should sound familiar to many enterprising amateur astronomers. What should warm the heart of any amateur astronomer, while they man their telescope alone on a cold winter's eve, or as they gaze at the blinking glare of their computer monitor, is that there are still numerous avenues via which ambitious amateurs can significantly contribute to the evolving story of transiting extrasolar planets (exoplanets). In the brief review below, I'll summarize the current state of the field of transiting exoplanets, and then elucidate the ways that resourceful amateurs—those with and without access to telescopes—can contribute to the field, both in discovering new transiting exoplanets and in characterizing existing ones.

1. Transiting planets: the state of the field

The notion that we might be able to detect planets in other solar systems by the diminution of light when the planet passes in front of the star along our line-of-sight (a so-called transit) is not a new one. Struve (1952) presciently predicted that Jupiter-size planets should create transit dips on the order of a few percent more than half a century ago, and noted that the methods of the day even then were likely sufficient to achieve the precision necessary to detect these dips. The nearly half-century wait until the detection of a transiting exoplanet was not due to a lack of precision from observers, but mostly due to the fact that planetary theorists did not predict how odd the first exoplanets we detected around stars similar to our own would turn out to be. Although, Struve (1952) hypothesized that it might be possible for planets to exist a mere few stellar radii from their host stars, other planetary theorists were not so sanguine; they predicted that extrasolar systems would have orbital configurations similar to our own solar system, with Jupiter-mass planets in orbits of several years or more (Isaacman and Sagan 1977). Thus any aspiring transit observer faced the daunting prospect of hoping to detect a single transit only once every few years. As a result Struve's prescient suggestion remained largely forgotten for decades.

Although the credit for the discovery of the first exoplanet rightly goes to Wolszczan and Frail (1992), for their discovery of what would turn out to be three planets (Wolszczan 1994) in what can only be described as an extreme environment orbiting a millisecond pulsar (a so-called "dead" star that has burned its nuclear fuel and already gone supernova), the true imagination of the scientific community was not excited until the discovery of a planet, 51 Peg b, around a star similar to our own (Mayor and Queloz 1995). This first detection of an exoplanet around a sun-like star, made via the radial velocity (RV) technique, which indirectly reveals the presence of planets by the doppler shift in the stellar lines from the subtle tugging back and forth of the planet on the star, began the trickle that turned into a flood of exoplanet discoveries—at the time of writing the RV technique has confirmed the discovery of ~700 exoplanets in ~550 extrasolar systems (exoplanet.eu; accessed 23 March 2012).

For those of us who would eventually become enamoured with transiting planets, there was something else captivating about 51 Peg b—something that would reinforce the impressive foresight of Struve's (1952) prediction that planets might be able to survive close to their host stars. This planet was not the true Jupiter analog that planetary theorists were expecting, with a few-year orbital period; instead, it was a so-called hot Jupiter—a Jupiter-mass planet orbiting with a period of a mere few days and thus roasting near its star with an equilibrium temperature in excess of ~1000 K. For the subset of planets that transit their host star, this meant that rather than having to wait several years between transits, they would occur every few days. Also, the chance that the planet would actually transit its star would greatly increase for these close-in planets (for a planet to transit, the cosine of the orbital inclination, $cos\ i$, multiplied by the orbital distance during eclipse (the semi-major axis for a circular orbit), a, must be less than the radius of the star, R_*: $a \sin i < R_*$). The expected fraction of exoplanets that transit their stars is a healthy ~10% for hot Jupiters, and a much smaller fraction for planets of increasing orbital periods. It was this gift from nature—that these hot Jupiter planets exist and can survive, even briefly, roasting next to their host stars—that led to the explosion of interest in using transits to detect exoplanets, and as a result allowed the true potential of Struve's prescient prediction to be achieved.

