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Status and Prospects of Planetary Transit Searches: Hot Jupiters Galore

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Abstract. The first transiting extrasolar planet, orbiting HD 209458, was a Doppler wobble planet before its transits were discovered with a 10 cm CCD camera. Wide-angle CCD cameras, by monitoring in parallel the light curves of tens of thousands of stars, should find hot Jupiter transits much faster than the Doppler wobble method. The discovery rate could easily rise by a factor 10. The sky holds perhaps 1000 hot Jupiters transiting stars brighter than $V = 13$. These are bright enough for follow-up radial velocity studies to measure planet masses to go along with the radii from the transit light curves. I derive scaling laws for the discovery potential of ground-based transit searches, and use these to assess over two dozen planetary transit surveys currently underway. The main challenge lies in calibrating small systematic errors that limit the accuracy of CCD photometry at milli-magnitude levels. Promising transit candidates have been reported by several groups, and many more are sure to follow.

1. Three Waves of Extrasolar Planet Discovery

1.1. Doppler Wobble Planets

In the first wave of extrasolar planet discovery, Doppler wobble surveys have sustained a discovery rate of 1 or 2 planets per month since the debut of 51 Peg (Mayor & Queloz 1995). The extrasolar planet catalog now holds over 100 Doppler wobble planets, filling in the top-left quadrant of the planet mass m vs. orbit size a discovery space (Figure 1). The Doppler wobble planets have a roughly uniform distribution on the $\log m$–$\log a$ plane, with two clear and interesting boundaries, a maximum planet mass $m \lesssim 10\ m_J$, and minimum orbit size $a \gtrsim 0.03$ AU ($P > 3$ d). In their second decade, Doppler surveys will extend the catalog to larger orbits and push down to somewhat lower masses as precision radial velocities improve from 3 to 1 m s^{-1}.

1.2. Hot Jupiter Transits

A second wave, the hot Jupiter discovery era, is fast approaching. The Doppler wobble surveys establish that hot Jupiters, with $P \sim 4$ d and $a \sim 0.05$ AU, are orbiting around $\sim 1\%$ of nearby sun-like stars. A fraction of these, $P_t \approx R_\star/a \sim 10\%$, will have orbital inclinations close enough to edge-on so that the planet transits in front of its star. We may therefore expect that 1 star

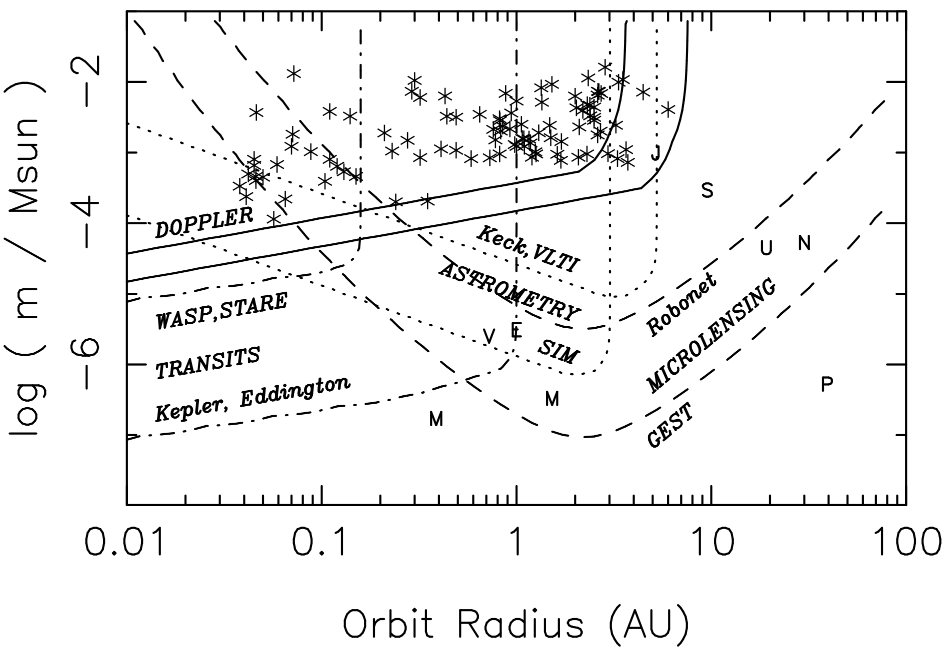

Figure 1. Planet detection thresholds on the planet mass vs. orbit radius plane for four indirect methods including Doppler (——), transits (− · −) microlensing (- - -), and astrometry (· · ·). The 9 solar system planets, and 100 extrasolar planets (∗) are also indicated.

