Detection of Intermediate-Period Transiting Planets with a Network of Small Telescopes: transitsearch.org

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ABSTRACT

We describe a project (transitsearch.org) currently attempting to discover transiting intermediate-period planets orbiting bright parent stars, and we simulate that project's performance. The discovery of such a transit would be an important astronomical advance, bridging the critical gap in understanding between HD 209458b and Jupiter. However, the task is made difficult by intrinsically low transit probabilities and small transit duty cycles. This project's efficient and economical strategy is to photometrically monitor stars that are known (from radial velocity surveys) to bear planets, using a network of widely-spaced observers with small telescopes. These observers, each individually capable of precision (1%) differential photometry, monitor candidates during the time windows in which the radial velocity solution predicts a transit if the orbital inclination is close to 90°. We use Monte Carlo techniques to simulate the performance of this network, performing simulations with different configurations of observers in order to optimize coordination of an actual campaign. Our results indicate that transitsearch.org can reliably rule out or detect planetary transits within the current catalog of known planet-bearing stars. A distributed network of skilled amateur astronomers and small college observatories is a cost-effective method for discovering the small number of transiting planets with periods in the range $10\text{d} < P < 200\text{d}$ that orbit bright ($V < 11$) stars.

Subject headings: planetary systems — solar neighborhood

1. Introduction

Over the past seven years, Doppler radial velocity (RV) measurements have led to the discovery of over one hundred planets within a sample of several thousand bright, nearby Sun-like stars. As the catalog of worlds continues to grow, our view of extrasolar planets is shifting from an anecdotal collection of individual systems, e.g. 51 Pegasi, υ Andromedae, or 47 Ursae Majoris, to a more complete statistical census, in which categories and populations of planets can be clearly delineated (Marcy, Cochran, & Mayor 2000).[1] Yet the planetary systems from which we can learn the most — those that transit — remain anecdotal at best.

For each system, there is a chance that the planet will periodically transit the surface of the star as seen from Earth. An eclipsing Jupiter-mass planet on a 3-day orbit produces a periodic ~1.5% dimming of the parent star that lasts for about 3 hours. At present (August 2003) only a single transiting planet — HD 209458b, $P = 3.525$d — has been studied in detail (Charbonneau et al. 2000; Henry et al. 2000), while a second object (OGLE TM-56-b, Konacki et al. (2003)) has been recently announced, but not studied as extensively. HD 209458b has provided a scientific bonanza, including direct and accurate measurements of the planet's radius ($1.35 \pm 0.06 R_{\rm Jup}$; Brown et al. (2001)), mass ($0.69 \pm 0.05 M_{\rm Jup}$; Mazeh et al. (2000)), density, and even sodium in its atmosphere and hydrogen in its exosphere (Charbonneau et al. 2002; Vidal-Madjar et al. 2003).

The excitement generated by HD 209458b has led to a major push by the community to find additional transiting planets. A website maintained by Keith Horne[2] lists, along with

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[1] An up-to-date version of the planetary census can be found at http://cfa-www.harvard.edu/planets/

[2] http://star-www.st-and.ac.uk/~kdh1/transits/table.html

the project described in this paper, an additional twenty-four ground-based collaborations that are engaged in various efforts to discover planetary transits. In total, these surveys yield a reported capacity for discovering 148 planets per month. Despite this activity, however, an important corner of parameter space receives extremely little coverage; there is currently no other organized effort to detect intermediate-period planets which transit bright ($V < 11$ parent stars). We describe a strategy for detecting such transits, which we have adopted for the www.transitsearch.org collaboration.

Our basic approach is to harness a network of small independent telescopes to obtain multiple differential-photometric time-series of *known* planet-bearing stars during the well-defined time windows in which transits are predicted to occur. If several independent observers simultaneously measure a characteristic diminution or brightening at the predicted times of ingress or egress, then there is strong evidence that the star is exhibiting a transit, and follow-up confirmation can then be obtained at the time of the next predicted transit. The observational campaign is coordinated through a website: www.transitsearch.org.

2. Scientific Motivation

Any transits which our network uncovers will occur for planets which occult bright ($V < 11$) stars. This is an advantage. Such stars are precisely those for which the RV method can provide accurate orbital parameters and accurate values for $M \sin(i)$, both of which are required to usefully characterize the planetary properties. Furthermore, a bright parent star facilitates accurate photometry. The exquisite precision (1.1×10^{-4}) HST light curves which have been produced for HD 209458b (Brown et al. 2001) depend on the $V = 7.64$ magnitude of the parent star. Brown et al. (2001) report that in order to obtain optimal photon noise-limited precision with HST for HD 209458b, photometric measurements of 80 s duration (60 s integration plus 20 s CCD readout) were required. The critical ingress and egress periods were thus time-resolved into approximately 20 samples each. A $V \sim 9$ star, which produces ∼6 times fewer photons, would require 6-minute cadencing to obtain the same photometric precision, and the periods of ingress and egress would be resolved into only a few time intervals. For considerably dimmer stars ($V \sim 14$, say) photometric precision will necessarily be compromised.