The transition of this potential into reality started with the first detection of a transiting exoplanet in September 1999. From the unassuming location of a parking lot, using a size of telescope (10-centimeters) that even some amateurs might consider modest, Charbonneau *et al.* (2000) obtained photometry of a known RV-detected hot Jupiter, HD 209458, and observed the characteristic loss of light resulting from the planet transiting across its star (Figure 1; Charbonneau 2001; Jayawardhana 2011. Henry *et al.* 2000 would discover that HD 209458 transits its host star independently). Since that seminal discovery, ~230 planets in ~200 systems have been confirmed to transit their stars, while the Kepler space satellite has identified an additional ~2,300 likely candidates (although many of these systems will remain candidates for the near-term future, because they are not amenable to RV follow-up and confirmation, most of these candidates stand a very good chance of being bona fide planets (Morton and Johnson 2011)) ranging in size from larger than Jupiter to smaller than Earth (Batalha *et al.* 2012). This impressive wealth and diversity in the current sample of known transiting exoplanets offers a compelling opportunity for both professionals and amateurs alike in both adding to the sample by detecting transiting exoplanets especially around bright host stars (section 2), as well as characterizing the atmospheres and orbits of known transiting exoplanets (section 3).

2. How amateurs can assist in detecting new transiting exoplanets

2.1. Searching for transits of known RV detected exoplanets

Excitingly, the very same method that was used to discover the first transiting exoplanet is one that amateurs can continue to use to discover planets. The first transiting exoplanet was discovered by looking at a relatively bright star that was already known from the RV technique to harbor an exoplanet. Not only does the RV technique reveal the period, eccentricity, and the minimum mass of the planet, it also reveals when the planet is expected to pass in front of its star along our line of sight (with an uncertainty of tens of minutes to a few hours in the best cases). Many of these radial velocity stars are relatively bright, and the expected transit depths for giant planets (~1% percent typically) are achievable with modest, CCD-equipped, amateur telescopes from pristine sites. Thus, all that is required is for interested amateur astronomers to be convinced to look at specific stars at specific times and obtain and share the hopefully-resulting high quality light curves. This was exactly the motivation behind one website that is soon to be retired, and another, which is being routinely updated with new RV exoplanet discoveries, that should adroitly take its place. The soon to be retired website is *Transitsearch.org*, which details the following details of known planets detected via the RV method: the Right Ascension, declination, expected transit depth, estimated percentage chance that the planet will actually transit in front of its parent star, and lastly, and most importantly, the ephemerides of the predicted transit window around which interested amateurs are encouraged to search for the tell-tale dip that would indicate that the known RV-detected planet in fact transits its star. Luckily the functionality of *Transitsearch.org* has been included in the NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu/), which should allow interested amateurs to follow up on the latest RV discoveries.

A campaign organized by *Transitsearch.org* was exactly how one of the brightest transiting exoplanets that have been discovered to date was found; HD 17156b (Barbieri *et al.* 2007) was a known RV-detected exoplanet with a period of ~21.2 days and an eccentricity of *e* ~0.67. The orientation of its elliptical orbit compared to the Earth's line-of-sight was fortuitous such that, despite its longer period, it still had a relatively high chance (~13%) of transiting its parent star. Photometry obtained during the predicted transit window by a series of amateurs using telescopes that ranged in size from 0.18 m to 0.40 m revealed a ~1% dip, resulting in the confirmation of one of the brightest transiting planets discovered even to this day. This wasn't *Transitsearch.org*'s only success; another *Transitsearch.org* campaign assisted in the discovery that another bright RV-detected exoplanet (HD 80606b) transited its star (Fossey *et al.* 2009; Moutou *et al.* 2009; Garcia-Melendo and McCullough 2009).

