Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S1743921318002569

TESS Science and Follow-Up in the Southern Hemisphere

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Abstract. The Transiting Exoplanet Survey Satellite (*TESS*) is an MIT-led NASA mission that will spend two years searching for transiting exoplanets via an all-sky survey that starts in the Southern Hemisphere. Launched in 2018 April, *TESS* is expected to discover thousands of Earth- to Neptune-sized planets, and over ten thousand giant planets, around the closest, brightest, stars. These planets will become our best targets for learning more about planet formation and evolution, planet composition, and atmospheric make-up. More detailed information about *TESS*, and instructions on how to access and work with the data once they are available, was given in Workshop 3, *Getting ready for TESS*, held earlier during the Symposium (p. 224).

Keywords. stars: planetary systems - surveys

1. TESS Overview

NASA's newest exoplanet mission, the Transiting Exoplanet Survey Satellite *(TESS*), was launched successfully on 2018 April 18, and when its scientific programme commences it will search for evidence of transiting exoplanets around stars within 300 pc of the Sun. Technical details of the spacecraft and its instruments can be found at https://tess.mit.edu.

The spacecraft is designed with four identical cameras (each with a $24^\circ \times 24^\circ$ field of view imaged by an array of four 2K×2K CCDs) that will be stacked to form a $24^\circ \times 96^\circ$ 'observing sector' on the sky. *TESS* will spend its first year surveying the southern ecliptic hemisphere, splitting the sky into 13 of these sectors and with one camera centred on the south ecliptic pole, forming a continuous viewing zone roughly 12° in radius. Each sector will be observed for a total of 27.4 days, during which *TESS* will complete two full orbits of the Earth. The data will be down-linked every 13.7 days while the spacecraft passes through perigee (Ricker *et al.* 2014).

The same observing strategy will then be repeated in the northern ecliptic hemisphere during the second year of the nominal two-year mission. The planned pattern will result in ∼85% total coverage (with a lack of coverage around the Ecliptic equator, which is currently being surveyed by *K2*, the second phase of NASA's *Kepler* mission). About 65% of the sky will be observed for 27 days, and about 20% observed for up to one year, depending on the proximity to the continuous viewing zones at the ecliptic poles (see Figure 2 of the Report of Workshop 3 (p. 226)).

Throughout the survey the cameras will observe some ∼120,000 pre-selected stars at a 2-minute cadence, and will take Full Frame Images (FFIs) of the entire field of view every 30 minutes. The *TESS* camera CCDs and FOV described above result in a pixel scale of $21''.1$. When taking into account the effects of photon-counting noise from the star and

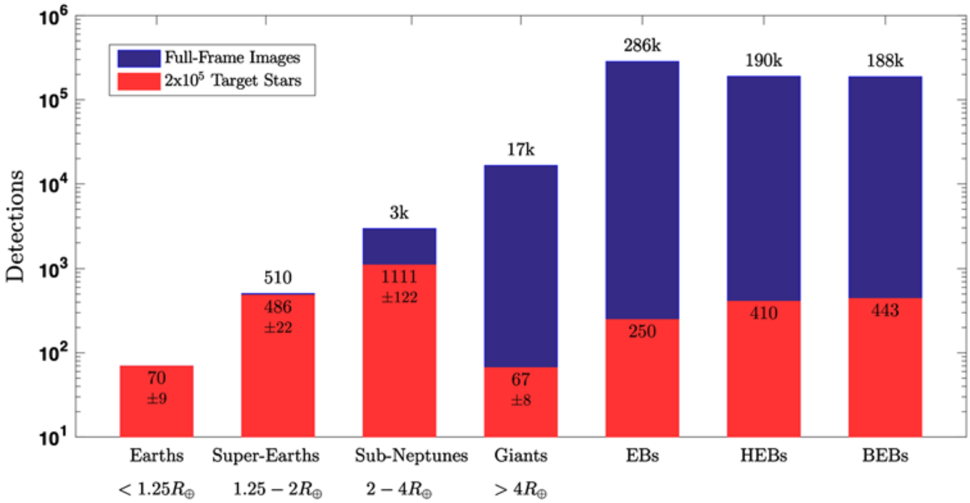

Figure 1. Mean numbers of planets and eclipsing binaries detected in the *TESS* simulation. Results are shown for the 2×10^5 target stars observed with 2-minute sampling, and for stars in the full-frame images observed with 30-minute sampling. The statistical error from Poisson fluctuations and input planet occurrence rates are shown. For eclipsing binaries an additional systematic error could be up to 50%. (*Reproduced, with kind permission, from Sullivan et al. 2015*).

the background (zodiacal light and light from faint unresolved background stars), read-out noise, and a term representing additional systematic errors that cannot be corrected by co-trending, the expected 1-σ photometric precision of the *TESS* cameras around the brightest target stars will be better than 0.1% (Ricker *et al.* 2014). *TESS* data will have no proprietary period, and will be released to the public once they have been calibrated, reduced and approved by NASA and MIT.

2. Planet Yield

Simulations of the mission's predicted planet yield were carried out by Sullivan *et al.* (2015), who constructed a model of the local stellar and planetary populations and combined it with a model for *TESS*'s photometric precision to predict the properties of the planetary systems that *TESS* is likely to detect. For the stars, they used the TRILEGAL stellar population synthesis model (Girardi *et al.* 2005), modifying the output stellar luminosity–radius relation to match eclipsing binary (EB) radii and interferometric radii. For the planets, they used occurrence rates derived from the *Kepler* mission; for host stars with $T_{\rm eff} > 4000$ K they used the rates calculated by Fressin *et al.* (2013), while for stars below that threshold they used the rates determined by Dressing & Charbonneau (2015).

