Planets in the Galactic Bulge: Results from the SWEEPS Project

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Abstract. The exoplanets discovered so far have been mostly around relatively nearby and bright stars. As a result, the host stars are mostly (i) in the Galactic disk, (ii) relatively massive, and (iii) relatively metal rich. The aim of the SWEEPS project is to extend our knowledge to stars which (i) are in a different part of the Galaxy, (ii) have low masses, and (iii) have a large range of metallicities. To achieve this goal, we used the *Hubble Space Telescope* and its Advanced Camera for Surveys to look for transiting planets around F, G, K, and and M dwarfs in the Galactic bulge. We photometrically monitored $\sim$180,000 stars in a dense stellar field in the Galactic bulge continuously for 7 days. We discovered 16 candidate transiting extrasolar planets with periods of 0.6 to 4.2 days, including a new class of ultra-short period planets (USPPs) with $P < 1.2$ days. Radial velocity observations of two brightest candidates support the planetary nature. These results suggest that planets are equally abundant in the Galactic bulge and around low-mass stars (within a factor $\sim$2), and the metallicity distribution holds even for the stars in the Galactic bulge. The USPPs occur only around low-mass stars which suggest that close-in planets around higher-mass stars are either irradiately evaporated, or that the size of the inner disk hole decreases with decreasing mass of the host stars.

1. Introduction

More than 250 extrasolar planets have been discovered within the past few years, most of them through the radial velocity (RV) measurements, and some through transits and microlensing (see J. Schneider, Extrasolar Planet Encyclopaedia for

an up-to-date listing). These discoveries have led to tremendous advancements in our knowledge of exoplanets. However, the exoplanet discoveries have so far been mostly around relatively nearby and brighter stars: all of the 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 pc, and the small number of the microlensing detections have host stars as far away as 6 kpc. In addition, 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). In contrast with the RV results, an intensive transit search in the globular cluster 47 Tuc (Gilliland et al. 2000) found *no* hot Jupiters around ∼34,000 cluster members, compared to the ∼17 expected from the frequency in the solar neighborhood. This discrepancy was tentatively attributed to either environment or metallicity effects, since 47 Tuc stars lie in a very dense stellar environment and are significantly metal-poor compared to those in the solar neighborhood. Indeed, 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 heavy element abundance favor planet formation at other parts of the galaxy?

Our SWEEPS (Sagittarius Window Eclipsing Extrasolar Planet Search) project was designed to provide answers to these key 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.

2.   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 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.

3.   Analysis

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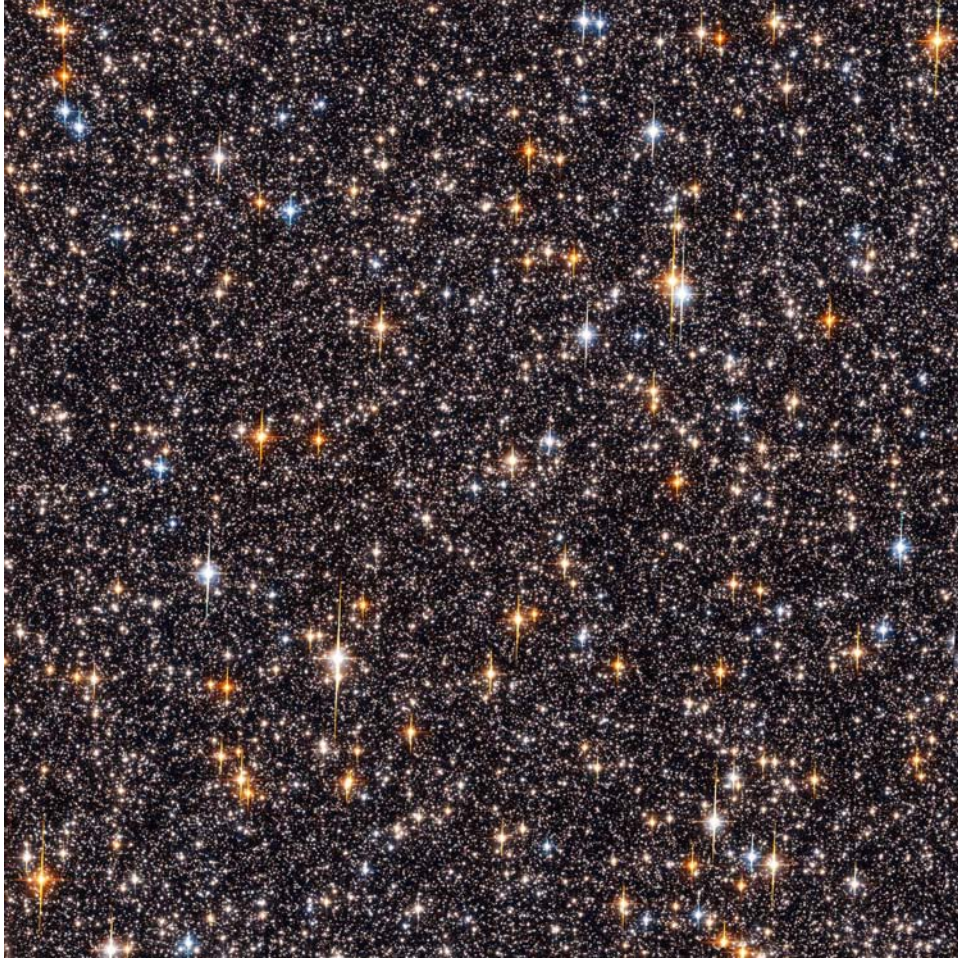
Figure 1.   V (F606W) and I (F814W) composite image of the SWEEPS field, which has a size of 202 x 202 arcsec. There are 245,000 stars down to $V \sim 30$, out of which there are 180,000 stars brighter than $V \sim 26$ around which the observations are sensitive to detecting Jovian planets.