With over ~230 confirmed transiting exoplanets, and Kepler's trove of an additional ~2,300 candidates, an additional transiting exoplanet, even if it is discovered by amateurs, may not seem especially significant. However, this is not the case. It may seem counterintuitive, but it is actually the brightest stars—the ones that amateurs can easily access—that have not been adequately searched by professional astronomers for transiting exoplanets. Many of the existing wide-field, ground-based efforts to detect transiting exoplanets examine fainter stars (V ~8 and fainter) so as to not saturate their detectors, and to allow a great number of stars to be observed simultaneously in the field-of-view of the telescope. However, planets orbiting brighter hosts will always be more favorable for follow-up solely due to the increased number of photons. There are several professional endeavors that seek to fill in this parameter space, by both following up known RV-detected planets—an example is the Transit Ephemeris Refinement and Monitoring Survey (TERMS; Kane *et al.* 2009)—and by searching for transiting planets around relatively bright hosts—examples include the ground-based KELT-survey (Pepper 2007) and the proposed space-based Transiting Exoplanet Survey Satellite (TESS; Ricker *et al.* 2010).

At the current juncture, there still could be at least a handful of RV detected planets that could prove to be a needle of a transiting exoplanet in the haystack of all the RV candidates to date. Even for a dedicated amateur, robustly detecting a 1% transit dip on stars with visual magnitudes on stars as faint as V~8 is not for the faint of heart (Bruce Gary's (2012) *Exoplanet Observing for Amateurs: Second Edition*, which is freely available for download, is an excellent resource that explains the challenges associated with and how to actually achieve such precision; http://brucegary.net/book_EOA/x.htm). However, for the especially dedicated, ambitious amateur, observing from a pristine site with an equally impressive amateur telescope, observing the RV targets listed in the NASA Exoplanet Archive at the specified times may be just the opportunity to add to the short list of RV-detected exoplanets that have been found by amateurs to transit their host stars.

2.2. Planet Hunters

For those amateurs who don't necessarily have access to a telescope, but do have access to a computer, time, and enthusiasm, there is a way they may still discover transiting exoplanets—that way is Planethunters: a citizen science project (http://www.planethunters.org/; Fischer *et al.* 2012) that allows amateurs to seach for planets using data from the Kepler space telescope. NASA's Kepler spacecraft is a 0.95-m telescope in an Earth-trailing orbit (Borucki *et al.* 2011) that is designed to provide ultraprecise photometry of 150,000 stars in a 115-square degree patch of the sky near the constellation of Cygnus; the goal is to discover exoplanets of varying sizes and with periods out to a year, and therefore to determine the frequency of Earth-like planets in the habitable zones of other stars. The Kepler photometry is indeed extremely precise (Borucki *et al.* 2009), but nonetheless it has a variety of noise sources that are both intrinsic (photon-noise), and instrument-related hiccups (systematic errors in astronomy "lingo"); to detect the transits of "wee" planets despite this noise, the Kepler team has developed a variety of algorithms to pick out the tell-tale dips in the light curve. However, those of us who have developed such computer algorithms to accomplish simple tasks know that the human eye and brain are often better at pattern recognition than any algorithm. Thus instead of a single computer algorithm looking for periodic transits in each of the 150,000 light curves that Kepler observed, what if a series of amateurs could be convinced to look at these 150,000 light curves? Would they be able to detect planets that the algorithms had missed? Or possibly, something even more interesting?

Planet Hunters—an interface that allows users to scroll through a great many of the 150,000 Kepler light curves and identify possible transiting exoplanets—was developed to answer this very question. Perhaps, not surprisingly, the answer has turned out to be that indeed a dedicated group of citizen scientists (over 100,000 at last count) can discover transiting exoplanet candidates that Kepler's best algorithms missed on its first pass. At the time of writing, four planetary transiting exoplanetary candidates have been discovered by Planet Hunter collaborators (Lintott *et al.* 2012). It should be acknowledged that these objects are just "candidates" at this present time, which means they have yet to be confirmed as bona fide exoplanets with masses less than the deuterium-burning limit (< 13 Jupiter masses). The RV method is one of the most common ways for astronomers to confirm candidates as planets; the candidates discovered to date with Planet Hunters, however, are unsuitable for such follow-up with a signal too small to be realistically detected with our current best RV precision. There thus remains the possibility that these candidates are false positives (one of the most common false positives for transiting exoplanets is an eclipsing binary star blended or diluted by a tertiary or background star along the line of sight). Analytical research, however, has demonstrated that only a slim percentage of Kepler candidates (< 5–10%) can be expected to be false positives (Morton and Johnson 2011). For the amateur astronomers volunteering with the