in 1000 should be "winking" at us. During each transit, the starlight dims by $\Delta f/f \approx (r/R_\star)^2 \sim 1\%$ for a time $\Delta t \approx (PR_\star/\pi a) \approx 3$ hours. A CCD camera that can monitor $\sim 30,000$ stars in parallel for ~ 60 clear nights should therefore be able to discover ~ 30 hot Jupiters with periods out to ~ 10 days.

If ongoing transit surveys live up to these expectations, the hot Jupiter discovery rate could soon rise to 10 or even 100 times that of current Doppler wobble surveys. Transits may reveal thousands of hot Jupiters in the next 5 years. A large catalog of hot Jupiters will help to establish how their abundance, maximum mass, and minimum period depend on star mass, age, metallicity, and environment. Several hundred should be bright enough for radial velocity work to establish masses to go along with radii from transits, establishing relationships between mass, radius, orbit, and age. Perhaps 10 will be bright enough for atmospheric studies via scattered starlight (Cameron et al. 1999), transit spectroscopy (Seager and Sasselov 2001; Brown 2001; Charbonneau et al. 2002), and detection of infrared thermal emission (Charbonneau 2003; Richardson et al. 2003).

1.3. Transits from Space

A third wave of discovery will arrive with the $\sim$ 2007 launches of Kepler (NASA) and Eddington (ESA). These missions deploy CCD cameras on wide-field space telescopes designed to detect transits of Earth-sized planets with $\Delta f/f \sim 10^{-5}$. Stellar variability may be a limiting factor. If successful, and depending on the abundance of low-mass planets, the yield may be $\sim 10^4$ hot Jupiters, $\sim 10^2$ "hot Earths", and a handful of "habitable" Earths. The first discoveries will be hot Jupiters and Earths. After 3–4 years, by $\sim$ 2011, the catalog may include Earth-analogs in the "habitable" zone.

2. The First Transits: HD 209458b

Since hot Jupiters with $P \approx 4$ d have a 10% transit probability, we expect 1 in 10 of the shortest-period Doppler wobble planets to exhibit transits. Dramatic verification of this prediction came with the discovery of the first extrasolar planet transits (Charbonneau et al. 2000). HD 209458 dims by 1.6% for 3 hours every 3.5 days. This star is so bright ($V = 7.8$) that the transits could be discovered with a remarkably small (10 cm!) wide-angle (6°) CCD camera (STARE). The wide field is essential for high-precision differential photometry of stars this bright, so that comparably bright comparison stars can be measured simultaneously.

The HD 209458 transits were quickly confirmed by several groups (Henry et al. 2000; Jha et al. 2000). The most spectacular light curves by far were captured by using the HST/STIS spectrograph with a wide slit (Brown et al. 2001). The transit shape, recorded in exquisite detail, fits an immaculate limb-darkened star occulted by the circular silhouette of the planet, yielding the orbit inclination $i = 86^\circ.6 \pm 0^\circ.2$ and planet radius $r = 1.35 \pm 0.06\ r_J$. With an rms accuracy better than 10^{-4}, significant limits were placed on moons ($r_{\rm moon} < 1.2\ r_\oplus$) and rings ($r_{\rm ring} < 1.8\ r_\oplus$). With $m \sin i = 0.69\ m_J$ from the star's Doppler wobble, this hot Jupiter is clearly a "bloated" gas giant. Transit spectroscopy (Seager and Sasselov 2001; Brown 2001) detects Na I absorption from the extrasolar planet atmosphere (Charbonneau et al. 2002).

