Transiting Planets
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Transiting Planets in the Galactic Bulge from SWEEPS Survey and Implications

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Abstract. The SWEEPS (Sagittarius Window Eclipsing Extrasolar Planet Search) program was aimed at detecting planets around stars in the Galactic bulge, not only to determine their physical properties, but also to determine whether the properties of planets found in the solar neighborhood, such as their frequency and the metallicity dependence, also hold for the planets in the Galactic bulge. We used the Hubble Space Telescope to monitor 180,000 F, G, K, and M dwarfs in the Galactic bulge continuously for 7 days in order to look for transiting planets. We discovered 16 candidate transiting extrasolar planets with periods of 0.6 to 4.2 days, including a possible new class of ultra-short period planets (USPPs) with $P < 1$ day. The facts that (i) the coverage in the monitoring program is continuous, (ii) most of the stars are at a known distance (in the Galctic bulge), (iii) monitoring was carried out in 2 passbands, and (iv) the images have high spatial resolution, were crucial in minimizing and estimating the false positive rates. We estimate that at least 45% of the candidates are genuine planets. Radial velocity observations of the two brightest host stars further support the planetary nature of the transiting companions. These results suggest that the planet frequency in the Galactic bulge is similar to that in the solar neighborhood. They also suggest that higher metallicity favors planet formation even in the Galactic bulge. The USPPs occur only around low-mass stars which may suggest that close-in planets around higher-mass stars are irradiately evaporated, or that planets are able to migrate to and survive in close-in orbits only around such old and low-mass stars.

1. Introduction

Transit surveys have allowed detailed follow-up studies of many extrasolar planets, leading to quantitative determinations of several important physical properties. However, most of the transit surveys suffer from uneven sampling, and large uncertainties in their detection efficiencies. As a result, it is difficult to use these data to determine statistical properties such as the frequency of occurence of planets. In addition, the exoplanets discovered so far have been mostly around relatively nearby and bright stars: all of the radial velocity (RV) detections and a large number of transit detections are confined to host stars within about 200 pc, a few of the transit detections have host stars as far away as 2 kpc, and the small number of the microlensing detections have host stars as far away as 6 kpc. Furthermore, the RV detections have been mostly confined to relatively higher-mass stars, although RV studies are now being extended to M dwarfs (Marcy, 2005; Butler *et al.* 2004; Bonfils *et al.* 2004). Fischer & Valenti (2003) find that the frequency of planets in the RV sample rises rapidly with metallicity. So, some of the key questions in the study of extrasolar planets, at present, are the following: (i) Are planets equally abundant in other parts the Galaxy? (ii) Are planets equally numerous around lower mass stars? (iii) Are hot Jupiters common around a very different population? (iv) Does higher metallicity favor planet formation in other parts of the Galaxy?

Our SWEEPS (Sagittarius Window Eclipsing Extrasolar Planet Search) project was designed to provide answers to these questions. At a distance of ~ 8.5 kpc, the Galactic bulge has a large concentration of stars whose metallicities range over $-1.5 < [Fe/H] < +0.5$ (Rich and Origlia, 2005; Zoccali *et al.* 2003; Fulbright *et al.* 2005), and hence is an ideal choice for this study. We used the *HST* and the Wide Field Camera of the Advanced Camera for Surveys to monitor ~180,000 F, G, K and M dwarfs with $18.5 < V < 26$ in a dense stellar field (3.3×3.3 arcmin) in the Galactic bulge for transits by orbiting Jovian-sized planets. The facts that (i) the coverage in the monitoring program is continuous, (ii) most of the stars are at a known distance (in the Galctic bulge), (iii) monitoring was carried out in 2 passbands, and (iv) the images have high spatial resolution, were crucial in minimizing the false positive rates, and accurately estimating the fraction of genuine planets.