Planet Hunter citizen project, I'm going to guess that having the opportunity to discover a candidate that has a 90 to 95% chance of being an exoplanet, just by sitting down at one's computer, has a pretty sweet ring to it. For those amateurs interested in searching for and possibly detecting an exoplanet, data on new Kepler targets and more data on existing targets are released every few months.

3. How amateurs can assist in the characterization of transiting exoplanets

For the talented and ambitious amateur, observing night after night of potentially flat light curves, and scrutinizing subtle dips that may or may not be due to clouds, seeing variations, and so on (see section 2.1), may not sound particularly appealing. What may sound considerably more attractive is to observe the transits of known transiting exoplanets. Known transiting exoplanets have transit depths up to a few percent of the stellar flux from stars as bright as V~6, with the majority of candidates with V~10 or fainter; thus detecting these transits will still only be accessible to experienced amateurs with modest or larger aperture telescopes with a sensitive camera. While it may be an intriguing challenge in its own right for an amateur to robustly detect the ~1% transit dips of most transiting exoplanets, amateurs may be even more intrigued that professional astronomers frequently use the light curves shared by amateurs to learn a great deal about exoplanets' orbits (section 3.1) and in the future, possibly even their atmospheres (section 3.2).

3.1. Characterization of the orbits of exoplanets

Observing a great number of transits of an exoplanet can be very helpful to professionals to characterize the orbit, and as a result the properties, of a transiting exoplanet. Transit-timing (Holman and Murray 2005; Agol *et al.* 2005) is one such obvious example where astronomers look for small differences in the timing of transits from a strictly periodic orbit that might be the telltale signs of other smaller planets in that system that are gravitationally tugging the known planet back and forth. Other small asymmetries in the light curves that may become apparent after frequent observations include transit-duration or inclination variations that may result from precession, or may be the tell-tale signs of exomoons or starspots. What usually happens in the cases that amateur observations prove to be useful is that after a professional astronomer analyzes their own data, they observe an intriguing hint of one of these aforementioned effects; confirming these effects often requires comparison to a robust archive of transit observations—an archive that is often provided by amateur observers. One such search for transit—more aptly eclipse—timing variations that benefited from access to a robust archive of amateur observations was from my own research.

