TESS: Mission Update

George Ricker (MIT)
TESS PI

Astronomy and Astrophysics Advisory Committee
National Science Foundation
Alexandria VA
25 February 2019

collaboration including:
MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, NGIS, SpaceX, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Princeton University, Vanderbilt University...

Graphics Credits: Zach Berta-Thompson (U. Colorado)
• TESS is on orbit and sky survey is underway!
  ‣ 18 April 2018 SpaceX F9 launch and commissioning was fully successful
  ‣ Special resonant orbit achieved is spot on
  ‣ No significant eclipses by Earth or Moon for next 20 years
  ‣ Science instruments fully commissioned
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• **Science Survey Sectors 1-7 completed; Sector 8 in Progress**
TESS Search Space: 200 light-years
All-sky

Kepler Search Space: 3000 light-years
0.25% of the sky
Exoplanet Population pre-TESS

- Gl436b
- GJ3470b
- GJ1214b
- HD97658b
- HD219134b
- HD219134c
- GJ1132b
- TRAPPIST-1bcd
- HAT-P-11b

TESS — Discovering New Earths and Super-Earths in the Solar Neighborhood
We predict TESS will fill in this region
## TESS and Kepler

<table>
<thead>
<tr>
<th>Mission Comparison</th>
<th><strong>Kepler</strong></th>
<th><strong>TESS Prime</strong></th>
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<tbody>
<tr>
<td><strong>Main goal</strong></td>
<td>Measure frequency of Earths</td>
<td>Find planets around bright stars</td>
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<tr>
<td><strong>Duration</strong></td>
<td>8 years (4 Kepler + 4 K2)</td>
<td>2 years</td>
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<tr>
<td><strong>Orbit</strong></td>
<td>Heliocentric (373 d)</td>
<td>High-Earth (13.7 d)</td>
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<tr>
<td><strong>Bandpass</strong></td>
<td>0.4 – 0.8 µm</td>
<td>0.6 – 1.0 µm</td>
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<tr>
<td><strong>Optical area</strong></td>
<td>7100 cm²</td>
<td>114 cm²</td>
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<tr>
<td><strong>Field of view</strong></td>
<td>105 deg²</td>
<td>2304 deg²</td>
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<tr>
<td><strong>% of pixels retained</strong></td>
<td>0.003% (1 min) 6% (30 min)</td>
<td>8% (2 min) 100% (30 min)</td>
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<tr>
<td><strong>Dwell time per star</strong></td>
<td>Kepler: 4 years K2: 3 months</td>
<td>Typically 1–2 months</td>
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<tr>
<td><strong>Magnitude of planet hosts</strong></td>
<td>10-16</td>
<td>6-13</td>
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**Etendue Comparison**

<table>
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<tr>
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<th>$A_{optics}$ [m²]</th>
<th>$\Omega_{gross}$ [deg²]</th>
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<th>Etendue [m² deg²]</th>
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<tr>
<td><strong>TESS</strong></td>
<td>0.0114</td>
<td>2304</td>
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<td>26.3</td>
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<tr>
<td><strong>Kepler</strong></td>
<td>0.71</td>
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<td>6.30</td>
<td>4.2</td>
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TESS is the highest etendue optical space mission yet flown: ~6 times greater than Kepler

Bryson et al. 2010  
Ricker et al. 2016
TESS Observatory During Integration and Testing
Advantages of TESS’s 13.7 Day Lunar Resonant (P/2) Orbit
Advantages of TESS’s 13.7 Day Lunar Resonant (P/2) Orbit

- Extended Observations: ~300 hrs per orbit
- Thermal Stability: <30 mK/day (passive control only)
- Earth/Moon Stray Light Level: $10^6$ times less than LEO
- Low Radiation Levels: Outside of Earth’s Radiation Belts
- Excellent Pointing Stability: No Drag, No Gravity Gradient
- Station keeping propellant: none required for ~100 years
- High Downlink Rates: 100 Mbit/s (185 GB in ~5 hr at Apogee!)
TESS P/2 Resonant Orbit is Near Perfect!