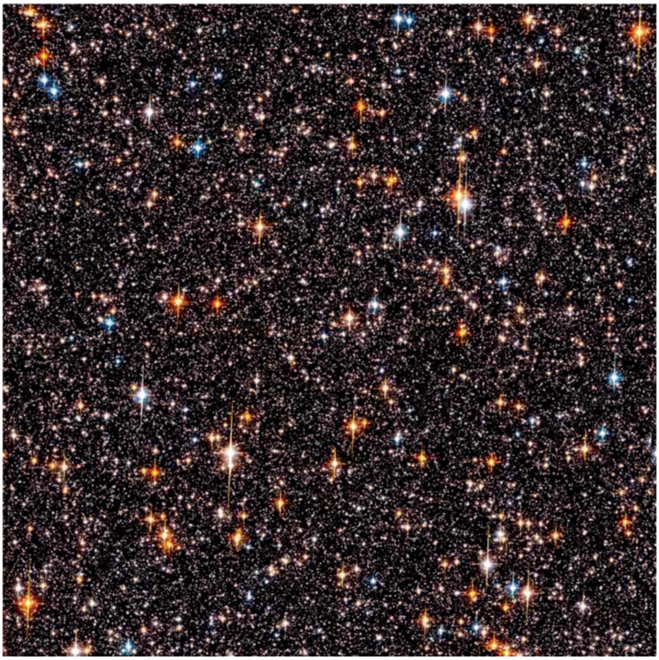

Figure 1. V (F606W) and I (F814W) composite image of the SWEEPS field, which has a size of 202×202 arcsec. There are 245,000 stars down to $V \sim 30$, out of which there are 180,000 stars brighter than $V \sim 26$ around which the observations are sensitive to detecting Jovian planets.

2. Details of Observations

The SWEEPS field lies in the Sagittarius-I Window of the Galactic bulge. We monitored this field for planetary transits over a continuous 7-day interval during February 22-29, 2004. At the distance of the Galactic bulge, an M_0 dwarf of 0.5 $M_\odot$ has an apparent visual magnitude of ~ 25.5, for which the HST photometry is capable of detecting

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planetary transits. The observations include 254 exposures in F606W (wide V) and 265 exposures in F814W (I) for the primary time series, all with an exposure time of 339 sec.

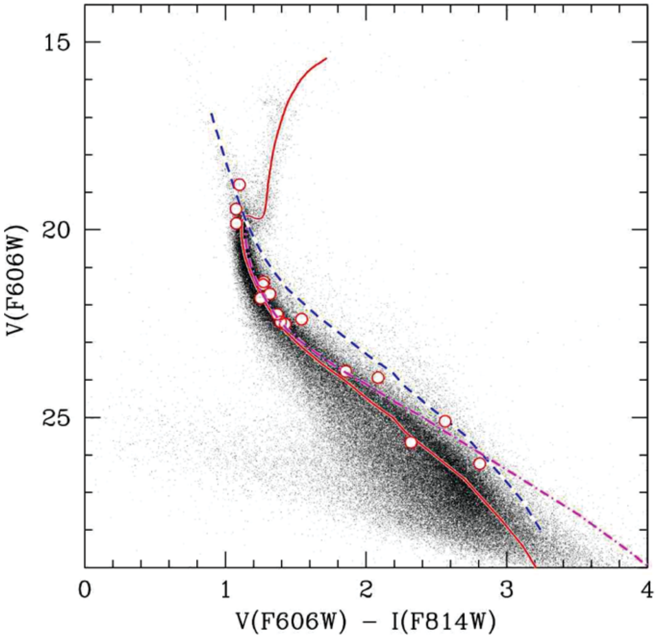

Figure 2. The color-magnitude diagram (CMD) of the SWEEPS field as derived from the deep, combined ACS images, with total integration times of 86,106 and 89,835 s in the V and I filters, respectively. The red (solid) line shows a 10-Gyr old solar-metallicity isochrone which is the dominant bulge population. The dashed blue (upper) line shows an unevolved main sequence, representative of the foreground young disk population. An higher-metallicity isochrone with [Fe/H]=0.5 is shown by the dot-dashed (magenta) curve. Large circles represent the 16 host stars with transiting planet candidates.

3. Photometry and Search for Planets

The analysis technique employed is Difference Image Analysis (DIA; e.g., Alard 1999), similar to the procedure adapted by Gilliland *et al.* (1999, 2000) for the analysis of 47 Tuc data. Combining together all the exposures taken in each filter using the above procedure produces extremely deep, twice-oversampled V (F606W) and I (F814W) images. Figure 1 shows the combined image of the SWEEPS field in F606W and F814W filters.

The absolute photometry (Vegamag system) of the stars in the SWEEPS field was determined from twice-oversampled co-added images of the entire dataset in V and I. The DAOPHOT II PSF-fitting photometry package was used for this purpose, with the photometric zero-points taken from the calibration work at STScI (Sirianni *et al.* 2005).