The transitsearch.org collaboration is geared to survey planets with $10\text{d} < P < 200\text{d}$. This sensitivity to longer-period transits occurs because we can narrow our observations to specific predicted time windows. The detection strategy thus involves no data folding, and does not demand stable photometry over multiple nights or seasons.

Why would an intermediate-period transiting planet be of interest? Although the measured ($1.35 R_{\rm Jup}$) radius of HD 209458b is broadly consistent with its being a gas-giant composed primarily of hydrogen (Guillot et al. 1996; Burrows et al. 2000), recent work by Guillot & Showman (2002); Bodenheimer, Laughlin, & Lin (2003); Baraffe et al. (2003) all suggest that our understanding of irradiated giant planets is incomplete. These three studies agree that standard evolutionary models can recover the observed radius of HD 209458b only if the deep atmosphere is unrealistically hot. The recent studies incorporate realistic atmospheric temperature profiles; the no-core models of HD 209458b have a radius of $\sim 1.1 R_{\rm Jup}$, which is much too small.

Three resolutions to this problem have been suggested. Bodenheimer, Laughlin, & Lin (2003) show that HD 209458b might be receiving interior tidal heating through ongoing orbital circularization resulting from perturbations due to a second planetary companion, whereas Guillot & Showman (2002) propose that strong insolation-driven weather patterns on the planet are leading to conversion of kinetic wind energy into thermal energy at pressures of tens of bars. Burrows, Sudarsky & Hubbard (2003) argue that the size discrepancy stems largely from improper interpretation of the transit radius, and that the measured radius of HD 209458b in fact lies much higher up in the planetary atmosphere than is generally assumed.

In any event, an accurate size and mass determination for an intermediate-period planet will be of great help in resolving the observed size discrepancy for HD 209458b. A planet with intermediate period cannot not have significant internal tidal dissipation, but would still be receiving a modest amount of kinetic heating from the mechanism suggested by Guillot & Showman (2002). Furthermore, the Burrows, Sudarsky & Hubbard (2003) theory for HD 209458b is readily extended to predict effective transit radii at different planetary masses and temperatures; the discovery of an intermediate period transiting planet would provide a useful test of such predictions.

Intermediate-period planets are also interesting because they can harbor dynamically stable large satellites. Tidal interactions likely removed any satellites larger than $R = 70$km orbiting HD 209458b. Mars-mass moons, however, can last for 5 Gyr in the Hill Sphere of a $1M_{\rm Jup}$ planet orbiting a $1M_{\odot}$ star in a 27 day (0.18 AU) orbit, whereas in a 54 day (0.28 AU) orbit, Earth-mass moons are dynamically stable (Barnes & O'Brien 2002). Brown et al. (2001) report that with HST, detections of satellites as small as $1R_{\oplus}$ are feasible. Therefore, an intermediate-period planet found by our survey could be followed up to search for large moons, and, additionally, planetary rings. Prior to space-based missions such as KEPLER (Borucki et al. 2003), the detection of a large moon orbiting an intermediate-period transiting planet is the best prospect for finding a habitable world.

3. How Many Planets Transit Bright Stars?

Regardless of scientific benefit, our survey can be successful only if there are additional transiting planets to be found orbiting bright stars, and only if the telescope network is sensitive and responsive enough to definitively confirm or rule out the occurrence of transits for individual stars.

The *a priori* probability that a planet transits its parent star as seen from the line of sight to Earth is given by

$$\mathcal{P}_{\rm transit} = 0.0045\,\frac{1\,{\rm AU}}{a}\,\frac{R_\star}{R_\odot}\,\frac{1-e\cos(\pi/2-\varpi)}{1-e^2}\,, \qquad (1)$$

where a is the semi-major axis of the orbit, $R_\star$ is the radius of the star, e is the orbital eccentricity, and ϖ is the argument of periastron referenced to the plane of the sky. Using the parameters of the current radial velocity planet catalog[3], we find that among the 17 Doppler wobble planets with periods $P < 10$d, there are $\langle n \rangle = 1.75$ expected transits, and indeed, within this group, a transiting case (HD 209458b) is known. Sixteen of the planets with $P < 10$d have reported non-detections (although in some cases unpublished and unverified). These non-detections include HD 68988b, HD 168743b, and HD 217107b, which can be ruled out on the basis of observations made with the transitsearch.org network. Only one $P < 10$d planet, HD 162020b ($P = 8.428$d), has, to our knowledge, not yet been checked for transits.