3. Scaling Laws for Planetary Transit Surveys

Discovery of transits depends on the planet (mass m, radius r, orbit size a), on the star (mass $M_\star$, radius $R_\star$, luminosity $L_\star$, distance d, galactic latitude b, dust extinction K) and on experimental parameters (aperture D, field of view θ, quantum efficiency Q, bandwidth $\Delta\lambda$, angular resolution $\Delta\theta$, sky brightness $\mu_{\rm sky}$, duration t, duty cycle f). Scaling laws can help in optimizing and comparing the discovery potentials of current experiments.

The planet catch (N_p planets) is

$$\frac{dN_p}{d\log a\ d\log m} \approx \left(\frac{\theta^2 d^3}{3}\right)\left(\frac{n_\star}{e^{d|\sin b|/H}}\right)\left(\frac{df_p}{d\log a\ d\log m}\right)\left(\frac{R_\star}{a}\right) . \qquad (1)$$

The four factors are: (1) The survey volume, $(\theta^2 d^3/3)$, covering a solid angle θ^2 out to distance d. (2) The star number density $n_\star\ e^{-d|\sin b|/H}$, with a local density $n_\star \sim 0.02$ F,G,K stars pc^{-3} $M_\odot^{-1}$, and galactic disk scale height $H \approx 300$ pc. (3) The number of planets per star, $(df_p/d\log a\ d\log m) \equiv \eta_p \approx 0.05$, for $a > 0.03$ AU ($P > 3$d) and $m < 10\ m_J$. This gives 0.007 hot Jupiters (3–5d, 1–10 m_J) per star, consistent with the findings of Doppler wobble surveys. (4) The orbit alignment probability, $P_t \approx R_\star/a$.

The signal-to-noise ratio for transit detection is

$$\frac{S}{N} \approx \frac{(r/R_\star)^2 \; f_\star}{(f_\star + f_{\rm sky})^{1/2}} \left(\frac{P \; R_\star}{\pi \; a} \frac{t \; f}{P} \right)^{1/2} \quad . \tag{2}$$

The transit depth $\Delta f \approx (r/R_\star)^2 f_\star$ must be detected against Poisson noise from the star and sky photons. The time available to do this is the transit duration $\Delta t \approx (P R_\star / \pi a)$, and the S/N improves as $\sqrt{\Delta t \; N_t}$, where $N_t \approx t f / P$ is the number of transits observed in time t. The number of sky and star photons scale as $f_{\rm sky} \propto (D^2 \; Q \; \Delta\lambda) \; (\Delta\theta^2 \; \mu_{\rm sky})$ and $f_\star \propto (D^2 \; Q \; \Delta\lambda) \left(L_\star d^{-2} e^{-Kd} \right)$, respectively.

The survey distance d is the maximum at which transits are detectable (e.g., $S/N > 10$). In ground-based surveys, sky noise sets this faint limit, and the planet catch then scales as

$$\frac{dN_p}{d\log a \; d\log m} \propto \left(\frac{\eta_p \; r^3}{a^{7/4}} \right) \left(\frac{L_\star^{3/2} \; n_\star}{R_\star^{5/4} \; e^{3Kd/2}} \right) \theta^2 \left(\frac{D^2 Q \; \Delta\lambda \; f \; t}{\Delta\theta^2 \; (S/N)^2 \mu_{\rm sky}} \right)^{3/4} \quad , \tag{3}$$

where the planet, star, and experimental parameters are grouped.

To estimate the discovery rate, consider a typical hot Jupiter ($r = r_J$, $P = 4$ d, $a = 0.05$ AU) orbiting a sun-like star ($L_\star = L_\odot$, $M_\star = M_\odot$, $R_\star = R_\odot$). For a fiducial set of transit survey parameters ($D = 1$m, $\theta = 1^\circ$, $\Delta\theta = 1$ arcsec, $Q = 0.3$, $\Delta\lambda = 2000$Å, $t = 60$ d, $f = 0.25$, $S/N = 10$, $\mu_{\rm sky} = 18$ mag arcsec^{-2}, $K = 0.5$ mag pc^{-1}), evaluation of the above expressions indicates that hot Jupiter transits can be detected on sun-like stars down to $V \approx 18$, out to $d \approx 2.5$ kpc, at a rate of 12 planets per month.

