Scientific Frontiers in Research on Extrasolar Planets
ASP Conference Series, Vol. 294, 2003
D. Deming and S. Seager, eds.

Spectroscopic Follow-Up Observations of Planetary Transit Candidates Identified by Project Vulcan

David W. Latham

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Abstract. We have used the CfA Digital Speedometers to carry out spectroscopic follow-up observations of 35 planetary transit candidates identified by project Vulcan. Nine of the candidates prove to have stellar companions with orbital motions consistent with the transits found by Vulcan. This demonstrates that Vulcan has succeeded in identifying real photometric variations of the sort expected for transits by close-in giant planets, with dips of up to a few percent and periods of up to several days. Three of the systems with orbital solutions are double-lined spectroscopic binaries, and grazing eclipses are the source of the photometric variations. Another two of the systems are triples, with a constant third star diluting the depth of the eclipses in a nearby eclipsing binary. For the four systems that are single-lined, the orbital solutions suggest that the light curves are due to eclipses by small M-dwarf companions. A few of the candidates, all with marginal transit detections, show no velocity variations at the level of about 0.5 km s^{-1}. If they have orbital companions responsible for the observed photometric variations, the masses must be less than about 10 Jupiter masses.

1. Introduction

Although it was recognized many years ago that a Jupiter-sized planet would generate an observable dip in the light of its parent star if it happened to be aligned properly to transit in front of the star (e.g., Borucki 1984), it wasn't until giant planet candidates were discovered in short-period orbits (e.g., Latham et al. 1989; Mayor & Queloz 1995) that the chances for observing such an event seemed good enough to get serious about actually trying the experiment. An early example was the search for a transit at the time predicted by the spectroscopic orbit for the HD 114762 system (Robinson et al. 1990). Soon after the discovery of a planet orbiting 51 Peg with a very short period, several groups quickly recognized the feasibility of ground-based photometric searches for transits of close-in giant planets, with the expectation that roughly one out of a thousand solar-type dwarfs should show transits with periods shorter than a week or so.

One of the first groups to get started with serious observing was project Vulcan (Borucki et al. 2001). This team developed and put into operation at Mount Hamilton, California, a CCD photometer fed by a small fast lens (8 cm aperture and 30 cm focal length) covering a 7° x 7° field. A small lens and wide field were chosen so that transit candidates identified by the project would be brighter than $V = 13$ mag and thus would be bright enough for spectroscopic follow-up observations at high resolution and good signal-to-noise ratio, as would be required for the determination of a spectroscopic orbit for a giant planet.

A photometric dimming that is 1 or 2% deep and lasts a few hours does not necessarily imply that there is a giant planet orbiting the star, because there are various configurations involving only stars that can also produce such an event. An obvious case that can mimic a planetary transit is an eclipsing binary where the depth of the eclipse is small either because the eclipse is grazing, or because the secondary star is much smaller than the primary, or because the light of a third star has diluted the eclipse. In the case of grazing or diluted eclipses involving two nearly equal stars, the light curve should be roughly V-shaped. This should be distinguishable from the more box-shaped light curve expected for a planet passing in front of a star, if the photometry is good enough. However, the eclipse of a K giant by a solar-type dwarf or the eclipse of a hot main-sequence star by an M dwarf can look very similar to a planetary transit. These two classes of shallow eclipses are expected to be fairly common in a magnitude-limited sample, where roughly a third of the stars will be K giants and roughly another third will be main-sequence stars hotter than mid F.

High-resolution spectroscopy is a good way to identify transit candidates that are actually eclipsing binaries. From a single spectrum of an eclipsing binary involving two nearly equal stars it will often be obvious that there are two spectra, because the velocity separation is quite often larger than the line widths. Even if the primary star is much brighter than the secondary, so that the spectrum is single-lined, the expected velocity amplitude is tens of km s^{-1}, and only a few observations with a velocity precision on the order of 1 km s^{-1}, say, are needed to show that the light curve is due to a companion star and not a planet.

2. Spectroscopic Observations of Vulcan Transit Candidates

Starting in the summer of 1999, the Vulcan team supplied us with transit candidates that they had identified, first for a field in Cygnus, and then for a field in Perseus. The candidates all had transits less than a few percent deep and periods mostly shorter than a week. Some examples of the light curves for good candidates are shown in Borucki et al. (2001) and Jenkins et al. (2002). Altogether 35 candidates were provided, but several of these were considered to be very marginal detections, either because the transits were not much deeper than the photometric noise, or because only a very small number of transit events had been identified. We then started observing the candidates with the CfA Digital Speedometers (Latham 1992) on the 1.5-m Wyeth Reflector at the Oak Ridge Observatory located in the Town of Harvard, Massachusetts and on the 1.5-m Tillinghast Reflector at the Whipple Observatory on Mt. Hopkins, Arizona. These instruments use photon-counting intensified Reticon detectors to record 45 Å in a single echelle order centered at 5187 Å with a resolution of 8.5 km s^{-1}. For slowly-rotating stars of spectral type F and later the typical radial-velocity precision for a single exposure is 0.5 km s^{-1}.

The template spectra for our velocity correlations are drawn from an extensive library of synthetic spectra calculated by Jon Morse for a grid of Kurucz model atmospheres. This allows us to optimize the effective temperature, rotational velocity, and surface gravity of the template spectrum for each star, assuming solar metallicity (for this project). The temperatures and gravities determined this way allow us to make rough estimates of the radii of the stars.