Nominal LRP Angle = 37.33 deg

Min Perigee Radius = 6.64 Rₚ
Max Perigee Radius = 23 Rₚ

Year

Perigee Radius, rₚ (Rₚ)

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043

6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Kozai oscillations will stabilize the orbit exactly as planned
Kozai oscillations will stabilize the orbit exactly as planned
Stable TESS orbit behavior is anticipated for >25 years
• Photometric precision of Sector 5 light curves is \(~200\) ppm at \(T_{\text{mag}} = +10\)
  ‣ Below L3 requirement of 230 ppm
• Bright object limiting noise floor is \(~20\) ppm
  ‣ Well below Level 1 requirement of 60 ppm
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Commissioning Completed:
24 July 2018

TESS Science Survey Began:
25 July 2018
TESS Year 1: Initial Southern Hemisphere Pointings

Ecliptic Plane

Sector 1

Sector 2

Sector 3

Continuous Viewing Zone

Camera 1

Camera 2

Camera 3

Camera 4

24°

96°
Official “First Light” Image from TESS Sector 1

(1 of ~1200 FFIs from Sector 1)
Discovering New Earths and Super-Earths in the Solar Neighborhood
Science Sector #1: Ecliptic Coordinates

North Ecliptic Pole

Galactic Plane

South Ecliptic Pole

1
All Year 1 Science Sectors: Ecliptic Coordinates

North Ecliptic Pole

Galactic Plane

South Ecliptic Pole
All Year 1 Science Sectors: **Celestial Coordinates**

**Known Planets:**
- WASP Survey
- HATS Survey
- Other Surveys

Figures: Andras Pal
All Year 1 Science Sectors: Celestial Coordinates

Known Planets:
- WASP Survey
- HATS Survey
- Other Surveys

Figures: Andras Pal
• Initial Full Data Release on December 6th
  ▸ 6 weeks earlier than originally planned
  ▸ Accompanying documentation included
  ▸ Posted here at MAST for public download

• Initial 8% of Sky Survey
  ▸ Sectors 1 and 2 (of 26 scheduled over next two years)
  ▸ ~30,000 light curves at 2 min cadence
  ▸ ~2000 Full frame images at 30 min cadence

• Full sensitivity for the two sectors surveyed
  ▸ ~ 3500 square degrees
  ▸ ~20,000,000 stars and galaxies brighter than $I_{mag} = +18$ (S/N > 10)
  ▸ Continuous viewing of the Large Magellanic Cloud for 2 months
    • Anticipated in full 12 month survey: microlensing events, variable stars, ...
TESS Objects of Interest (TOI) Evaluation Effort
TOI Steering Committee:
Natalia Guerrero, Sara Seager, Chelsea Huang, Avi Shporer, Michael Fausnaugh, Karen Collens, Sam Quinn, Ana Glidden, Scott Dynes, George Ricker, Dave Latham, Roland Vanderspek
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Team Goal:
Issue prompt Alerts for Ground Observers to establish masses for TESS-discovered small planets ASAP, thus satisfying TESS’s Level 1 Mission Requirements
385 TOIs (so far!)

Yield from 5 sectors:

104 TOIs with TESS $R_p < 4R_E$
54 false positives
189 alerted with QLP parameters
196 alerted with SPOC parameters

TESS small planets ($< 4R_E$) thus far:

Mass measurements underway: 30
Mass measurements complete: 6

QLP = MIT Quick Look Pipeline
SPOC = NASA Ames Kepler-derived Pipeline
Rate since Jan 1:
26 publications in 53 days
=> 1 per ~2 days
ABSTRACT

We report the detection of a transiting planet around π Men (HD 39001), using data from the Transiting Exoplanet Survey Satellite (TESS). The solar-type host star is unusually bright ($V = 5.7$) and was already known to host a Jovian planet on a highly eccentric, 5.7-year orbit. The newly discovered planet has a size of $2.14 \pm 0.04 \, \text{R}_\oplus$ and an orbital period of 6.27 days. Radial-velocity data from the HARPS and AAT/UCLES archives also displays a 6.27-day periodicity, confirming the existence of the planet and leading to a mass determination of $4.82 \pm 0.86 \, \text{M}_\oplus$. The star's proximity and brightness will facilitate further investigations, such as atmospheric spectroscopy, astroseismology, the Rossiter-McLaughlin effect, astrometry, and direct imaging.

