TESS Project Update

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(MIT)

ExoPAG 23
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TESS is a collaboration including:
MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, NGSS, SpaceX, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, Aarhus University-Denmark, Harvard College Observatory, Cornell University, Princeton University, Vanderbilt University...
TESS Montage of Sectors 1-26 from Prime Mission

South Ecliptic Pole View
(Yr 1: Sectors 1-13)

North Ecliptic Pole View
(Yr 2: Sectors 14-26)

Graphics:
R. Vanderspek
TESS Project Update:

Exoplanet Observations
Many TESS transiting exoplanet discovery papers are in press or in preprint.
**TESS Publications on arXiv by Year**

![Graph showing TESS, Kepler, and Swift publication rates over years following launch.]

- **TESS** publications have been increasing steadily over the years following launch.
- In 2020, there were 305 papers (~6 papers per week).
- As of 7/27, 170 papers have been published in 2020.

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**TESS—Discovering New Earths and Super-Earths in the Solar Neighborhood**

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GRR/210104
TESS Exoplanets Detected as of 12/31/20:

- 2440 Planet Candidates ("TOIs")
  ➡ ~1/3 of PCs have $R_{PC} < 4 \ R_{\oplus}$
- See https://exoplanetarchive.ipac.caltech.edu/
Figure 1. Left: An illustration of all the stars for which we extracted photometry from the TESS Primary Mission FFIs in terms of their equatorial coordinates. Right: The photometric precision of the time series, compared to expected theoretical precision estimated in Sullivan et al. (2015) (solid line). The dashed horizontal line is a reference indicating 20 ppm precision.
TESS’s Exceptional Pointing Stability is a Key to its Photometric Precision

1 min: 0.5 arcsec (3$\sigma$) = 24 millipix

1 hr: 13 milliarcsec (3$\sigma$) = 0.6 millipix ~ 20 Si atomic spacings!

Values are 4x better than the original mission requirement
2,440 TESS planet candidates

TESS image data courtesy of NASA/MIT/TESS: Natalia Guerrero & Team: Ethan Kruse (USRA), Greggy Bazile
3,189 transiting planets from other surveys
There are thousands of worlds across the night sky

TESS image data courtesy of NASA/MIT/TESS: Natalia Guerrero & Team: Ethan Kruse (USRA), Greggy Bazile
TESS Follow-Up Program (TFOP)— (S. Quinn, private comm)

Add’l TESS Level 1 masses in process:

- 45 masses
- Abstract on TESS wiki: 27
- Private communication only: 18

Public TESS Level 1 masses:

- 42 masses
- Accepted to Journal: 36
- Preprint only: 6

Progress toward Level 1 Req’m’t of 50 measured masses

Spectroscopic contributions toward Level 1 systems have (or will) come from many teams, using facilities such as:

- HARPS
- HARPS-N
- ESPRESSO
- CARMENES
- PFS
- HIRES
- FEROS
- MINERVA-Australis
- Veloce
- CHIRON
- CORALIE
- SOPHIE
- TRES
- FIES
- NRES
- McDonald-Tull
- IRD
- iSHELL
- SPIRou
- ANU2.3m
- APF
- SONG
- FIDEOS
- Tautenburg
- SALT/HRS
- IGRINS
- NEID
- EXPRES
- MAROON-X
- ...and more

...despite many months of follow-up lost to COVID-19 closures (with most northern PRV facilities closing for at least a couple months and all southern PRV facilities -- HARPS, ESPRESSO, PFS -- still closed and just now starting to reopen).
TOI 1233: a “Super-Earth” and three sub-Neptunes orbiting the bright Sun-like star HD 108236

Multiple small planets hosted by a bright star provide cosmic laboratories to test models of planet formation and evolution.

HD 108236: the brightest Sun-like star to host at least four transiting planets.

Late Breaking: 5th TOI-1233 Planet from CHEOPS was announced today (Bonfanti et al. 2021)
**The K2 & TESS Synergy I: Updated Ephemerides and Parameters for K2-114, K2-167, K2-237, & K2-261**

- Established updated ephemerides and system parameters for three Jovian sized planets and a sub-Neptune with orbital periods less than 12 days

- The updated ephemerides significantly reduce the uncertainty in prediction of future times of transit, which is essential for planning observations with the James Webb Space Telescope and other future facilities

- The TESS extended mission is expected to observe more than half of the K2 fields, enabling this type of analysis on a larger number of systems

Map of K2 targets that were observed in TESS years 1 (red) and 2 (blue)

The difference in time of transit predicted by the K2 discovery papers as compared to the updated predictions from TESS, projected to the year 2030. The shaded regions indicate 1, 2, and 3-sigma confidence intervals.
TESS Project Update:
Extended Mission
TESS Data Cadences in Extended Mission

