A TESS SEARCH FOR DISTANT SOLAR SYSTEM OBJECTS: YIELD ESTIMATES

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As the NASA Transiting Exoplanet Survey Satellite (TESS) fulfills its primary mission (Ricker et al. 2015), it is executing an unprecedented survey of almost the entire sky: TESS's approved extended mission will likely extend sky coverage to $\sim 94\%$, including 60% of the ecliptic (R. Vanderspek, *priv. comm.*).

In Holman et al. (2019) we demonstrated that 'digital tracking' techniques can be used to efficiently 'shift-and-stack' TESS full frame images (FFIs) and showed that combining $\sim 1,300$ exposures from a TESS sector gives a 50% detection threshold of $I_C \sim 22.0 \pm 0.5$, raising the possibility that TESS could discover the hypothesized Planet Nine (Trujillo & Sheppard 2014; Brown & Batygin 2016; Fortney et al. 2016; Batygin et al. 2019). We note that the threshold realized in practice may skew brighter (e.g. $I_C \gtrsim 21.5$), due to the combined effects of stellar contamination and un-modelled stray light (L. Bouma, *priv. comm.*).

The practical constraint on this technique is the number of mathematical operations to be performed when trying all plausible orbits:

$$N_{\rm op} = N_{\rm sec} N_{\dot\alpha} N_{\dot\beta} N_\gamma N_{\rm pix} N_{\rm exp}$$

$$\sim 2 \times 10^{16} \left(\frac{N_{\rm sec}}{26\,{\rm sectors}} \right) \left(\frac{T}{27\,{\rm day}} \right)^3 \left(\frac{P}{21''} \right)^{-3} \left(\frac{d}{25\,{\rm au}} \right)^{-4} \left(\frac{N_{\rm exp}}{1,300} \right) \left(\frac{N_{\rm pix}}{16\,{\rm Mpix}} \right), \tag{1}$$

where $N_{\rm sec}$ is the number of sectors, $N_{\dot\alpha}$ and $N_{\dot\beta}$ the number of angular velocity bins to be searched, N_γ the number of distance bins, T the observational span, P the sky-plane resolution, d the distance, $N_{\rm exp}$ the number of exposures, and $N_{\rm pix} \propto P^{-2}$ the number of pixels (see Holman et al. (2019) for more details[*]). The successful Bernstein et al. (2004) search of HST data required $N_{\rm op} \sim 10^{16}$.

In this note, we demonstrate that this technique has the potential to discover hundreds of Kuiper Belt Objects (KBOs) and Centaurs in TESS FFI data.

VERY DISTANT OBJECTS

Distant objects (e.g. Planet-9) must move sufficiently within the span of observations to be distinguishable from stationary, background sources. Assuming a minimum detectable displacement of $n_p \sim 5$ pixels[†], TESS can detect moving objects at distances of $d \lesssim 900 \left(\frac{5\,{\rm pix}}{n_p} \right)$ *au*. At this distance, the number of operations required to exhaustively search a sector becomes trivially small ($N_{op} \sim 10^{10}$) due to the small number of physically plausible pixel-shifts required.

KUIPER BELT OBJECTS (KBOS)

Eqn. 1 indicates that a KBO search will require $N_{op} \sim 10^{16}$ for the entire nominal TESS mission, similar to the Bernstein et al. (2004) search, but we emphasize that CPUs are now at least 10^3 cheaper per GFlop[‡] than in 2004. The surface density of KBOs near the ecliptic brighter than $I_C = 22.0$ is $\sim 0.2\,{\rm deg}^{-2}$ (Gladman et al. 2001; Fraser et al. 2014), where we have assumed average colors of $V - R \sim 0.6$ and $R - I_C \sim 0.6$ for these objects (Peixinho et al.

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[*] Eqn 1 properly accounts for all 26 sectors, correcting an error in Holman et al. (2019).