(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
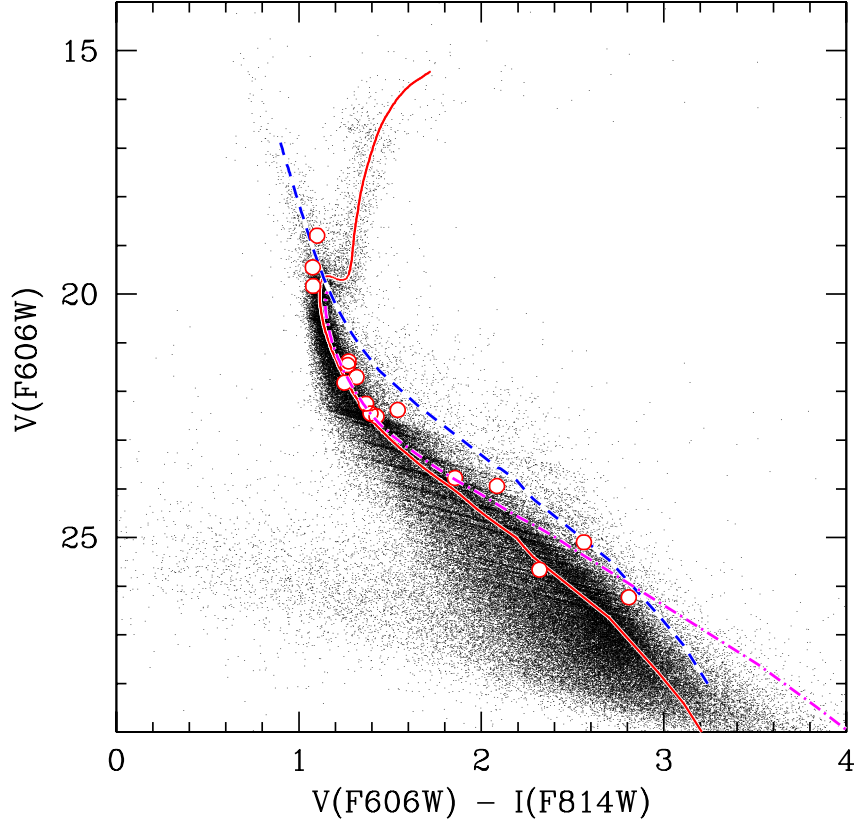
Figure 2.   The color-magnitude diagram (CMD) of the SWEEPS field as derived from the deep, combined ACS images, with total integration times of 86,106 and 89,835 s in the V and I filters, respectively. The red (solid) line shows a 10-Gyr old solar-metallicity isochrone which its the dominant bulge population. 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 dashed magenta (lower) curve. Large circles represent the 16 host stars with transiting planet candidates.