Subject headings: planetary systems, planets and satellites: detection, stars: individual (HD 39001)
"The discovery of a terrestrial planet around a nearby M dwarf during the first *TESS* observing sector suggests that the prospects for future discoveries are bright. It is worth remembering that 90% of the sky has not yet been surveyed by either *TESS* or *Kepler.*"
Dragomir et al. (2019)  
arXiv:1901.00051

THE LONGEST PERIOD TESS PLANET YET: A SUB-NEPTUNE TRANSITING A BRIGHT, NEARBY K DWARF STAR

DIANA DRAGOMIR1,2, JOHANNA TESKE1,3,4, MAXIMILIAN N. GÜNTHER1,5, DAMIEN SÉGRANSAN6, JENNIFER A. BURT1,5, CHELSEA X. HUANG1,5, ANDREW VANDERBURG2,3, ELISABETH MATTHEWS7, XAVIER DUMUSQUE8, KEIVAN G. STASSUN9, JOSHUA PEPPER10, GEORGE R. RICKER1, ROLAND VANDERSPREK1, DAVID W. LATHAM11, SARA SEAGER12,13, JOSHUA N. WINS14, JON M. JENKINS15, THOMAS BEATTY16,17, FRANÇOIS BOUCHY9, R. PAUL BUTLER1, JEFFREY D. CRANE1, JASON D. EASTMAN11, JIM FRANCIS1, B. SCOTT GAUDI8, ROBERT F. GOEKE1, DAVID JAMES11, TODD C. KLAUS12, RUDOLF B. KUHN20,21, CHRISTOPHE LOUIS18, MICHAEL B. LUND9, SCOTT MCDERMOTT22, MARTIN PARGAERT11, FRANCESCO PEPE9, JOSEPH E. RODRIGUEZ11, LIZHOU SHA1, STEPHEN A. SHECTMAN1, ROBERT J. SIVERD1, AYLIN GARCIA SOTO1, DANIEL J. STEVENS16,17, IAN B. THOMPSON4, JOSEPH D. TWICKEN13, STÉPHANE UDRY9, STEVEN VILLANUEVA JR4, SHARON X. WANG9, BILL WOHLER23, XINYU YAO10, ZHRUCHANG ZHAN12, and THE TESS TEAM

ABSTRACT

We present the discovery of the longest-period planet yet, located in the Habitable Zone of a solar-like star, HD 21749 (V = 7.58, T eff = 5790 K). A transit signal was first discovered by the KELT-South team during their photometric survey of bright stars, and was confirmed by follow-up radial velocities. The KELT transits have been analyzed using a Lomb-Scargle periodogram (LS) and by fitting transit models to the data. The RV data have been obtained with the PFS, HARPS, and the TESS planet candidates (TOI 186.02). The TOI 186.02 transit signal is consistent with an orbit that is in agreement with the RV data, and the planet candidate is located at a distance of 16 pc. The planet candidate is a Jupiter-sized object with a mass of 1.2 Earth masses, a radius of 1.24 Earth radii, and an orbital period of 2.84 years. The planet is located in the Habitable Zone of its host star, HD 21749.

Keywords: TESS, Planet, Habitable Zone, Photometric, Radial Velocities, RV, Orbit, Transit, Discovery.
Just in case you thought TESS was only about exoplanets…
Time Domain Astrophysics with TESS Full Images

Solar System Objects:
* Thousands in 2 years...
  - Occultation Events
  ✓ Comets
  ✓ Asteroids

Explosive & Variable Extragalactic Sources:
* Thousands (?) in 2 years...
  ✓ Supernovae
  ✓ AGNs
  ✓ Blazars
  ✓ Quasars
  ✓ Tidal Disruption Events
  ✓ Gamma-ray Bursts
  ✓ Kilonovae (Gravitational Wave Counterparts)
  ✓ Hypernovae

