Transiting Planets
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Kinematics of the SWEEPS transiting planet candidates

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Abstract. In 2004 a deep sequence of HST images of the Bulge was used to identify sixteen transiting extrasolar planet candidates (the SWEEPS candidates; Sahu *et al.* 2006), of which at least seven are likely to be true planets. Of these, SWEEPS-4 is almost certainly in the disk, and was shown through radial velocity followup to contain a planetary companion; the identification of the remaining fifteen candidates was left undetermined.

We have used a repeat visit in 2006 to attach proper motions to some 180,000 objects, including all sixteen SWEEPS candidates. This has allowed us to build a sample of bulge stars to unprecedented purity. A population of more than 13,000 bulge objects is kinematically isolated, with fewer than thirty disk contaminants. We use the mean bulge and disk populations to test the balance of kinematic associations for the sixteen SWEEPS candidates. Assuming both the detectability and the astrophysical false-positive fraction to be similar for disk and bulge, we find the fraction of stars with planets in the bulge to be consistent with that in the disk.

1. Introduction

The SWEEPS project used ACS/WFC on HST to uncover sixteen transiting planet candidates towards the bulge, of which perhaps half are likely to be genuine transiting planets (Sahu *et al.* 2006). All but two of these objects are in regions of the CMD with significant bulge/disk overlap. It was therefore desired to obtain proper motions in order to attempt kinematic identification with bulge or disk. Proper motions have great potential to reveal the nature of the inner Milky Way; selection of a pure-bulge sample is critical to uncovering the formation history and even present content of the bulge (e.g. Kuijken & Rich 2002) while constraints on the nature and spatial variation of the motion of stellar populations within the Bulge allow testing of dynamical galaxy models to a level not available for external galaxies.

2. Extraction of Relative Proper Motions from HST Photometry

The first epoch observations included 265 exposures in F814W and 254 in F606W, at 339 seconds each and with subpixel dithers that well and redundantly sample pixel phase-space. In 2006, ten 345-second exposures in F814W were taken with a four-way sub-pixel dither. Mutual misalignment and rotation between epochs are of order 5 pixels and $< 8''$

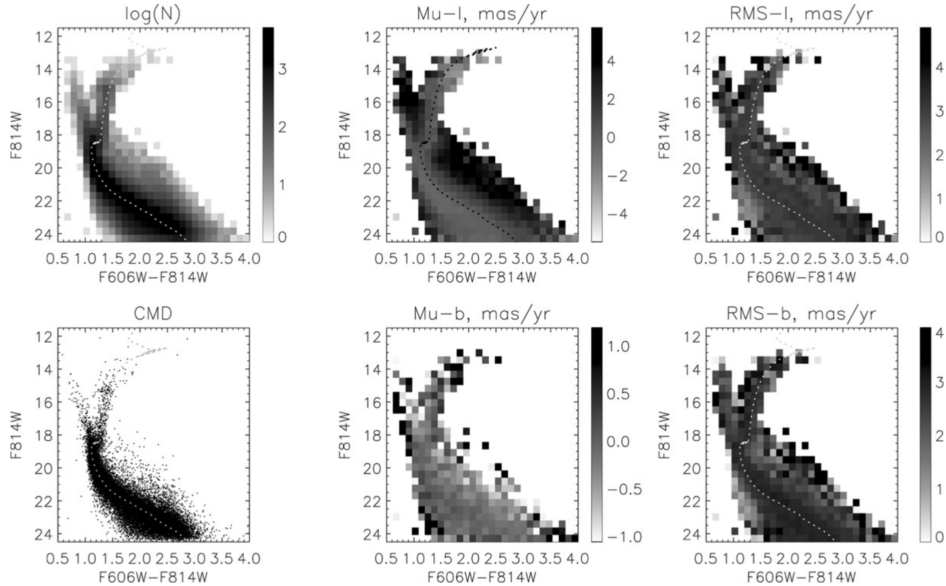

Figure 1. Proper motion Hess diagrams for our field, with mean-Bulge isochrone from SWEEPS photometry (Sahu *et al.* 2006). The Bulge is clearly visible in μ_l, σ_b and σ_l. Solar reflex motion contributes a relatively insignificant trend $|\mu_{l,b}| < 0.2$ mas yr^{-1} (e.g. Vieira *et al.* 2007)