[†] TESS pixels are $\sim 21''$ across
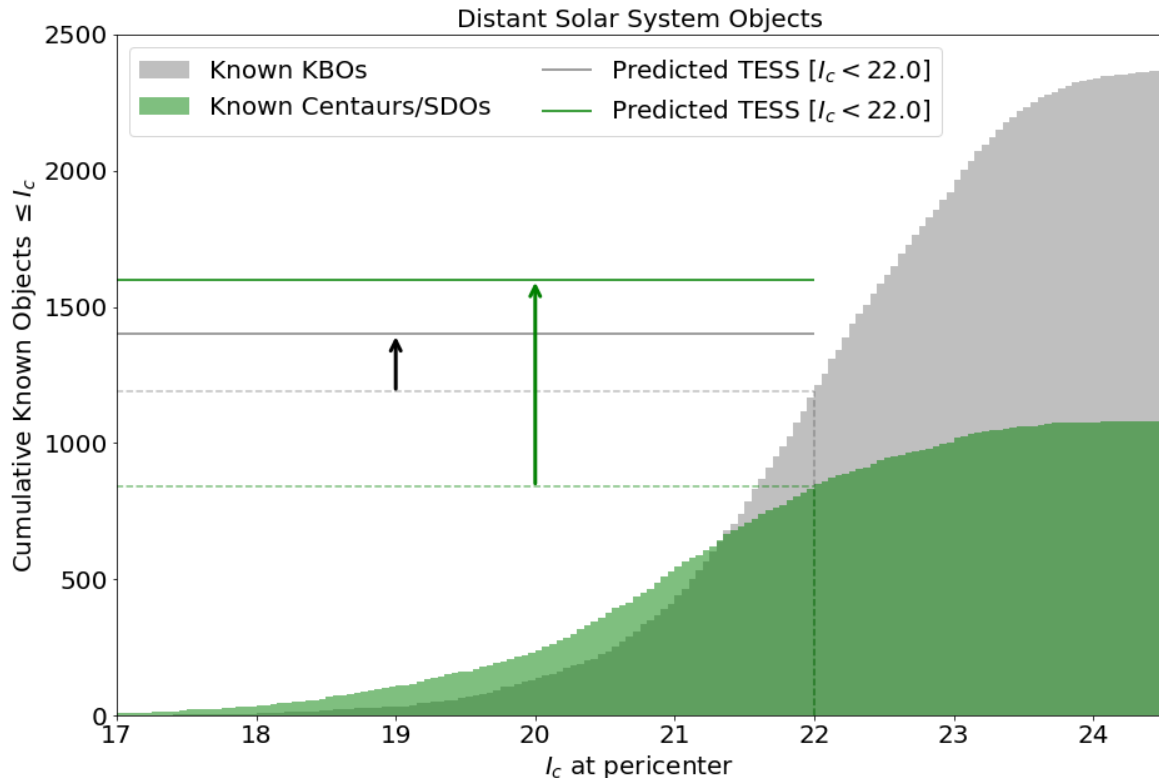
[‡] https://en.wikipedia.org/wiki/FLOPS

Figure 1. Cumulative histograms of known KBOs (gray) and Centaurs/SDOs (green) are plotted as functions of I_c (at pericenter), along with dashed lines indicating the current known numbers with $I_C < 22.0$. Our predicted TESS yields for $I_C < 22.0$ are plotted as solid horizontal lines, indicating significant numbers of expected discoveries.

2015). Most KBOs orbit within $12°$ of the ecliptic (Brown 2001), and we estimate that by the end of its extended mission, TESS will have observed $\sim 80\%$ of this region, for an effective area of $7,000\,\mathrm{deg}^2$ yielding $\sim 1,400$ KBOs brighter than $I_C = 22.0$ within 12 degrees of the ecliptic. In Figure 1 we compare the known population of KBOs with the predicted yield, demonstrating that TESS has the potential to discover ~ 200 *new* KBOs with $I_c \geq 22.0$.

CENTAURS

A TESS search for Scattered Disk Objects (SDOs) and Centaurs (with $d \gtrsim 10\,au$) is also computationally feasible ($N_{op} \sim 4 \times 10^{17}$). For Centaurs and SDOs, the combined surface density is $\sim 0.1\,\mathrm{deg}^{-2}$ (Larsen et al. 2001), but they are more broadly distributed in ecliptic latitude than are KBOs. Their latitude distribution is poorly known due to the comparatively small area of previous surveys. Conservatively, we assume a discovery area twice that for KBOs, yielding $\sim 1,600$ objects. In Figure 1 we compare the known population of Centaurs and SDOs with our predicted yield, demonstrating that many remain to be discovered. TESS has the potential to discover ~ 750 *new* Centaurs/SDOs with $I_c \geq 22.0$.

OTHER

Searching for objects with $d \ll 10\,au$ becomes increasingly challenging because $N_{op} \propto d^{-4}$. For the asteroid belt, $N_{op} \sim 10^{18}$, which is likely infeasible. However, one could restrict a search to (e.g.) prograde orbits within $\pm 5°$ of the ecliptic, reducing the number of angular velocity bins to be searched, $N_{\dot{\alpha}} \times N_{\dot{\beta}}$, (and hence N_{op}) by a factor of 30.

Alternatively, bright objects such as the interstellar comet *2I/Borisov*, currently around 17th magnitude, need little stacking, facilitating a well-characterized all-sky survey to constrain their occurrence-rate.

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REFERENCES

Batygin, K., et al. 2019, arXiv e-prints, arXiv:1902.10103

Bernstein, G. M., et al. 2004, AJ, 128, 1364

Brown, M. E. 2001, AJ, 121, 2804

Brown, M. E., et al. 2016, ApJL, 824, L23

Fortney, J. J., et al. 2016, ApJL, 824, L25

Fraser, W. C., et al. 2014, ApJ, 782, 100

Gladman, B., et al. 2001, AJ, 122, 1051

Holman, M. J., et al. 2019, Research Notes of the American Astronomical Society, 3, 160

Larsen, J. A., et al. 2001, AJ, 121, 562

Peixinho, N., et al. 2015, A&A, 577, A35

Ricker, G. R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003

Trujillo, C. A., et al. 2014, Nature, 507, 471