About 245,000 stars are detected in this combined image down to $V \sim 30$, of which 180,000 stars are brighter than $V \sim 26$ around which our program is sensitive to detecting Jovian planets. The color-magnitude diagram (CMD), presented in Figure 2, shows two stellar components: a dominant population of old stars with a main-sequence turnoff near $V = 19.6$ and well-populated sub-giant and giant branches, and a less numerous, closer, younger and brighter main sequence. We associate the old population with the Galactic bulge, and the younger objects with the foreground Galactic disk (Kuijken & Rich 2002,

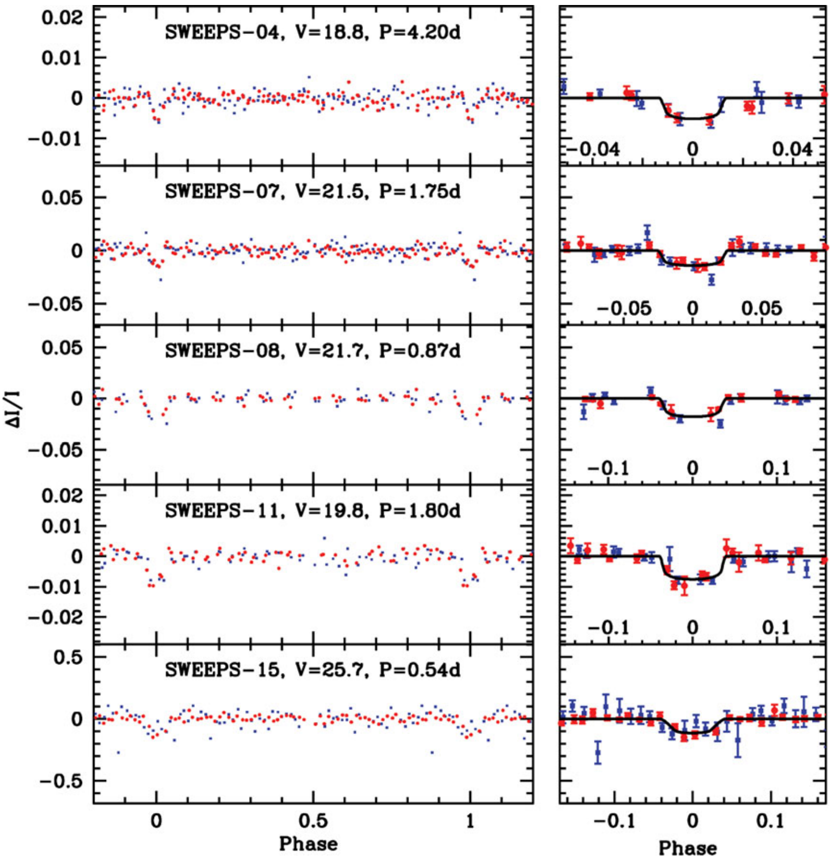

Figure 3. Five examples of observed transit light curves. The left panels show the entire light curve, phased at the derived orbital period, and the right panels show magnified views of the transit with 2σ error bars. The light curves have been binned in phase to a bin width of 1/6th of the transit duration. (Blue) squares are the V-band observations, and (red) circles are the I-band observations. The black solid curves are the best-fitting model transit light curves.

Zoccali *et al.* 2000). A modified version of the code developed by Kovacs *et al.* (2003) was used for transit search.

4. Detection and Screening for False Positives

A series of criteria as described by Sahu *et al.* (2006) was employed to eliminate false positives, which include eliminating candidates with (i) a transit depth implying a companion radius $> 1.4R_J$ (ii) ellipsoidal light variations, (iii) secondary eclipses, (iv) different transit depths in V and I. We also eliminated objects in which the photo-center of the transit signal is offset with respect to that of the uneclipsed star. As an additional check, we doubled the period and re-calculated the transit depths, and eliminated candidates with varying primary and secondary depths. This process led to the detection of 16 candidate planets. The magnitudes of their host stars range from V=18.8 to 26.2, corresponding to stellar masses of 1.24 to 0.44 $M_\odot$. Figure 3 shows a few typical examples of the observed transit light curves.