Among the aggregate of 27 planets having periods in the range $10\text{d} < P < 200\text{d}$, the expected number of transiting planets is $\langle n \rangle = 0.72$. Almost none of the parent stars in this group, however, have yet been monitored for transits, due to low individual transit probabilities and increasingly uncertain transit ephemerides. The main sequence stars harboring intermediate-period planets therefore represent the primary targets for our network. We also note that among the 67 known planets with $P > 200$d, one expects $\langle n \rangle \approx 0.6$ additional transiting cases. However, as the planetary period becomes longer, follow-up becomes increasingly difficult due to uncertainties in the transit times and long

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[3]see, e.g., http://www.transitsearch.org/stardatabase/index.htm

intervals between occultations.

The transit probability for any given planet is not a strictly declining function of semi-major axis. For example, the highest *a priori* transit probability for any known planet belongs not to one of the short-period hot Jupiters (which tend to average $\mathcal{P}_{\rm transit} \sim 12\%$), but rather to the $P = 550$d planet orbiting ι Draconis. In this system, a large planetary semi-major axis (1.34 AU) is more than offset by the $12.8 R_\odot$ stellar radius (Allende Prieto & Lambert 1999), and favorable orbital geometry (e=0.7, $\varpi = 94°$; Frink et al. (2002)) which lead to $\mathcal{P}_{\rm transit} = 15.4\%$, with the next predicted transit occuring on April 4, 2004. An extreme case such as this leads to a transit depth which is hard to detect from the ground (and impossible for our network) but there are other intermediate-period planets which have surprisingly high transit probabilities (e.g. HD 38529b: $P = 14.5$d, $\mathcal{P}_{\rm transit} = 13.7\%$, or HD 74156b: $P = 51.6$d, $\mathcal{P}_{\rm transit} = 4.3\%$).

In addition to the current census, more planets with periods suitable for transitsearch.org will soon be emerging from the RV surveys. Currently, within the 10d $< P <$ 200d range, there are five known planets orbiting stars with $V < 6$, seven orbiting stars with $6 < V < 7$, six orbiting stars with $7 < V < 8$, and two planets each in the $8 < V < 9$, and $9 < V < 10$ ranges. If we assume that every available chromospherically quiet main sequence dwarf with $V < 6$ has been adequately surveyed for $P <$ 200d planets, and that each magnitude bin of unit width contains 1.8× as many stars as available for bin $(V - 1)$ (Cox 2000), then we expect that roughly $9 + 16 + 29 + 52 + 94 = 200$ detectable planets with $P <$ 200d exist in orbit around stars with $V < 11$, indicating that close to 180 additional planets in this category can be detected using current RV techniques for bright stars. Statistically, this implies that 6 intermediate-period transiting planets orbit bright nearby stars.[4] The goal of

[4]A similar calculation shows that 6 additional *short-period* ($P <$ 10d) transiting planets are likely to be orbiting bright stars

the transitsearch.org network is to find one of these transits.

4. Transit Detection With Small Telescopes

In the past several years, a number of amateur astronomers have detected the HD 209458b transits and have shown that the $\sim 1\%$ dimunition produced by a transiting Jovian planet is readily observable via differential photometry obtained with small (8-10 inch aperture) telescopes fitted with commercial-grade CCD detectors. A report of one of these observations (Arto Oksanen, Sky & Telescope, January 2001) raised a provocative question: Is it a realistic possibility for a network of small-college observatories and highly experienced amateurs to discover a new transiting system? If so, many small telescopes can be organized to maintain a time-intensive volunteer-based transit survey of known planet-bearing stars during predicted transit epochs.

In order to investigate the viability of detecting transits using low-cost equipment and software, we designed and documented an end-to-end procedure which allowed us to observe an HD 209458b transit. Our demonstration observatory consists of a Meade LX-200 8-inch f/10 telescope fitted with a Santa Barbara Instruments Group ST7E 765x510 pixel CCD. Slewing, auto-guiding, and aperture photometry are accomplished with a laptop running Mira 6.0 software.

With a focal reducer, the CCD image of a target region covers $36' \times 24'$, which is generally large enough to admit several $V = 9 - 11$ comparison stars for differential photometry. In the case of HD 209458, a field star HIP 108793 ($V = 8.33$) is situated $12'$ away. We acquire the target field prior to the predicted start of ingress, and obtain successive 2s CCD exposures at a cadence of 35s per frame. The short 2s exposures are used to avoid pixel saturation by HD 209458. The small overall duty cycle is caused by the need to acquire auto-guiding images and to read out the CCD. Sequences of 20 exposures are averaged together to produce composite measurements of the brightness of the stars in the field within 12 minute intervals. Using standard aperture photometry techniques, photoelectron counts from the target star are compared to counts from the comparison star(s) in the field. A transit manifests itself by the characteristic changes in the brightness of the target star during the predicted times of ingress and/or egress. This phenomenon is shown in Figure 1, for HD 209458b during the transit of 10/19/01. Photometric errors for each 12 minute bin are of order 0.003 magnitudes, and are dominated by atmospheric scintillation. We note that simple improvements, such as the use of a spot neutral-density filter to increase open-shutter time and reduce the difference in brightness between the target and a typical comparison star, could considerably improve precision.