4. Transit Searches Wide and Deep

For this review, two dozen teams returned e-mail questionaires providing information on their transit search experiments. The large number of teams makes it impossible to report more than summary information, which is collected in Table 1, and summarized in Figure 2.

The experiments break into two main groups, wide and deep. Because the planet catch scales as $\theta^2 D^{3/2}$, wider fields of view enable small telescopes to compete. For each experiment I have used the scaling laws to evaluate the faint magnitude, the maximum distance, and the hot Jupiter discovery rate. Summing over all experiments, the potential discovery rate approaches $\sim$ 200 planets per month.

The wide-angle survey teams follow STARE and Vulcan in deploying small ($\sim$ 10 cm) wide-angle ($\sim$ 10°) CCD cameras. These experiments use a CCD pixel size > 1 arcsec, sacrificing angular resolution to expand the field of view. The faint limit at $V \sim$ 12–13 reaches to $d \sim$ 300–500 pc, comparable to the galactic disk scale height, so that target fields cover the entire sky.

The deep survey teams employ existing CCD cameras, often mosaics, on established (1–4 m) telescopes. The faint limits at $V \sim$ 19–21 reach to $d \sim$ 4–5 kpc (limited by dust), so that galactic plane and open cluster fields are primary targets.

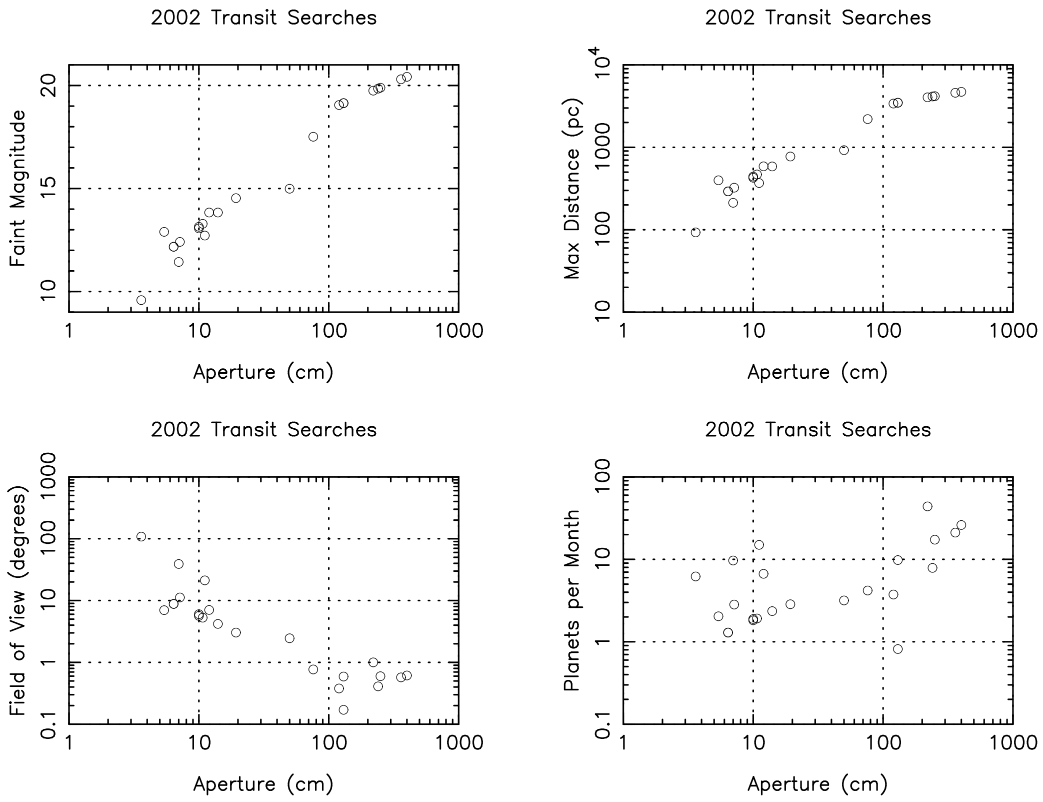

Figure 2. Parameters and discovery potential for the 2002 transit surveys listed in Table 1.