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, Zoccali et al. 2000). A modified version of the code developed by Kovacs et al. (2003) was used for transit search.
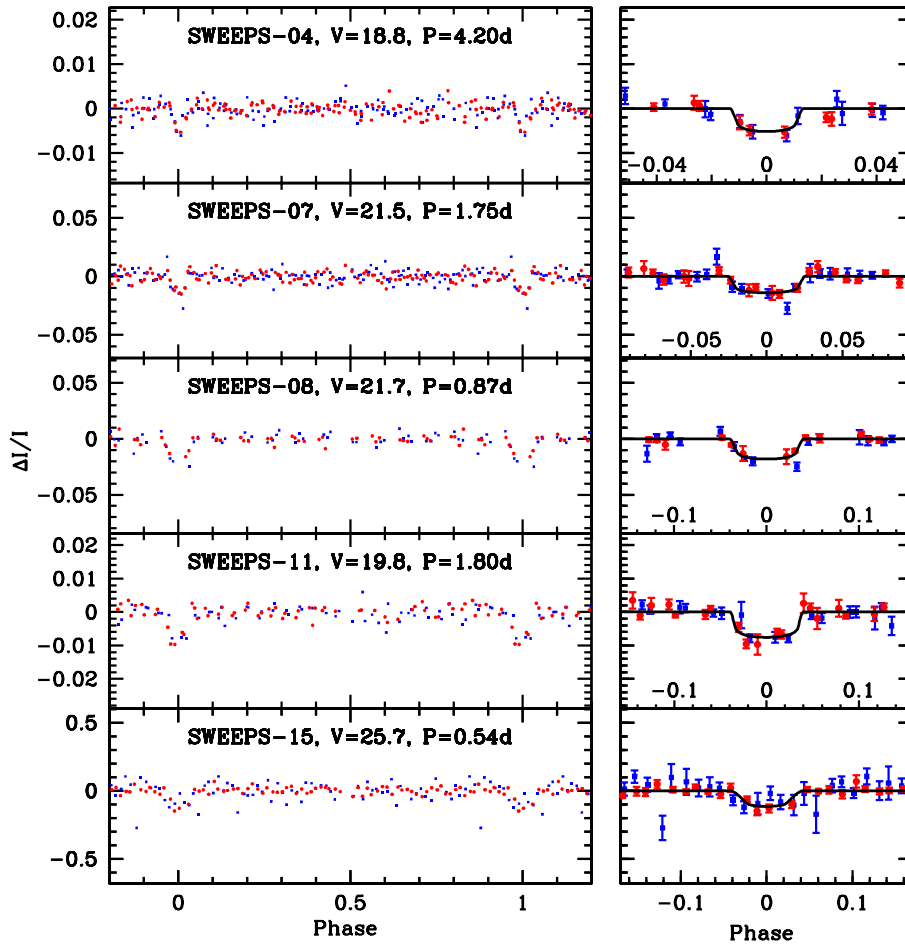
Figure 3. Five examples of observed transit light curves. The left panels show the entire light curve, phased at the derived orbital period, and the right panels show magnified views of the transit with 2σ error bars. The light curves have been binned in phase to a bin width of 1/6th of the transit duration. (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.