For our purposes here, this observation tells us two things. First, transiting planets are readily detected with standard amateur-oriented equipment. Second, we can assume that many observers worldwide will have similar observational configurations, and will be capable of obtaining differential photometry of comparable precision.

5. Monte Carlo Simulation

In order to evaluate the viability of a collaboration-based transit survey of known planet-bearing stars, we have performed a Monte Carlo study which models realistic incarnations of the transitsearch.org network. This simulation is written in IDL[5] and makes heavy use of the IDL Astronomy User's Library[6].

The simulation is initialized with the following inputs: a list of observers and a target

[5]http://www.rsinc.com

[6]http://idlastro.gsfc.nasa.gov

list of known planet-bearing stars. Each observer has an associated location (latitude and longitude) and weather (average fraction of clear/cloudy nights per year). Each target has an associated position (RA and Dec), period P, estimated transit probability $\mathcal{P}_{\rm transit}$ calculated from equation 1, and a transit ephemeris. The actual ephemeris for any given system can be obtained from fits to existing RV data, but for simplicity in this simulation, transit ephemerides are generated randomly instead. In cases where a single star hosts multiple planets, it is listed in the target list with multiple entries. Once observers and targets have been set up, several record-keeping logs are also initialized.

The first Monte Carlo step is to assign which targets will host real transits in the simulation. The program calculates a true/false condition for each target based on its $\mathcal{P}_{\rm transit}$. The simulation then enters its main loop which proceeds through an observing campaign night-by-night; within each night there is nested a loop which proceeds through the observer list one-by-one. That inner loop over observers proceeds as follows.

Before assigning a target to an observer, the simulation first must determine if the weather is favorable for the night. While season-based weather patterns have not been figured into the model, the fraction of clear and cloudy nights at each observing location is known[7]. Using these probabilities, the night's weather for each location is determined in Monte Carlo fashion. If clear or cloudy, all observers common to the location will be affected identically. If the weather is determined to be partly cloudy, each observer must be dealt with independently, allowing for the possibility that some observers in a given location will be able to observe while others are not.

For each observer, the Julian date (JD) of sunrise and sunset at the observer's location

[7]For locations in the US, such data are available from http://www.ncdc.noaa.gov/oa/climate/online/ccd/cldy.html

are calculated for the current date in the campaign. The JD of sunset, the position of each target, and the observer's location are used to calculate airmasses for each target in the target list. Any targets that pass the airmass cutoff (2.5 in our simulations) at sunset are then checked to ensure they will pass the airmass limit for at least four hours. Thus a night of data will consist of at least four hours of time-series photometry, and we allow it to be as long as nine hours if the target is up (and the Sun is down).

With the narrowed list of targets that are up, the simulation next checks to see if any targets are near transit. We assume that transit ephemerides are accurate to within $\sim$5% of an orbit. If the observer's night overlaps at all with this margin of error for a target that is up, then that observer is assigned to that target. The likelihood of *two* observable stars being at transit in a given night is low, but if such a case does occur, the observer is assigned to the higher transit probability. Although there will be fewer opportunities to observe the longer-period planets, we feel it is justified to concentrate resources on targets where the probability of successfully observing a transit is higher.

Thus, only if an observer has a target near-transit and favorable weather, the simulation generates the night's photometry via Monte Carlo. Photometry is generated with an arbitrary zeropoint and gaussian noise. Additionally, for those targets that the simulation has randomly designated "real" transits, a simple linear ingress/egress and flat transit bottom based on HD 209458b are input into the photometry. We scale the ingress/egress times with the period of the planet in order to simulate long-period transits. Data from the system described in §4 (like that plotted in Figure 1) are the template on which we base our noise amplitude and transit depth. Many transitsearch.org observers are capable of photometry with higher precision, so we feel this conservative simulation is reasonable.

An observer's photometry for a night is very simply analyzed by calculating the Spearman's rank correlation for the data. Basically, this determines whether a linear trend has been detected between the beginning and end of a night's data and returns a confidence-level for such a trend. This simple analysis fits the overwhelming majority of cases where portions of ingress or egress have been observed, but will fail in the exceedingly rare case where the transit is perfectly centered in the night's time window.