- **FFI cadence reduced to 10 min**
  - Replaces prime mission’s 30 minute cadence

- **“Postage Stamps” are augmented**
  - 120s cadence is unchanged
  - 20s cadence has been added

- **Solid State Recorder (SSR) volume usage**
  has increased from ~30% to ~50% in
  Extended Mission
  - Margin is needed in case a DSN downlink does
    not occur for a given TESS orbit, and a make-up
    DSN pass is needed during the following orbit

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![Graph showing SSR fill percentages for Prime and Extended Missions]

- **Fill % of SSR:**
  - 100%: 50%
  - 75%: 37.5%
  - 50%: 25%
  - 25%: 12.5%

- TESS’s on-board data storage budget
  for the Prime and Extended Missions
Faint Star Search with TESS FFIs

**Goal:** To search for new planet candidates around faint stars using TESS FFIs (Sector 1 - present)

- **Initial search:** $10.5 < \text{TESS mag} < 13.5$ ($20 \times 10^6$ stars)
- **Deeper search:** $13.5 < \text{TESS mag} < 15$ ($50 \times 10^6$ stars)

**Results so far:** 58 new candidates from search of 400k stars with TESS mag < 13.5 in Sector 1

**Projected Results:** 3000+ new candidates from initial search; potentially an additional 7000+ from deeper search

**Basis:** Modifications of QLP by M. Kunimoto and T. Daylan (in progress)
TESS can photometer an enormous number of stars!

Star Count Data in I band
(HST Guide Star Catalog v2.3, B. Lasker et al. 2008)

TESS — Discovering New Earths and Super-Earths in the Solar Neighborhood

GRR/210104

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## Growing Number of TESS High Level Science Products (HLSPs) at MAST

<table>
<thead>
<tr>
<th>TESS Data HLSP</th>
<th>Initial Year</th>
<th>Authors</th>
<th>TESS Data Source</th>
<th>Initial Number of Sectors</th>
<th>Number of Objects</th>
<th>Remarks/Future Work</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>TASOC LCs</td>
<td>2019</td>
<td>R. Handberg et al.</td>
<td>FFIs</td>
<td>2 (S1-S2)</td>
<td>~ 1.7 million in 2 sectors</td>
<td>Add’n of co-trending</td>
<td>Asteroseismology</td>
</tr>
<tr>
<td>Eleanor LCs</td>
<td>2019</td>
<td>A. Feinstein et al.</td>
<td>FFIs</td>
<td>13 (S1-S13)</td>
<td>~ 13 million in 13 sectors</td>
<td>T=16 mag limit</td>
<td>Time domain astrophysics</td>
</tr>
<tr>
<td>PATHOS LCs</td>
<td>2019</td>
<td>D. Nardillo</td>
<td>FFIs</td>
<td>13 (S1-S13)</td>
<td>&gt; 200,000 in 13 sectors</td>
<td></td>
<td>Open and globular clusters, young stellar associations</td>
</tr>
<tr>
<td>CDIPS LCs</td>
<td>2019</td>
<td>L. Bouma et al.</td>
<td>FFIs</td>
<td>13 (S1-S13)</td>
<td>&gt; 670,000 in 13 sectors</td>
<td></td>
<td>Young cluster and moving group candidate stars</td>
</tr>
<tr>
<td>SPOC LCs</td>
<td>2020</td>
<td>D. Caldwell et al.</td>
<td>FFIs</td>
<td>13 (S14-S26)</td>
<td>~ 4 million in 13 sectors</td>
<td>T=13.5 mag limit</td>
<td>Exoplanets</td>
</tr>
<tr>
<td>QLP LCs</td>
<td>2020</td>
<td>X. Huang et al.</td>
<td>FFIs</td>
<td>26 (S1-S26)</td>
<td>~ 10 million in 26 sectors</td>
<td>S27 onwards; Extension to T=15 mag (Kunimoto et al. in prep)</td>
<td>Exoplanets, Variable Stars</td>
</tr>
<tr>
<td>DIAMANTE LCs</td>
<td>2020</td>
<td>M. Montalto et al.</td>
<td>FFIs</td>
<td>13 (S1-S13)</td>
<td>~ 1 million in 13 sectors</td>
<td></td>
<td>Exoplanets</td>
</tr>
<tr>
<td>TICA FFIs</td>
<td>2020</td>
<td>M. Fausnaugh et al.</td>
<td>FFIs</td>
<td>4 (S27-S31)</td>
<td>~ 15 million per sector (T &lt; +17 limit; estimate based on GSC 2.3)</td>
<td>Front end product from MIT QLP with BCS added; Prompt releases for Yr 3+</td>
<td>Asteroids, NEOs, transients, binary stars and WDs, new classes of time variability studies</td>
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[https://archive.stsci.edu/hlsp/qlp](https://archive.stsci.edu/hlsp/qlp)
Comparison: “Special Planets” anticipated from TESS Primary and Extended Missions