The rejected candidates include 165 eclipsing binaries in which the secondary is likely to be a stellar companion (Sahu *et al.*, in prep.), out of which 125 show ellipsoidal variations.

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Table 1. Properties of the SWEEPS Planet Candidates

ID	RA (2000)	Dec (2000)	Transit Depth	Per (d)	Stellar Mass ($M_\odot$)	Stellar Rad. ($R_\odot$)	V	I	R_P (R_J)	Error in R_P (R_J)	a (au)	a (R_*)
SWEEPS-01	17:58:53.29	-29:12:33.5	0.019	1.566	0.81	0.75	22.25	20.88	1.01	0.13	0.025	7.08
SWEEPS-02	17:58:53.38	-29:12:17.8	0.079	0.912	0.55	0.50	25.10	22.53	1.37	0.25	0.015	6.48
SWEEPS-03	17:58:53.57	-29:11:44.1	0.015	1.279	0.79	0.72	22.51	21.09	0.87	0.11	0.021	6.35
SWEEPS-04	17:58:53.92	-29:11:20.6	0.005	4.200	1.24	1.18	18.80	17.70	0.81	0.10	0.055	9.93
SWEEPS-05	17:58:54.60	-29:11:28.2	0.034	2.313	0.66	0.61	23.94	21.85	1.09	0.10	0.030	10.57
SWEEPS-06	17:58:57.29	-29:12:53.4	0.004	3.039	1.09	1.36	19.45	18.37	0.82	0.21	0.042	6.68
SWEEPS-07	17:58:57.69	-29:11:14.5	0.012	1.747	0.90	0.85	21.46	20.19	0.90	0.11	0.027	6.93
SWEEPS-08	17:58:59.24	-29:13:28.7	0.015	0.868	0.87	0.81	21.70	20.39	0.98	0.09	0.017	4.50
SWEEPS-09	17:58:59.60	-29:12:11.8	0.020	1.617	0.79	0.73	22.45	21.06	1.01	0.12	0.025	7.38
SWEEPS-10	17:59:02.00	-29:13:23.7	0.096	0.424	0.44	0.41	26.23	23.42	1.24	0.23	0.008	4.41
SWEEPS-11	17:59:02.67	-29:11:53.5	0.006	1.796	1.10	1.45	19.83	18.75	1.13	0.21	0.030	4.41
SWEEPS-12	17:59:04.44	-29:13:17.1	0.014	2.952	0.86	0.80	21.82	20.57	0.91	0.11	0.038	10.33
SWEEPS-13	17:59:05.95	-29:13:05.6	0.009	1.684	0.91	0.86	21.38	20.11	0.78	0.12	0.027	6.67
SWEEPS-14	17:59:07.56	-29:10:39.8	0.017	2.965	0.80	0.73	22.38	20.84	0.93	0.09	0.037	10.98
SWEEPS-15	17:59:07.64	-29:10:23.7	0.099	0.541	0.49	0.45	25.66	23.34	1.37	0.30	0.010	4.90
SWEEPS-16	17:59:08.44	-29:11:40.6	0.053	0.969	0.68	0.62	23.78	21.92	1.40	0.18	0.017	5.83

R_P: radius of the planet, R_J: radius of Jupiter, a: orbital radius, R_*: stellar radius.

There are, however, several other astrophysical situations that can potentially produce shallow light-curve dips mimicking planetary transits, which we briefly discuss below. We note that, unlike most other ground-based observations, the HST observations do not suffer from blending problems or "red noise", which makes the detections more robust.

(a) A stellar binary with a grazing eclipse can produce a depth similar to that due to a planetary transit. The expected number of grazing incidences can be predicted using the properties of the stellar eclipsing binaries that do not show ellipsoidal variations. By assuming that these are drawn from a population with randomly distributed inclinations, and taking the binary parameters and the detection efficiencies associated with these systems into account, we estimate that a maximum of 1.4 of the 16 candidates could be a grazing system masquerading as a planetary transit.

(b) A deeply eclipsing stellar binary, whose light is blended with a brighter constant star, can produce an eclipse in the combined light with a depth similar to that due to a planetary companion of a single star. The number of chance overlaps can be estimated from the 165 detected isolated eclipsing stellar binaries down to V = 27. Based on their surface density, we expect ∼0.8 candidates to be due to chance overlaps in the population down to V = 27. We estimate that out of our 16 planetary candidates, 2 could be due to physical triple systems.