The process of the preceeding five paragraphs is repeated for each observer in the observer list, and this constitutes one night of the campaign (the inner loop). The simulation then increments its internal "calendar" by one day and proceeds again — this repeats until the campaign ends (the outer loop).

For each target, the simulation keeps track of the number of no-correlations, 2-σ correlations, and 4-σ correlations observers have seen. Any 2-σ correlations are used to give a target a "free pass", allowing it to stay on the target list until more definite observations can be made. However, since the goal of any campaign is to observe as much of the target list as possible, targets must be eliminated from the list. Thus, a limit is set on the number of times a 4-σ correlation is shown before a star is dropped. This limit is generally low, for two reasons: in a real run, someone with access to a professional observatory will begin follow-up work, and additionally, in multiple realizations the 4-σ correlation was associated with false positives in less than 1% of all cases. Similarly, a limit is set on the number of times a target can produce a non-detection (no-correlation) before it is dropped from the list. This limit is generally fairly high, to avoid dropping an actually-transiting target simply because the transit occurred outside an observing window. Both drop limits scale with target planet period, as the 5% accuracy of ephemerides leads to exceedingly long observing windows for targets with periods as short as 100 days, leading necessarily to a higher number of non-detections.

In addition to this scorecard for each target, the simulation also generates many other record-keeping files, such as a log of the weather and observations of each observer for each night, and every photometry file that is generated. Certain variables of interest are also tracked, such as the summed transit expectation value from the remaining target list, updated whenever a target has been successfully eliminated from further observing.

6. Results

We have modeled several different configurations of observers, and a number of target lists. Addressed in this paper are five observer scenarios: a lone, dedicated observer at Mt. Hamilton near San Jose, CA; ten observers located at Mt. Hamilton; ten observers distributed across the U.S.; twenty observers split between San Jose and Sydney, Australia; and twenty observers distributed between eight worldwide locations. For comparison, a second run of a single observer has been made, but using a noise amplitude one-fifth that of the other runs, to represent an astronomer with access to a professional observatory. In each case, simulations are run for three target lists drawn from the pool of planet-bearing stars. The selection is based on planetary period, with maximum period cutoffs of 1000 days (essentially the complete listing of extrasolar planets), 365 days, and 100 days. In each case, 7 days is always the minimum period cutoff.

During trial runs, the 4-σ correlation and no-correlation limits were adjusted to minimize the number of false positives/negatives, while not making runs overly long. The values we used for these were such that there were no false positives among the amateurs, and two for the professional observer, for which the drop limits were lowered to match the reduced noise factor. While several actual transits were missed, these were due to incompleteness at the end of the run, not due to observers incorrectly ruling them out.

For each pair of observer list and target list, the simulation has been run 20 times to provide adequate statistics, and was analyzed to find a number of quantities, most importantly list completeness. Though it is possible to run the code until every target has been adequately observed, this usually leads to prohibitively long runs. Often, the end of a run is dominated by long period planets which provide few opportunities for observing, and depending on observer locations, may not *ever* be observed. Rather than running to absolute completion, we chose a fixed length for the run. In each case presented here, runs start near the end of summer, 2003, and end in January 2008. This generally means that the observers will not have completed the entire target list, but still provides a good demonstration of the differences between observer configurations.

The final list completeness is tallied in Table 1. Additionally, plots of targets remaining to be classified vs. time are shown in Figure 2, where we have recorded the JD on which targets were dropped and the number of targets remaining afterwards. A smoothed average curve is superimposed upon the target vs. time data from all 20 runs. Number of observers increases from left to right, as does the average physical separation between observers. The size of the target list increases downwards. The red curve is the test case for our professional astronomer.

In all cases, the curves show a characteristic delay time, in which observers begin to classify targets, but have not had enough nights to remove targets from consideration. At the ∼2 year mark, targets begin to become saturated, and the list of remaining targets shortens rapidly. Eventually, most targets are removed, and the curve flattens out as only the most difficult targets remain. As one would expect, having more observers increases the number of targets it is possible to cover by the end of the run, and additionally, it is easily seen in the 100 day list and 365 day lists that observers more evenly spread in longitude do a slightly better job completing the target list. Also, note that while a lone amateur observer virtually never amasses enough data to drop a target, even an observer with full access to a professional-grade telescope can do no better than 10 observers clustered around the same location.

The differences are better illustrated when we plot not the number of targets remaining, but the summed transit expectation value remaining on the target list (see Figure 3). It is easier to see the effect of longitudinal spread among observers. The second and fourth columns represent observers concentrated in one and two locations, respectively, and show almost three years before significant target completeness begins to show. By contrast, the third and fifth columns represent observers located over a larger spread in longitude, and they begin to make progress fully a year before their counterparts. Globally, the optimal configuration seems to be a large number of observers with maximal spread in longitude/latitude. From our data, we show that this configuration of observers can cover roughly 40% more of the probability-weighted target list than even the professional observer.