In Croll *et al.* (2011) I used the mid-transit times from twenty light curves obtained by amateur astronomers to rule out that the hot Jupiter WASP-12b was precessing at a detectable rate. The best-fit RV solution of WASP-12b indicated that, despite its very short orbital period (P ~26 hours), its orbit was mildly eccentric (e ~0.05)—that is, its orbit was not perfectly circular, but slightly elliptical in shape. Intriguingly, one of the secondary eclipse times (that is when the planet passes behind its star along our line-of-sight, and we experience a drop in flux due to the loss in light of the planet) for this planet was considerably offset from what one would expect for a circular orbit (Lopez-Morales *et al.* 2010), while another was not (Figure 2 top panel; Campo *et al.* 2011). If this discrepancy was not due to a systematic error or something more interesting, the best explanation for the offset of the times of secondary eclipse of this planet was that its orbit was precessing at a very rapid rate due to the stellar gravitational forces acting on the tidal bulge of the planet. The period of this precession is dependent on what is known as the tidal planetary Love number, k_2, of the orbit, which simply indicates how centrally condensed the planet is—that is, how massive the core of the planet is compared to its outer gaseous layers. For a planet like Jupiter, which has a ~10 Earth-mass core, k_2~0.5, while at the opposite extreme, a uniform density sphere will have a $k_2 = 3/2$ (Ragozzine and Wolf 2009). For the precession rate to be as rapid as these offset eclipse times indicated, the planet would, unexpectedly, have to have a very massive core. The best way to rule out this precession signal was to detect the secondary eclipse of this planet once again, and to determine whether the times were again offset from those of a circular orbit, or whether they fell exactly half an orbit after the transits. The problem was that professional astronomers had only observed a few more transits of this planet, and had not been routinely monitoring the transit, as was necessary to determine if the eclipses fell exactly half an orbit after the transits. Luckily, amateur observers had taken up the slack. By comparing my own observations of the secondary eclipse times of this planet with those published by both professional astronomers and a number of amateur astronomers shared on what is known as the Exoplanet Transit database (ETD; The Exoplanet Transit Database—http://var2.astro.cz/ETD/), I was able to show that the secondary eclipse times fell when we expected them, exactly half an orbit after the transits (Figure 2, bottom panel). This meant that the planet was not precessing at a detectable rate. The professionals and amateurs who shared their observations on the ETD likely had no idea at the time that their observations would eventually be used to elucidate whether we could answer how massive the core is of a gas giant planet ~1,400 light years (Chan *et al.* 2011) away from Earth.

3.2. Characterization of the atmospheres of exoplanets

Transiting exoplanets have been a significant boon to professional astronomers as it has allowed us to probe the atmospheric characteristics of these worlds many light-years from our own. One of the techniques for investigating the atmospheres of these alien planets is known as Transmission Spectroscopy, where one looks for minute transit-depth differences in and out of predicted absorption features from molecules in the atmospheres of these planets. These transit-depth differences result from the fact that the opacity of the planet's atmosphere is greater at the wavelengths of the absorption feature, meaning that the planet actually appears larger, resulting in the planet blocking out a greater fraction of the stellar light and thus having a deeper transit depth. Although the first detection of the atmosphere of an exoplanet used a type of instrument, size of telescope, and observing location not readily accessible to amateurs (Charbonneau *et al.* (2002) used the space-based, 2.4-m aperture Hubble Space Telescope and a spectrograph to disperse light over a narrower spectral range to detect sodium in the atmosphere of HD 209458), more recent detections may fall within the realm that may be accessible to particularly ambitious and technically astute amateurs. The planet HD 189733b orbits a bright host star (V~6) and appears to display a transit depth that decreases monotonically with wavelength (Sing 2011), likely due to scattering from a haze/cloud layer in the upper atmosphere of that alien world. Although the differences between the transit depth of this planet in B-band (a wavelength of λ~0.44 μm) and in z-band (l~0.91 μm) is too small (only ~0.05% of the stellar signal) to be currently accessible to amateurs, it is certainly possible that new planets (especially ones with large-scale heights and deep transits) may display larger transit-depth differences across the optical wavelength range. For this reason, avid amateurs and semi-professionals should consider observing transits over a range of wavelengths and publishing these light curves on the ETD. Given the host of complicating factors (starspots, limb-darkening, telluric atmospheric effects, and so on) that may masquerade as a possible signal, amateur observations alone likely won't be sufficient to confirm such a signal. However, an existing trove of precise amateur observations of the transit depths of exoplanets across a wide wavelength range may be just the thing a professional astronomer needs to believe the tentative signal in their own data, and to request higher precision follow-up observations. If helping to answer what gases are in the atmosphere of an alien world, or whether a planet has prominent clouds and/or hazes is of interest, then professional astronomers would certainly appreciate amateurs uploading as many high quality light curves of transits at various wavelengths/filters as possible to the ETD.

4. Concluding thoughts

The field of transiting exoplanets is a relatively new one. From this field's early days, though, the synergy between amateurs and professionals has been particularly potent. Hopefully this review has elucidated the myriad ways that passionate amateurs, whether they own an advanced telescope that is the envy of all their friends at the star party, or they simply have a modest computer and an internet connection, can ensure that this synergy continues in this field for years to come.