Our estimates suggest typical discovery rates of 3–10 planets per month for both wide and deep surveys. For multi-CCD mosaic cameras on 2–4 m telescopes, a discovery rate of 30 planets per month would be possible, if these telescopes could be dedicated to transit searches. It is delightful to realize that 10 cm telescopes can compete with a 4 m in the discovery of hot Jupiters.

The discovery rates in Table 1 may be good to a factor of 2, and should be regarded as ideal performance benchmarks for dedicated transit surveys, indicating also the relative discovery potential of different experiments. Actual performance will be degraded by many effects (crowding, moonlight, airmass, seeing, vignetting, weather, sub-optimal data analysis, competing observing programs). As a sanity check, Table 1 estimates 19,000 stars with $V < 13.8$ and 7 planets per month for the Vulcan experiment. For comparison, Borucki et al. (2001) analyzed 6000 stars down to $V = 13$, finding over 100 variables, about 50 eclipsing binaries, and 3 planetary transit candidates (all rejected by follow-up spectroscopy). Why this difference between ideal and actual performance? From Figure 6 in Borucki et al. 2001, Vulcan light curves achieved 1.5 times the photon noise for $V_{\rm sky} = 11.1$. The sky is 1.6 times brighter than $V_{\rm sky} = 11.6$ from Table 1, probably because Vulcan's PSF is wider than the 2-pixel (12 arcsec) FWHM gaussian adopted here. This should cut the survey volume by $(1.5)^{3/2}(1.6)^{3/4} = 2.6$. In fact moving the faint limit from $V = 13.8$ to $V = 13.0$ cuts the volume by a factor 3. This explains the difference between 19,000 and

Table 1. 2002 Planetary Transit Surveys

	program	D cm	$F/$	θ deg	CCD kxk	pixel arcsec	sky mag	star mag	d pc	stars 10^3	planets /month
1	PASS	3.6	1.4	108	1x1×15	98	5.6	9.6	93	18	6
2	Vulcan-S	5.4	5.6	6.98	4x4	6.1	11.7	12.9	397	6	2
3	HAT-1	6.4	2.8	8.84	2x2	15.5	9.6	12.2	292	4	1
4	WASP0	6.4	2.8	8.84	2x2	15.5	9.6	12.2	292	4	1
5	ASAS-3	7.1	2.8	11.2	2x2×2	13.9	9.9	12.4	323	8	3
6	PPS	10.0	2.8	5.66	2x2	9.9	10.6	13.1	441	5	2
7	PSST	10.7	2.8	5.29	2x1	9.3	10.8	13.3	468	5	2
8	STARE	10.0	2.9	6.03	2x2	10.7	10.5	13.1	427	5	2
9	SuperWASP	11.1	1.8	21.2	2x2×5	16.7	9.5	12.7	368	43	15
10	Vulcan	12.0	2.5	7.04	4x4	6.2	11.6	13.8	587	19	7
11	RAPTOR	7.0	1.2	39.1	2x2×4	34.4	7.9	11.4	212	28	10
12	RAPTOR-F	14.0	2.8	4.19	2x2	7.4	11.3	13.8	586	7	2
13	BEST	19.3	2.7	3.04	2x2	5.3	12.0	14.5	774	8	3
14	SSO/APT	50	1.0	2.46	0.8x1.1	9.4	10.7	15.0	923	9	3
15	TeMPEST	76	3.0	0.77	2x2	1.35	15.0	17.5	2200	12	4
16	PISCES	120	7.7	0.38	2x2×4	0.33	17.1	19.1	3395	11	4
17	ASP	130	13.5	0.17	2x2	0.30	17.1	19.1	3477	2	1
18	OGLE-III	130	9.2	0.59	2x4×8	0.26	17.1	19.1	3477	28	10
19	GOCATS	220	?	1.00	4x4×4	0.44	17.1	19.7	4036	126	44
20	STEPSS	240	?	0.41	4x2×8	0.18	17.1	19.8	4131	23	8
21	UStAPS	250	3.0	0.60	2x4×4	0.37	17.1	19.9	4176	50	17
22	EXPLORE-S	400	2.9	0.61	2x4×8	0.27	17.1	20.4	4707	75	26
23	EXPLORE-N	360	4.2	0.57	2x4×12	0.21	17.1	20.3	4586	61	21