7. Conclusion

These simulations show that while a single observer campaign is capable of discovering transits, this observer will generally leave 30-50% of the sky uncovered. Not only can multiple observers better cover the sky, they can also cover it more quickly. Additionally, the data reveal the importance of having not only multiple observers in multiple locations, but also in ensuring that the observers cover a wide range of longitudes in both hemispheres. Note, for instance, the difference in time to completion between the case where 10 observers are located in both San Jose and Sydney, and the case where 20 observers are scattered across nine worldwide locations. It is apparent that longitudinal coverage is important. One naturally expects that weather will be a key factor in determining time to completion, as it will most dramatically affect the length of a run that is confined to a single location. But the spread in longitude proves equally important, as one might guess from the process of viewing eclipses on Earth. Both timing *and* location are everything.

Most current work on transits is divided into two categories, our Mount Hamilton case (the single dedicated observer), and studies like OGLE which rely on time sequenced, wide-field snapshots that detect possible transits. However, we have shown that a single observer is at a disadvantage, no matter how powerful the telescope, while wide-field surveys suffer from false positives associated with binary stars, and additionally provide poor targets for follow-up radial velocity work. In the end, even confining a search to the known extrasolar planets produces a long list of potential targets that proves difficult to work through. We have shown that by handing the bulk of observing work to a dedicated team of observers with good longitudinal coverage, we may ensure that when a transit is expected to occur, there is *always* someone watching, and that this team will prove competitive with any other transit search venture.

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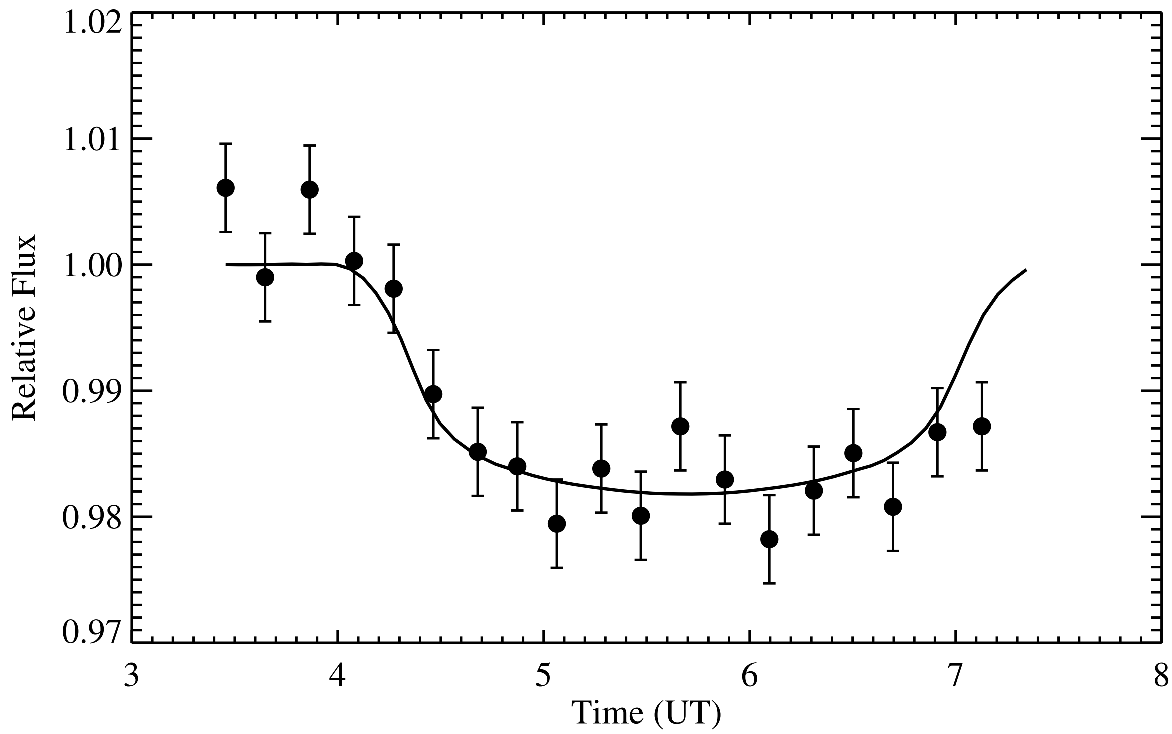

Fig. 1.— Detection of the planet transiting HD 209458, using the portable observatory described in the text. The data were taken from Fremont, CA on the night of 19/20 October 2001. The solid curve is the model of Brown et al. (2001).