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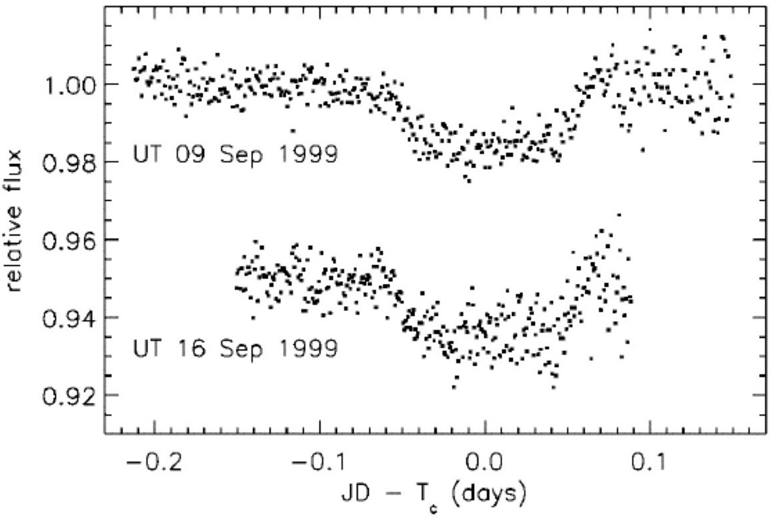

Figure 1. The dip in the light curve at JD – T_c = 0 day, signifies the first detection of the loss of light as a transiting exoplanet passes in front of its star. These observations were obtained with a 10-centimeter telescope set up in a parking lot. Figure obtained from Charbonneau *et al.* (2002).

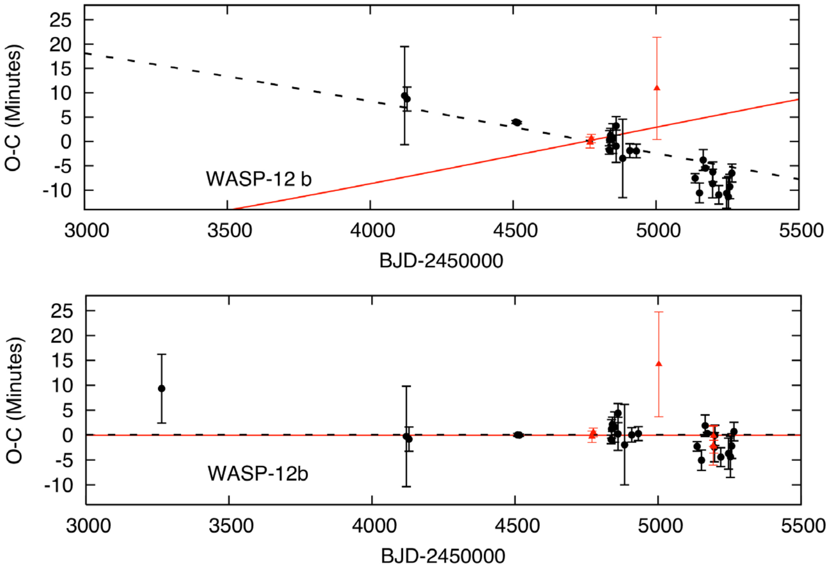

Figure 2. Transit (black points) and eclipse (red points) times of the hot Jupiter WASP-12b. The best-fit precessing model is shown with the dotted black line that indicates the expected transit times, while the solid red line indicates the expected eclipse times. The top panel indicates that a rapidly precessing model was favored before the addition of the Croll *et al.* (2011) eclipse times (bottom panel; red points); by comparing the Croll *et al.* (2011) eclipse times to the transit times of amateurs, it was shown that the planet was not precessing at a rate rapid enough to be currently detectable. Figure adapted from Croll *et al.* (2011).