(c) An ambiguity arises from the fact that, for masses between about 0.5 and ∼150 M_J, planets, brown dwarfs, and low-mass stars all have similar radii. To assess the expected number of low-mass stellar companions in our candidate sample, we have used the results from the RV followup of the OGLE transit candidates. We estimate that up to a maximum of 29% of the candidates can be due to stellar objects with planetary-size radii.

Taking all of the possible contaminants into account, we estimate that at least 45% of our transiting candidates are genuine planets (See Sahu *et al.*, 2006 and 2008 for more details).

5. Radial Velocity Followup

Most of the host stars are too faint for radial velocity followup observations, but SEEPS-4 and SWEEPS-11 were bright enough and lie in a relative uncrowded region so that we could obtain radial velocity observations of them, using the ESO 8m VLT and

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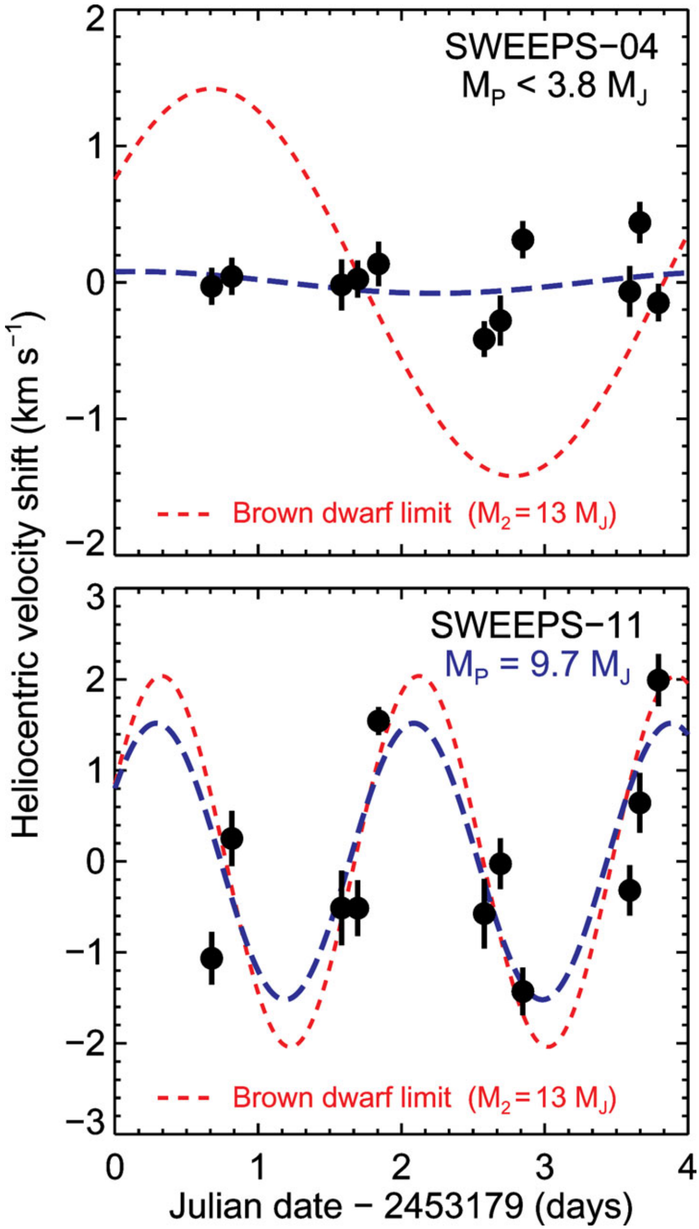

Figure 4. Radial-velocity measurements of SWEEPS-04 and SWEEPS-11 from VLT spectra. The measured radial velocities and their associated errors are shown as black points. The red (short-dashed) curves show the RV variation expected for a minimum-mass brown dwarf companion of 13 M_J. For SWEEPS-11, there is a clear detection of RV variations, which imply a planetary mass of 9.7 ±4.5 M_J. For SWEEPS-4, there is no detection, and at the 95% and 99.9% confidence levels, we rule out companions more massive than 3.8 M_J and 5.3 M_J. The zero-point uncertainty in phase due to the extrapolation from the 2004 February HST transit observations to the 2004 June date of the RV observations is 0.45 days.