respectively. Up to 265 measurements are available for each star in 2004 using a modified version of the Anderson & King routines; we combine the 2004-epoch measurements to produce a master catalogue from this epoch. Each position-estimate from 2006 is then mapped onto this 2004 master-list, producing up to ten proper motion estimates for each star. This mapping is computed separately for each star using 100-150 suitably selected nearby, well-measured objects. The proper motion error resulting is only 2 mas yr^{-1} at F814W=24, reaching 0.3 mas yr^{-1} at F814W=19. The Bulge shows intrinsic dispersion (σ_l, σ_b) for this field of (3.24, 2.85) mas yr^{-1} (Kuijken & Rich 2002), thus we have reached the precision necessary to observe real kinematic trends (Figure 1).

Proper motion cuts of $\mu_l < -2.0$ mas yr^{-1} and error $\sigma_l, b < 0.3$mas yr^{-1} ensure that objects are kept only with 6σ detections of motion, with similar cuts on a photometric crowding measure selecting preferentially isolated objects. The resulting catalogue contains 15,323 objects with perhaps 31 contaminants from the disk and galactic halo together (Clarkson et al. 2008 ApJ accepted) and is the largest HST pure-bulge dataset yet assembled. Scientific returns from this dataset include: 1. the galactic rotation curve from transverse motions alone; 2. variation of the l, b velocity ellipse as a function of distance; 3. the disk/bulge fraction of our sample (14% are disk objects) and 4. age and metallicity constraints on the bulge from a kinematically-cleaned sample.

3. Kinematics of the SWEEPS planetary candidates

We construct a mean bulge proper motion best-fit ellipse by taking a population-weighted average of the best-fit proper motion (not velocity) ellipses using the kinematic tracer objects of the previous section. We produce a mean (foreground) disk proper motion ellipse using stellar tracers in the nearest distance-bin. When we overplot the best-fitting mean-bulge and mean-disk proper motion contours, we find an apparent grouping of four objects within the 1σ contour of the disk, and all but two of the rest

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within the 1σ bulge contour (Figure 2). Furthermore, the object SWEEPS-04, which lies well within the 1σ ellipse of the disk population, resides on the upper disk sequence in the CMD (Sahu et al. 2006). However all objects are also within the 2σ ellipse of the bulge population.

We use the angular distribution of candidates in proper motion space to assess kinematic membership of the SWEEPS candidates. In $\{\mu_l, \mu_b\}$ space, let Θ_i be the counter-clockwise angle between the major axis of the best-fit bulge ellipse and the line joining the center of the best-fit bulge ellipse to the i-th candidate. The cumulative distribution function (CDF) of Θ_i is then used as an indicator of the angular distribution of the SWEEPS candidates in proper motion space. Should a large number of candidates reside in the disk, one would expect a sharp steepening in the CDF near Θ_d, the angle between the major axis of the bulge ellipse and the center of the disk distribution (Figure 2). Alternatively, if all sixteen candidates were bulge objects, then the CDF would be a straight line; no angle Θ_i would be preferred. We compare the observed cumulative distribution function (CDF) of the SWEEPS candidates to a large number of trial artificial datasets, in which sixteen objects are generated under the best-fit bulge and disk proper motion distributions. For each trial, the two-sided Kolmogorov-Smirnov (KS) statistic is computed between the trial and the observed distribution, yielding the associated formal probability that the SWEEPS candidates and the trial dataset are both realisations of the same probability distribution. This process is repeated for 10^5 trial datasets. This test is repeated for differing sizes of disk contribution N_d to the total population (for $0 \leqslant N_d \leqslant 16$) and the formal probability that the SWEEPS sample matches the distribution using each N_d is recovered.