A planet is labelled as being 'detected' if it transits at least twice while *TESS* observes the host star, and if the signal-to-noise of the transit in the folded light-curve is $\geqslant 7.3$. *TESS* is expected to detect roughly 1,000 sub-Neptune planets in the 2-minute cadence data, and up to 4,000 when considering the FFIs. For giant planets the expected detection rate is below 100 for the 2-minute data, but the numbers grow to 17,000 when considering the FFIs (see Fig. 1). Because of the 2:1 orbital resonance with the Moon, the orbit of *TESS* should remain stable, with minimal station keeping, for well over a decade. When considering a conservative one-year mission extension, Bouma *et al.* (2017) found that there would be no sharp fall-off in the rate of planet discoveries in the third year, and that the quantity of newly-detected planets with sub-Neptune radii does not depend strongly

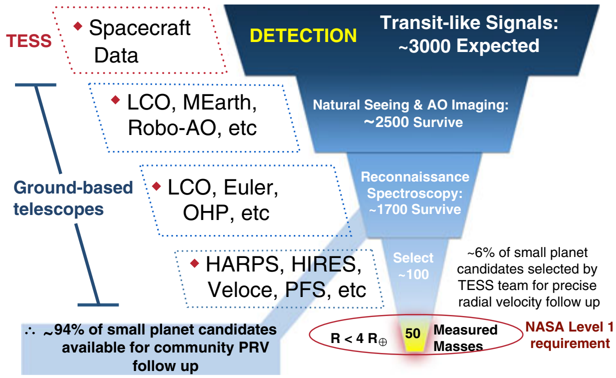

Figure 2. Flow chart of expected false positive vetting for short-cadence *TESS* planet candidates, highlighting the 1000+ exoplanet candidates that will require ground based follow-up to confirm/deny their planetary nature. (Based on information provided in Ricker *et al.* 2015).

on the observing strategy used (e.g., repeating one of the ecliptic hemispheres, focusing more on the ecliptic polar regions, filling in the ecliptic equator, etc).

The planets detected by *TESS* will include some of the best candidates for thorough characterisation, as they orbit stars that are (on average) 10 times closer and 30–100 times brighter than the stars observed by *Kepler*. Indeed, as of February 2018, only 73 of the 2287 confirmed, transiting *Kepler* planets have had their masses determined via radial velocity (RV) observations. *K2* is providing additional RV-amenable targets as it searches the ecliptic plane for evidence of transits around brighter stars in 80-day observing campaigns; as of February 2018, *K2* has released data from 14 different campaigns, resulting in 304 confirmed transiting planets, 32 of which have had their masses determined via RV follow-up efforts (Akeson *et al.* 2013). The mentioned increase in brightness is not due to any intrinsic difference in the stellar populations studied by *TESS* vs. *Kepler* or *K2*, but is an added benefit of *TESS*'s (almost) all-sky survey approach. By covering ∼400 times more area on the sky than *Kepler* did, *TESS* is able to target a much larger population of stars brighter than V=12, for which RV follow-ups become more feasible and planetary masses and compositions can thus be studied.

3. Follow-Up Efforts

The 21″.1 pixel scale of the *TESS* cameras means that thorough vetting is required to distinguish true exoplanets from false positive signals caused (for instance) by background eclipsing binaries or stellar blends (see Fig. 2). Once *TESS* downlinks its data every 13.7 days, the stellar light-curves will be analysed by NASA's SPOC pipeline and the MIT Quick Look Pipeline. These pipelines will identify Threshold Crossing Events, or light-curves that contain at least two transit signatures, and which will then be flagged for analysis by human vetters at the *TESS* Science Center. While the transit data alone can provide clues for identifying and removing some false positives (such as different depths in the odd and even transit events for a star, implying that the system is actually an eclipsing binary and *not* an exoplanet), many others are too subtle to be flagged properly during this step. The objects that survive these two stages of software pipeline and human visual vetting will be labelled as *TESS* planet candidates, and released to the public for additional study. We expect *TESS*'s two year primary mission to result in some 3,000 planet candidates. Those candidates will then require:

• Follow-up photometry: to search for additional transit signatures, refine the initial transit parameters and keep the transit ephemeris from going stale.

https://doi.org/10.1017/S1743921318002569 Published online by Cambridge University Press

• High-resolution imaging: to look for evidence of nearby stars that could have fallen into the same pixel as the *TESS* target star, and imparted either their own exoplanet/EB signal on the *TESS* pixel or contaminated the base flux level.

• Reconnaissance spectroscopy: to look for evidence of double-lined binary stars and obtain better stellar parameters such as T_{eff} and vsin i, which will determine whether the star is suitable for RV follow-up.

• Precise RV follow-up: for stars that pass all of the above checks and show no evidence of being false positives, precise RV instruments will be used to measure planetary masses and confirm the Keplerian nature of the transit signal.

The level of ground-based follow-up required to move these thousands of expected candidates to the category of confirmed planets will be extensive. As the *TESS* data have no proprietary period, telescopes and instruments around the globe will be able to participate and contribute to the verification and study of this new exoplanet population, which is expected to contain the best candidates for detailed composition and atmospheric characterisation. More detailed information about *TESS*, and instructions on how to access and work with the data once they are available, was given in Workshop 3, *Getting ready for TESS*, held earlier during the Symposium (p. 224).

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