the FLAMES/UVES spectrograph. For SWEEPS-11, we clearly detected RV variations, which indicate the mass to be 9.7 M_J. For SWEEPS-4, for which the transit detection has a high S/N, the RV variations were below the detection limit suggesting an upper limit

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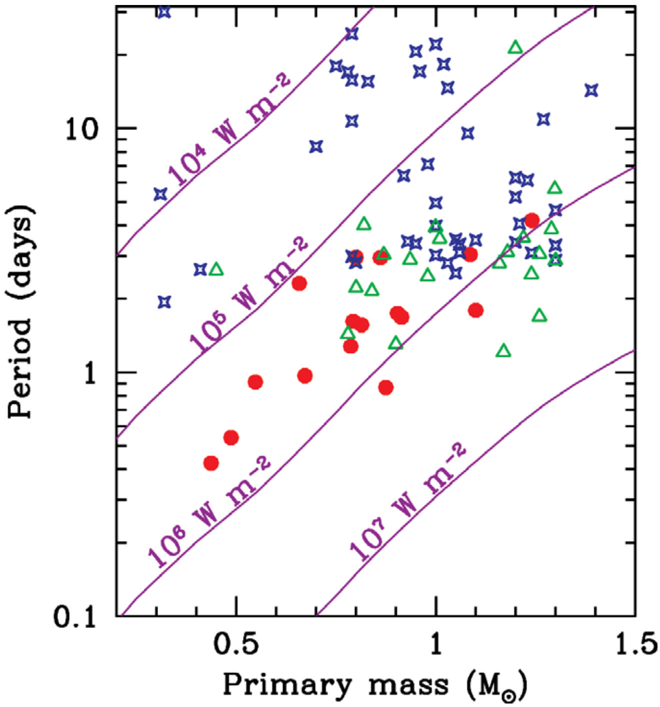

Figure 5. Orbital periods and host-star masses for extrasolar planets with periods up to ~12 days. Solid (red) circles are the 16 SWEEPS candidates, (green) triangles are transiting planets around brighter stars as derived from ground-based observations, and (red) crosses are for planets detected through RV variability. The SWEEPS candidates extend the range of planetary candidates orbital periods down to 0.42 days. Very few planets have irradiances above $2 \times 10^6 Wm^{-2}$ which corresponds to an equilibrium temperature of 2000 K. None in the SWEEPS sample have equilibrium temperatures larger than 2000 K. The absence of ultra-short-period planets around stars $> 0.9 M_\odot$ may be due to irradiative evaporation.

to its mass of 3.8 M_J. If only 50% of our candidates are genuine planets, the probability that both selected objects would be planets is 25%. If 30% of the candidates are genuine planets, this probability is only 10%. This gives us extra confidence that a large fraction must be planets, and supports our estimate that > 45% of the candidates are genuine planets.

The frequency of heirarchical triples in our sample deserves a special mention here. There are some theoretical papers which suggest that up to 90% of the close binaries may be in triple systems. Can we be sure that the candidates with RV observations are not heirarchical triples masquerading as planets? To answer this question, we need to first realize that what really matters is not what fraction of stars are in triples, but what fraction of triples will cause planetary transits; and in case of RV observations, what fraction will actually cause planet-like RV variations consistent with the derived orbital period, phase, etc. Physical triples can be identified by the variation in the shape of the spectral-line bisectors. But since the S/N in our observations is not enough to analyze the bisectors, we can take the statistics of the existing surveys. Taking the results from the literature, and after private communication with members of a few groups, we estimate that 10 to 20% of the objects may fall in this category. Thus the probability that the observed RV variations are due to stellar objects is small.

6. Ultra Short-Period Planets

Five of our candidates have periods of less than 1.0 day. We call them USPPs, noting that the shortest orbital period yet found among RV-confirmed planets is 1.2 days, whereas our USPPs extend the periods down to 0.42 day. Statistical analysis of possible false positives suggests that at least 2 of these USPPs are likely to be genuine planets.