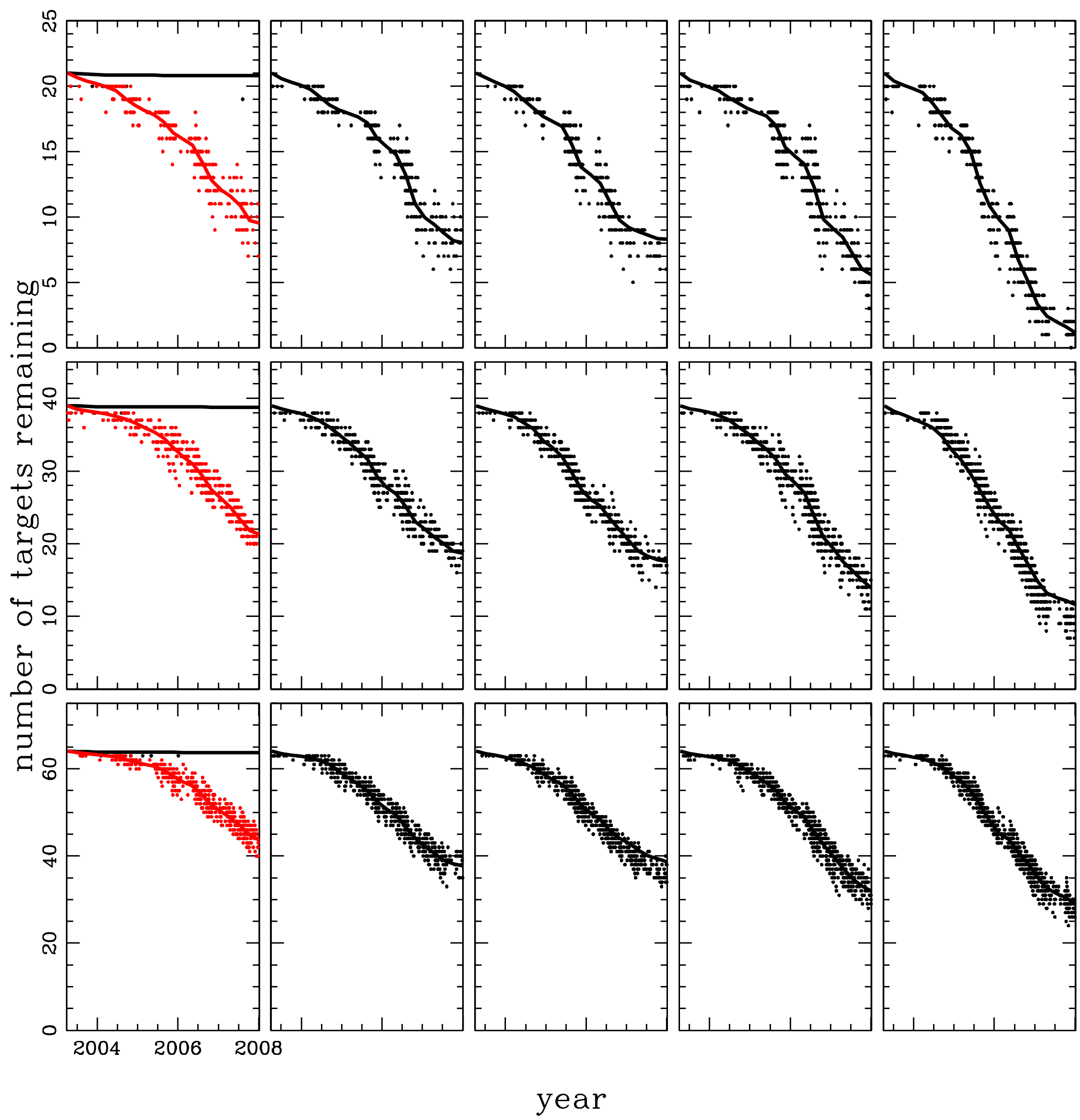

Fig. 2.— Simulated performance of sets of observers, showing number of targets remaining vs. time. The five columns of figures, from left to right, show survey results from (1) A single observer at Mt. Hamilton, CA, (2) ten observers on Mt. Hamilton, (3) ten observers spread across the continental US, (4) twenty observers divided between two locations, one in each hemisphere, and (5) twenty observers distributed world-wide. The three rows, from top to bottom, show results from period-limiting the target list at 100, 365, and 1000 days, respectively. The red curve represents a single observer on Mt. Hamilton, but with access to a telescope providing photometry ∼5 times as accurate. A point is generated for every date on which a target was dropped from the list; points from all 20 realizations are shown. The line is a smoothed average over realizations.