To maximize use of available information we have also applied the 2D Kolmogorov-Smirnov test to the set of positions in (μ_l, μ_b) space of all the candidates. We use the implementation in Numerical Recipes (Press *et al.* 1992; see also Metchev & Grindlay 2002). In two dimensions the equivalent K-S statistic D_2 is a function of the input distribution. We thus evaluate the significance of the maximum D_2 at each disk fraction N_d using Monte Carlo simulations. This produces an equivalent significance curve as a function of N_d (Figure 2).

Although the most probable disk population N_d differs slightly between the two tests, both are consistent (at 1σ) with a disk population in the range ($1 \leqslant N_d \leqslant 8$). If the fraction of stars hosting jovian planets with periods less than 4.2 days were identical between disk and bulge, we would expect the planet candidates to follow the same disk/bulge distribution as the stars in general. Our kinematic analysis would then suggest 14% of planet candidates - two candidates - would reside in the disk. This is entirely consistent with the actual distribution of candidate kinematics. However, the sample of SWEEPS transit planet candidates is too small to draw meaningful conclusions about the fraction of planets in the disk versus that of the bulge. Because we cannot state that the fraction of planet candidates in disk and bulge are inconsistent with each other, we cannot make any claims about the consistency or otherwise of the fraction of stars hosting planets between the disk and bulge.

We ask if the sub-population of five planet-host candidates with periods less than one day (the "Ultra-Short Period Planet" candidates, or USPP; Sahu *et al.* 2006) themselves are preferentially located in the disk or bulge. Here there is no obvious correlation between period and membership - two USPP fall within the 1σ ellipse of the best-fit disk, three fall within the 1σ ellipse of the best-fit bulge, and all are within 2σ of the best-fit bulge. Thus the USPP do not show any preferred kinematic association compared to the non-USPP candidates; the best that can be said is that the USPP as a family are unlikely to *all* be disk objects.

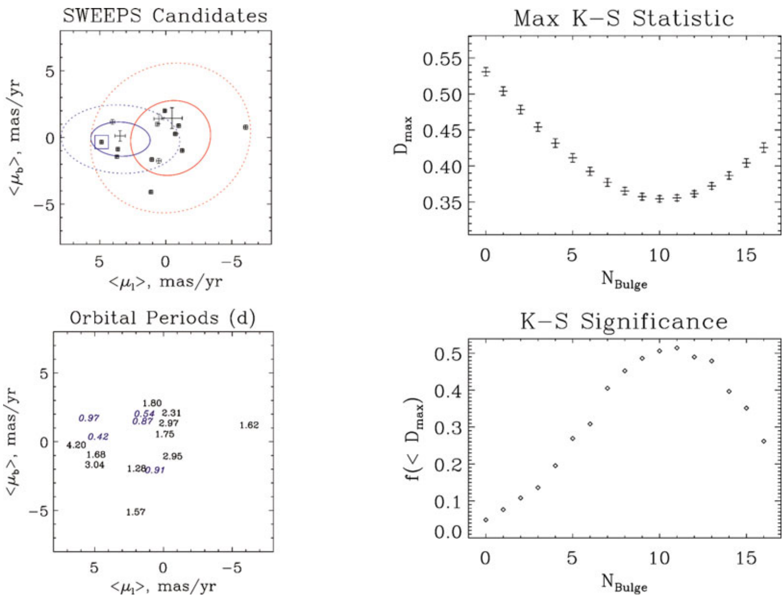

Figure 2. *Left Top:* Proper motions of the sixteen SWEEPS candidates. Left Bottom: as above, except the candidates are marked with their orbital periods. The orbital periods of the ultra-short-period transit planet candidates are given in italics. The 1σ and 2σ contours of the stellar distributions of bulge (right) and disk (left) are overplotted. SWEEPS-04 (box; period 4.2 days), known to lie in a likely disk-dominated region of the CMD, falls close to the the mean-disk proper motion. *Right top:* maximum 2D Kolmogorov-Smirnov statistic for 10^5 simulated proper motion distributions assuming 0-16 of 16 disk objects. *Right bottom:* relative significance of the match between simulated and observed distribution compared to two different simulations from the same distribution, from separate Monte-Carlo trials.

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