All 5 USPPs orbit stars of less than 0.88 $M_{\odot}$. USPPs thus seem to be analogs of hot Jupiters, but around lower-mass stars. We note that USPPs are not expected to be especially hot compared to previously known "hot Jupiters", since the irradiance from the low-mass primary at their locations is comparable to that of planets found around more massive stars. In fact, we argue below that irradiance levels may be one of the reasons why USPPs are not found around more massive stars. We also note that, in units of host stellar radii, the USPPs are no closer to their parents than the closest of the ordinary hot Jupiters. For example, the smallest orbital separation in units of stellar radii among the SWEEPS candidates is that of the USPP SWEEPS-10 (4.41 R_*), while the next smallest is that of SEEPS-11, a 1.8 day hot Jupiter orbiting a 1.1 $M_{\odot}$ star at 4.41 R_*. The shortest period RV-confirmed planet, OGLE-TR-56b has an orbital radius of 4.40 R_*.

USPPs do not raise an issue of stability against tidal breakup, since even at the closest of the observed separations a planet of more than 1.6 M_J will lie within its Roche radius.

7. Discussion

The sample of RV-detected planets in the solar neighborhood indicates that the frequency of occurrence of Jovian planets is 5 to 10% for F through K dwarfs, about one-tenth of which are hot Jupiters with periods less than 4.2 days. Our sample of candidates mainly belong to the Galactic bulge, the farthest such sample in the Galaxy, where the metallicity distribution is broader than in the solar neighbourhood. However, after taking into account the relation between planet frequency and metallicity in the local sample (Zoccali *et al.* 2003; Fulbright *et al.* 2006), we would expect the overall planet frequency in the bulge to be similar to that in the solar neighborhood. After correcting for geometric transit probability and our detection efficiency, we find that our 16 candidates (if all of them are assumed to be genuine planets) imply that about 0.42% of bulge stars more massive than $\sim$0.44 $M_{\odot}$ are orbited by Jovian planets with periods less than 4.2 days. Due to the small-number statistics and uncertainties in the detection efficiencies, this fraction is uncertain by perhaps a factor of 2. Thus, within the statistical errors, the overall frequency of occurrence of planets derived from the SWEEPS data is consistent with that in the solar neighborhood. For host stars more massive than 0.75 $M_{\odot}$, the observed period distribution of the SWEEPS planets is also consistent with that in the solar-neighborhood sample. However, for lower-mass stars, the SWEEPS period distribution is systematically shifted to shorter periods.

The frequency of planets around low-mass stars seems slightly smaller than the frequency of planets around higher-mass stars (which is consistent with the results from RV surveys), but given the small number statistics, the uncertainty is large and could possibly reach a factor of 2 or 3.

In order to discriminate between the disk and the Bulge stars through their proper motions, a set of second-epoch observations were taken in 2005. Analysis of the proper motions of the stars indicate that (i) the frequency of planets is similar among the Bulge and the disk stars, and (ii) the USPP hosts do not preferentially lie in the disk or the Bulge (Clarkson *et al.*, this volume; Clarkson *et al.* 2008).

The host stars of the detected planets preferentially lie towards higher-metallicity isochrones. This is consistent with the fact that metallicity favors planet frequency in the Galactic bulge, similar to the findings in the solar neighborhood. It is worth asking here whether the objects which lie above the solar-metallicity isochrone could be binaries rather than stars with higher metallicity? Indeed, for any individual object, it is impossible to distinguish between these two possibilities from the star's position in the CMD alone. However, we note that this effect is seen only in the fainter part of the CMD where the metallicity isochrones diverge. If this were due to binarity, we would expect to see some host stars above the isochrone even in the brighter part of the CMD, which is not observed. Metallicity offers a natural explanation on the positions of the host stars in the CMD, suggesting it to be an effect of metallicity rather than due to binaries.

The USPPs with orbital periods shorter than 1 day occur only around stars less massive than 0.88 $M_\odot$, and which have preferentially higher-metallicity. This suggests that planets orbiting very close to more massive stars might be evaporatively destroyed, or that planets can migrate to close-in orbits and survive there only around such old and low-mass stars.

These results thus indicate that the statistics on frequency and metallicity dependence of exoplanets in the solar neighborhood also apply to the Galactic bulge, which has a very different environment and chemical evolution. This gives us some confidence in extrapolating, and asserting that the same statistics may indeed apply to the Galaxy as a whole. Now, given the fact that the Galactic bulge is similar in its environment to Ellipticals — the most numerous of all galaxies in the Universe — dare we say that the planets are likely to be just as common in the entire Universe as they are in the our local neighborhood?

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