Our initial observations of the Vulcan candidates showed that 13 of the stars were too hot and/or were rotating too rapidly for us to derive reliable radial velocities, as expected for a magnitude-limited sample. With just one exposure we could see that several of the candidates had composite spectra, and after just two or three exposures we could see that several others were showing large variations in their radial velocities. Nevertheless, we continued to make additional exposures of the variable stars until we had enough observations to allow orbital solutions, because we wanted to check to make sure that both the period and the phasing of the orbital motion matched the transit observations. Furthermore, we wanted to see if the characteristics of the stellar secondaries were consistent with the observed light curves. We ended up with 9 orbital solutions where the period and phasing of the spectroscopic orbit proved to be consistent with the transit photometry, and the radii implied for the stars in the systems were consistent with the light curves.

The results for the 9 systems with orbital solutions are summarized in Table 1. The star names are the internal designations assigned by the Vulcan team, while $P_{\rm ph}$ and $D_{\rm ph}$ are the transit period (d) and depth (%) found by the Vulcan team (Borucki et al. 2001; Jenkins et al. 2002; Caldwell, private communication). $P_{\rm sp}$ is the period (d) of our spectroscopic orbit, while $T_{\rm eff}$, $v \sin i$ and $\log g$ are the effective temperature (K), rotational velocity (km s^{-1}), and log surface gravity (cm s^{-2}) of the template adopted for the velocity analysis of the primary eclipsing star. For the binaries with double-lined orbits M_1 and M_2, the primary and secondary masses ($M_\odot$), are the values derived assuming that $\sin i = 1$. For the single-lined binaries we assigned a mass to the primary assuming it was a main-sequence star with the same effective temperature as the template and then derived a mass for the secondary assuming $\sin i = 1$. The designations SB1, SB2, and SB3 in the final column indicate the detection of one, two, or three sets of lines in the spectra.

Cyg1433, Per1055, and Per4475 are all double-lined binaries with nearly equal components and thus must have grazing eclipses to produce the shallow dips observed in the light curves. For Cyg1433 and Per4475 the photometric periods found by the Vulcan team were half the actual orbital period, because the primary and secondary eclipses were so nearly the same that they were not recognized as distinct events. Cyg866 is a triple-lined system consisting of a short-period eclipsing binary with a double-lined orbital solution and a distant third star with a velocity that is about 7 km s^{-1} larger than the center-of-mass velocity of the eclipsing binary. For this system the two stars in the eclipsing binary show rapid rotation due to tidal synchronization with the orbit. The distant third star is rotating slowly, as expected. Per460 is also a triple, with an eclipsing inner binary that is single-lined and a distant third star with a velocity that is 4 km s^{-1} smaller than the center-of-mass velocity of the eclipsing binary. Cyg3047, Per4201, Per7307, and Per7585 are all single-lined binaries with M dwarf secondaries that are small enough to produce the observed eclipse depths, in some cases needing additional attenuation from misalignment.

Table 1. Nine Vulcan Transit Candidates with Spectroscopic Orbits

star	$P_{\rm ph}$	$D_{\rm ph}$	$P_{\rm sp}$	$T_{\rm eff}$	$v \sin i$	$\log g$	M_1	M_2	Type
Per460	3.566	3	1.7833	6500	50	4.0	1.2	0.37	SB2
Cyg866	0.94	1	1.8712	6500	60	4.0	1.20	1.01	SB3
Cyg1433	1.96	3	3.914	6750	30	4.0	1.39	1.34	SB2
Cyg3047	4.65	2	4.658	6250	35	4.0	1.2	0.45	SB1
Per1055	?	3	17.11	8000	10	4.0	1.81	1.75	SB2
Per4201	5.526	5	5.536	6500	16	4.0	1.2	0.55	SB1
Per4475	1.92	2	3.8436	7750	30	4.0	1.83	1.81	SB2
Per7307	1.5615	7	1.5619	5250	40	4.5	0.9	0.30	SB1
Per7585	3.668	6	3.6680	6750	16	4.5	1.2	0.37	SB1

Several of the Vulcan candidates with marginal transit detections showed no velocity variations at the level of about 0.5 km s^{-1}, which corresponds to a limiting mass of about 10 Jupiter masses for a period of one week and a solar-mass primary. Additional follow-up observations at much better velocity precision have been carried out and will be reported elsewhere.

Acknowledgments. I thank Bill Borucki, Doug Caldwell, Dave Koch, Larry Webster, and the rest of the Vulcan team for providing information about their transit candidates in advance of publication. Robert Stefanik organized the observations at the Oak Ridge Observatory, ably assisted by Joe Zajac and Joe Caruso, while Perry Berlind and Mike Calkins made many of the observations at the Whipple Observatory. Bob Davis managed our database and did the initial reductions. Jenny Posson-Brown and Sean Moran helped with the analysis of the data and the interpretation of the results. Sara Seager provided inspiration and Willie Torres provided expert advice.

References

Borucki, W. J., & Summers, A. L. 1984, Icarus, 58, 121

Borucki, W. J., Caldwell, D., Koch, D. G., Webster, L. M., Jenkins, J. M., Ninkov, Z., & Showen, R. 2001, PASP, 113, 439

Jenkins, J. M., Caldwell, D. A., & Borucki, W. J. 2002, ApJ, 564, 495

Latham, D. W. 1992, in ASP Conf. Ser. Vol. 32, IAU Coll. 135, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (San Francisco, ASP), 110

Latham, D. W., Stefanik, R. P., Mazeh, T., Mayor, M., & Burki, G. 1989, Nature, 339, 38

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

Robinson, E. L., Cochran, A. L., Cochran, W. D., Shafter, A. W., & Zhang, E.-H. 1990, AJ, 99, 672