<table>
<thead>
<tr>
<th></th>
<th>Prime Mission</th>
<th>Extended Mission</th>
<th>Prime + Extended Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total new small planets (R &lt; 4R&lt;sub&gt;E&lt;/sub&gt;)</td>
<td>908</td>
<td>1331</td>
<td>2239</td>
</tr>
<tr>
<td>Planets in or near habitable zone (0.5 &lt; S/S&lt;sub&gt;E&lt;/sub&gt; &lt; 2)</td>
<td>58</td>
<td>91</td>
<td>149</td>
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<tr>
<td>Planets with periods longer than 20 days</td>
<td>199</td>
<td>509</td>
<td>708</td>
</tr>
</tbody>
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Simulations from TESS Extended Mission Proposal (Sullivan+ 2015; Bouma+ 2017; Barclay+ 2018)
TESS Project Update:
Extended Mission
Sky Survey Plans
TESS Sky Coverage Maps

Year 1 of the Mission (Jul 2018-Jun 2019)
TESS Sky Coverage Maps

Adding Year 2 of the Mission (Jul 2019-Jun 2020)
TESS Sky Coverage Maps

Then Year 3 of the Mission (Jul 2020-Jun 2021)
Notes:
- Each TESS Ecliptic Pointing covers a 96° long swath in Ecliptic Longitude => ~27% of the Ecliptic per pointing
- Interior sectors of the Ecliptic swath could have 4 sectors of overlap => ~110 days of observation for those stars
- More than 60% of the Ecliptic could be covered during 5 sectors => ~ 60% of the K2 Planets would be re-observed
- Plan is somewhat complex so as to avoid undue impacts of Earth-Moon scattered light
**TESS Total Sky Coverage and Orbit Precession**

Sky Coverage in Prime plus Extended Mission:
88% in 51 months
(Includes 15 of the 20 K2 Fields)

Apparent migration on the sky of excess scattered light region as the TESS orbit precesses
### Timelines for the Coming Decade: TESS and Related Missions

<table>
<thead>
<tr>
<th>Year</th>
<th>TESS Prime</th>
<th>Extended</th>
<th>Extended Mission 2?</th>
<th>Extended Mission 3?</th>
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<tbody>
<tr>
<td>2018</td>
<td></td>
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<tr>
<td>2019</td>
<td>TESS Prime</td>
<td></td>
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<tr>
<td>2020</td>
<td></td>
<td>Extended</td>
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<td>2021</td>
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<td>2022</td>
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<td>2026</td>
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<td>2027</td>
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<td>2028</td>
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**Legend:**
- Exoplanet Mission
- Transient Observatory

- TESS — Discovering New Earths and Super-Earths in the Solar Neighborhood
- eRosita
- CHEOPS
- JWST Design Mission
- LIGO O4
- Ruben Telescope (LSST) 10 Year Survey
- ELTs [EELT + GMT + TMT]
- Roman Telescope (WFIRST)
- PLATO…ARIEL
TESS Science Conference II

August 2 - 6, 2021, MIT

tsc2@mit.edu
#TESScon2
@TessSciCon2
Takeaways: TESS’s Current Mission Status

- TESS’s unique lunar resonant orbit is greatly simplifying the mission
  - Stable operations in principle could last until 2038 or later
- TESS’s spacecraft stability is exquisite
  - < 20 milli-arcseconds (1/1000th pixel) on 1 hour time scales
- TESS’s camera performance is superb
  - Focus is stable to ~1µm on 1 hour time scales
  - Photometric precision is <20 ppm (3x better than planned) for bright stars
  - Achieving stacked FFI limiting magnitudes below $I_{mag} = +21$
- TESS’s initial sky survey sector-by-sector was completed successfully
- TESS’s extended mission commenced on July 5, 2020
- TESS’s full frame images are enabling a wide range of astrophysics discoveries
  - Rich trove of high-value exoplanet targets for future missions
  - Transient Science: Stellar Astrophysics, Extragalactic “Multi-Messenger Astronomy”, …
  - “Precovery” transient observations are routine
- TESS’s high science ranking by NASA in mid-2019
  - #1 for Scientific Merit in NASA’s 2019 Senior Review of Explorer Missions
  - Invited to the 2022 Astrophysics Senior Review (hopefully, extension to 2025...