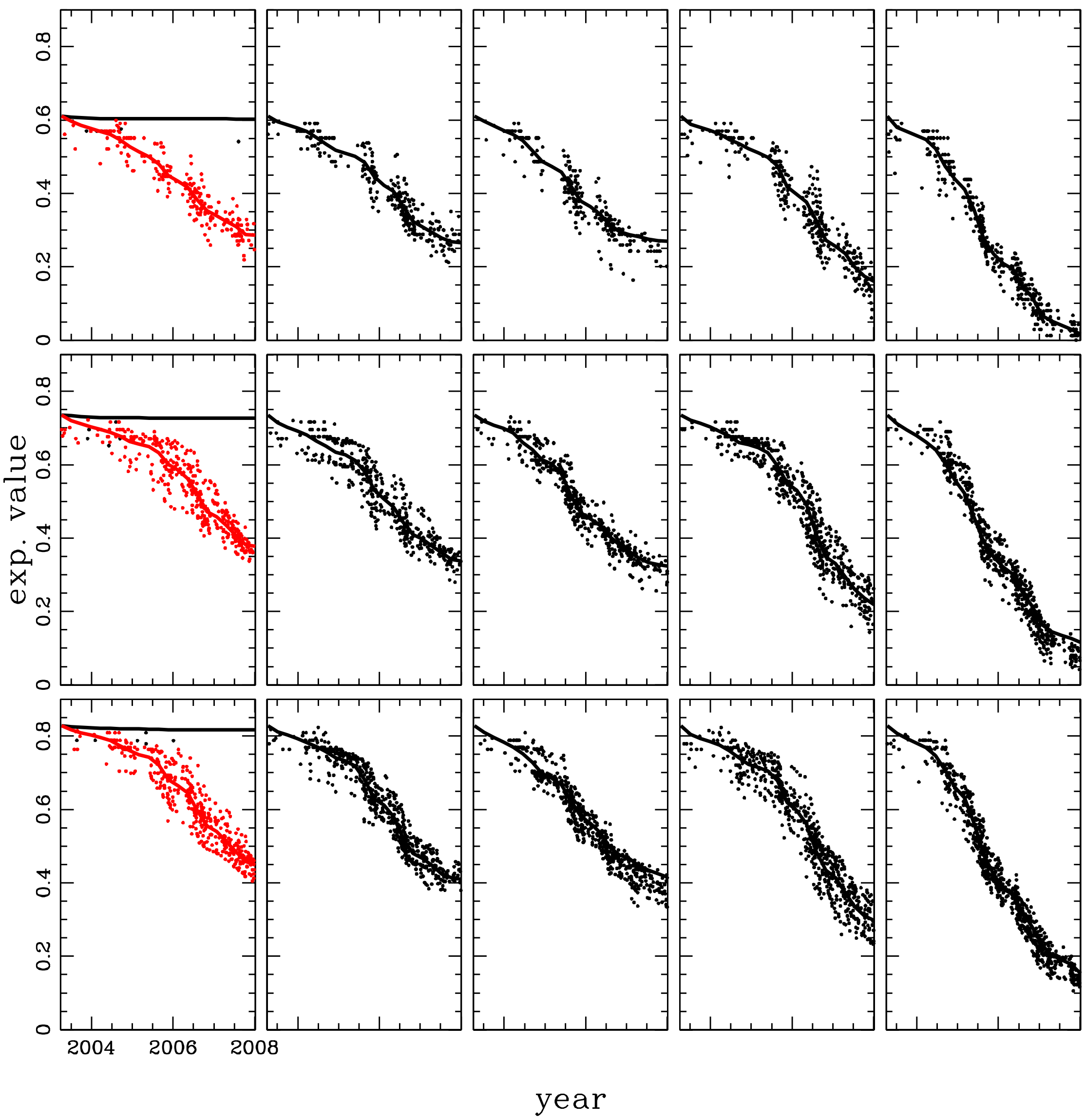

Fig. 3.— Simulated performance of sets of observers, showing remaining transit expectation value vs. time. The five columns and three rows of figures are as in Figure 2.

Table 1. Simulation Results

Observer Configuration	Period upper limit for target list		
	100d	365d	1000d
1 observer, San Jose	0.5 ± 1.5	0.4 ± 1.0	0.5 ± 0.7
1 professional observer, San Jose	55 ± 7	45 ± 4	47 ± 4
10 observers, San Jose	62 ± 5	52 ± 3	41 ± 3
10 observers, U.S.A.	65 ± 6	56 ± 3	44 ± 3
20 observers, San Jose & Sydney	74 ± 6	64 ± 4	50 ± 4
20 observers, worldwide	95 ± 3	76 ± 4	56 ± 3

Note. — Percent of target list completed by end of run for each observer configuration and target list. Observer configurations follow the same order as in Figure 2.