Total planets per month: 191

(See `http://star-www.st-and.ac.uk/~kdh1/transits/table.html` for additional information and links to project web pages.)

6000 stars, and validates our star count estimates. We still expect $7/3 \sim 2.3$ planets per month. We adopt $S/N > 10$ for transit detection, and the planet catch scales as $(S/N)^{-3/2}$. Perhaps Vulcan's effective threshold is even higher given that the elaborate self-calibration used to reduce systematic errors also suppresses weak transit signals. This comparison illustrates both the difficulty of optimizing performance, and the benefits of doing so, since most discoveries will be near the faint limit of the survey.

4.1. Special Target Transit Surveys

Three teams report using a strategy targeting specific stars to enhance their chances of planet discovery. The TEP team targets low-mass eclipsing binaries, enhancing the transit probability if the binary and planetary orbits are co-aligned, and the sensitivity to small planets due to the small stellar radii. CM Dra is now thoroughly probed for circumbinary planets down to $\sim 3\ r_\oplus$

(e.g., Deeg et al 1997; Doyle et al. 2000), and several other systems are under study.

Greg Henry (TSU) uses several robotic photometric telescopes at Fairborn Observatory to follow-up Doppler wobble planets in search of transits at known times of conjunction. This has lead for example to independent discovery of the transits of HD 209458b (Henry et al. 2000).

Tim Castellano and Greg McLaughlin (transitsearch.org) are coordinating a network of amateur observers to target stars with known planets. The times of transit, and the probability of a planet transit for a given star, are known in advance, thus limiting the observation time and data analysis.

4.2. Globular Cluster Transit Surveys

HST can resolve main-sequence stars in the crowded cores of globular clusters. Staring for 8 days at 47 Tuc, HST monitoring of 34,000 $V = 17$–21.5 main-sequence stars should have found 17 transits, but in fact found none (Gilliland et al. 2000). Hot Jupiter formation and/or survival is evidently inhibited, perhaps by low metallicity (Gonzalez 1998; Gonzalez et al. 2001; Santos, Israelian & Mayor 2001), ultraviolet evaporation (Armitage 2000), or collisional disruption (Bonnell et al. 2001) of the proto-planetary disks in this crowded stellar environment.

4.3. Open Cluster Transit Surveys

Janes (1996) recommended open clusters as ideal targets for planet transit surveys. Teams currently using 1–2.5 m telescopes to hunt transits in open cluster fields include PISCES (Whipple 1.2 m, Mochejska et al. 2002), GOCATS (LPL 1.6/2.2 m, C. Barnes), STEPSS (MDM 2.4 m, J. Burke et al.) and UStAPS (INT 2.5 m, Street et al. 2002). The clusters (number of nights) reported to be under analysis are PISCES: N6791(25), GOCATS: M35+M67(15), STEPSS: N1245(19), UStAPS: N6819(20/3), N6940(20/3), N7789(20/3+10). Although field stars usually dominate these surveys, the clusters provide samples of stars with a common age, metallicity and distance.

4.4. Galactic Plane Transit Surveys

Large (1–4 m) telescopes equipped with wide-field (0.5–1°) CCD cameras are capable probes of planetary transits of stars at large distances (2–4 Kpc). The galactic plane provides a high density of stars in the long narrow survey volume. These deep surveys will measure the abundance and period distribution of hot Jupiters in a variety of stellar populations throughout the galaxy well beyond the solar neighborhood.