4.   Results 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.
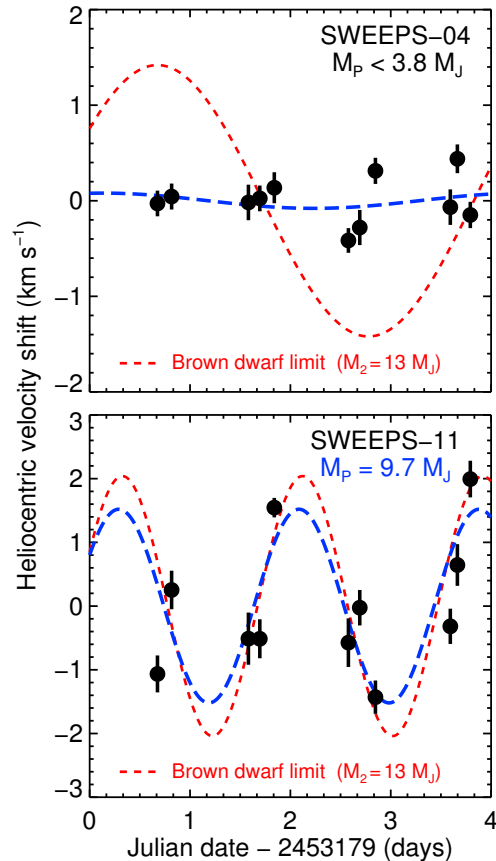

Figure 4.   Radial-velocity measurements of SWEEPS-04 and SWEEPS-11 from VLT spectra. The measured radial velocities and their associated errors are shown as black points. The red (short-dashed) curves show the RV variation expected for a minimum-mass brown dwarf companion of 13 M_J. For SWEEPS-11, there 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.

In addition to the 16 exoplanet candidates, we have also detected 165 low-mass eclipsing binaries, which we used to statistically estimate the possible contribution from grazing eclipses and low-mass stars. Unlike most other ground-based experiments, the HST experiment has (i) near-continuous time coverage, (ii) observations in 2 different bands, (iii) same exposure times for all observa-

tions, and (iv) same psf-characteristics in all the images. Such a consistent set of observations makes it possible statistically estimate the contributions from astrophysical false positives (such as grazing eclipses, low-mass stars, etc.) Furthermore, the HST observations do not suffer from blending problems or "red noise", which makes the detections more robust. Taking into account all possible contributions from other sources of false positives, we estimate that $\gtrsim 45\%$ of the candidates are genuine planets (See Sahu et al, 2006 and 2008 for more details).
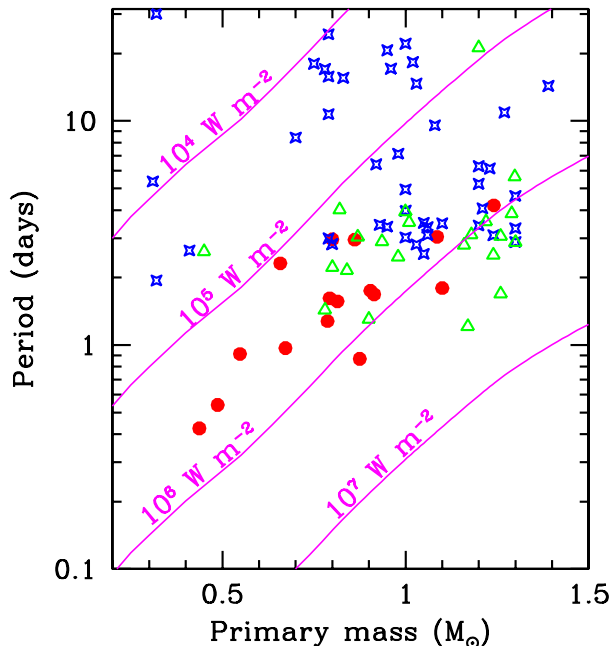

Figure 5. Orbital periods and host-star masses for extrasolar planets with periods up to ~12 days. Solid (red) circles are the 16 SWEEPS candidates, (green) triangles are transiting planets around brighter stars as derived from ground-based observations, and (red) crosses are for planets detected through RV variability. The SWEEPS candidates extend the range of planetary orbital periods down to 0.42 days. Very few planets have irradiances above $2 \times 10^6 W m^{-2}$ 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.

5. Radial Velocity Followup Observations

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 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 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 $\gtrsim 45\%$ of the candidates are genuine planets. .

6. Results

After correcting for geometric transit probability and our detection efficiency, our detections suggest that the frequency of planets in the SWEEPS field is similar to that in the local neighborhood.

The frequency of planets around low-mass stars is also similar to the frequency of planets around higher-mass stars, but given the small number statistics, the uncertainty is large which can easily be a factor of 2 or 3.

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.

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, and/or the size of the inner disk hole decreases with decreasing stellar radius so that Jovian planets around lower-mass stars can migrate to smaller radii.

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