The OGLE III team, using their 1.3 m microlensing survey telescope's new 0.6° CCD camera, have monitored $\sim 52,000$ galactic disk stars for 32 nights, and report 59 transit candidates with periods ranging from 1 to 9 days (Udalski et al. 2002). The EXPLORE team, using the CTIO 4 m and CFHT 3.6 m, have observed two galactic plane fields, finding 3 possible planetary transit candidates (Mallen-Ornelas et al. 2002).

Among the candidates already identified may be the first hot Jupiters discovered from their transit signatures. Since Jupiters, late M dwarfs, and brown dwarfs have similar radii, and partial eclipses can mimic transits by smaller bodies, confirmation of these extrasolar planet candidates now awaits radial velocity follow-up with $\sim$ 1 km s^{-1} precision to detect or rule out the star wobble signature of stellar and brown dwarf companions.

4.5. Wide-Angle Transit Surveys

Wide-angle transit surveys, following in the footsteps of Vulcan and STARE, may offer the most exciting discovery potential because they target bright stars for which follow-up radial velocity work can measure masses to go along with the radii from transits. The main challenge is to achieve $\sim$ 10^{-3}mag accuracy in differential photometry over a very wide field of view, in which airmass, transparency, differential refraction, seeing, and even the heliocentric time correction, all varying significantly across the field.

If the requisite accuracy can be achieved (e.g., Borucki et al. 2001), these surveys should discover hot Jupiters transiting thousands of bright nearby main-sequence F, G, K, and M stars. Given the modest survey depth ($\sim$ 400 pc), the targets are solar neighborhood stars distributed over the entire sky. For a conservative estimate, assume that $V = 7.8$ HD 208458b is the brightest. Since each magnitude quadruples the number of stars in the survey volume, if there is 1 brighter than $V = 8$, there should be 4 down to $V = 9$, 16 to $V = 10$, 64 to $V = 11$, 250 to $V = 12$, and 1000 to $V = 13$.

How long might it take to find the 1000 brightest stars transited by hot Jupiters? There should be 2–3 in each $10^\circ \times 10^\circ$ field. Assuming 2 months per field, it would take over 60 years for a single 10° CCD camera to survey the entire sky. Fortunately, with a dozen experiments already underway (Table 1), the hot Jupiter discovery era will likely be complete to $V = 13$ in $\sim$ 5 years.

4.6. When will the Fun Begin?

Expectations are high, but the number of new planets revealed by transits is still zero. Is something amiss? Many teams are working hard (Table 1), but the data analysis and computer processing requirements for a dedicated transit survey are challenging and have not yet been achieved by most of these groups. Several teams have reported their first batches of transit *candidates*, and it is likely that the first new planets are in these lists. However, we must expect that many (most?) of the transit candidates will be false alarms or transit mimics (stellar variability, parital eclipses, brown dwarf or white dwarf eclipses). Weeding out the mimics requires follow-up observations, e.g. multi-colour eclipse photometry, low-resolution spectroscopy, and medium-precision ($\lesssim$ 1 km s^{-1}) radial velocities, which are already underway.

What if discovery rates fail to meet our expectations? We must allow, of course, for the reduced efficiency of actual observing programs, and for some losses due to necessary shortcuts in the data analysis, but if discovery rates are still too low this will also be an interesting result. The hot Jupiter abundance found in Doppler wobble surveys may be higher than in some of the deeper fields targeted in transit surveys. It is also possible that HD 209458b is atypically large, and that most of the hot Jupiters are smaller and hence harder to detect by means of transits. Whatever the outcome, we should not have to wait long. Discoveries will materialize or not within a year.

5. Conclusion

With Doppler wobble surveys now reaching for long-period planets, is the extra-solar planet field approaching a discovery plateau? Emphatically no. The era of hot Jupiters is about to open with discovery rates that should rise to 10 or 100 times the 1 or 2 planets per month from ongoing Doppler wobble surveys. The next 5 years should bring us hot Jupiters galore.

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