Variable Stars:
* Millions in 2 years...
  ✓ Asteroseismology
  ✓ Brown Dwarfs
  ✓ Eclipsing Binaries
  ✓ Flare Stars
  ✓ Cepheids
  ✓ T Tauri Stars
  ✓ Cluster Gyrochronology
  ✓ White Dwarfs
  ✓ Neutron Stars
  ✓ Emission line stars (Be stars)
  ✓ RR Lyrae Stars
  ✓ WD Oscillations
  ✓ Novae
  ✓ Young Stellar Objects

✓ Preliminary TESS Results in Early Sectors
TESS also goes deep...

- In one hour:
  - 1% photometry at 16\textsuperscript{th} mag
  - <10% photometry at 18\textsuperscript{th} mag

- In 12 hours:
  - Approximately 10% photometry at 19.5 mag

\begin{figure}
\centering
\includegraphics[width=\textwidth]{teess_deep.png}
\caption{Transients and Time Domain Astrophysics with FFIs}
\end{figure}
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~300 Million Stars + Galaxies

Transients and Time Domain Astrophysics with FFIs

1% Photometry in 1 hour at 16th mag

Small Exoplanet Transits

Ricker et al. 2016
TESS and Depth

Plot Credit: Mansi Kasliwal
TESS and Depth

![Graph depicting various types of explosions and their peak luminosities versus characteristic timescales]

Plot Credit: Mansi Kasliwal
TESS and Depth

![Diagram of supernovae classifications]

- Relativistic Explosions
- Kilonovae
- Luminous Supernovae
- Thermonuclear Supernovae
- Core-Collapse Supernovae
- Classical Novae
- Luminous Red Novae
- Intermediate Luminosity Red Transients
- Calcium-rich Gap Transients

B. Shappee 2015

Plot Credit: Mansi Kasliwal
TESS and Depth

![Graph showing the relationship between peak luminosity and characteristic timescale for different types of astronomical events. The graph is labeled with various categories such as Coma, Kilonovae, and Virgo. Key points include Relativistic Explosions, Luminous Supernovae, and Core-Collapse Supernovae. The diagram also highlights different types of transients like Intermediate Luminosity Red Transients and Classical Novae.]

B. Shappee 2015
Plot Credit: Mansi Kasliwal
TESS and Depth

B. Shappee 2015

Plot Credit: Mansi Kasliwal
TESS and Depth

B. Shappee 2015

Plot Credit: Mansi Kasliwal
Supernovae Detected by TESS in Early Observations

M. Fausnaugh+ 2019
Supernovae Detected by TESS in Early Observations

M. Fausnaugh+ 2019
Supernovae Detected by TESS in Early Observations

... 35 More SN in process

M. Fausnaugh+ 2019
### TESS Enables Time-Domain Astronomy in the Coming Decade

<table>
<thead>
<tr>
<th>Year</th>
<th>TESS</th>
<th>CHEOPS</th>
<th>JWST</th>
<th>LIGO</th>
<th>LSST</th>
<th>NGLT’s</th>
<th>PLATO</th>
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<tbody>
<tr>
<td>2018</td>
<td>Prime Mission</td>
<td>CHEOPS Baseline Mission</td>
<td>JWST Design Mission</td>
<td>O3</td>
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- TESS: Discovering New Earths and Super-Earths in the Solar Neighborhood
- CHEOPS: CHEOPS Baseline Mission
- JWST: JWST Design Mission
- LIGO: O3, O4
- LSST: Ten Year LSST Survey
- NGLT’s: EELT, GMT, TMT
- PLATO: PLATO
TESS Early Mission Takeaways

• 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 on 1 hour time scales*

• TESS’s camera performance is superb

• TESS’s sky survey sector-by-sector is well underway
  ▶ *Sectors #1-7 are complete; #8 in progress*

• TESS’s full frame images are enabling a wide range of astrophysics discoveries
  ▶ *Also Stellar Astrophysics, Planetary Astronomy, Extragalactic “Multi-Messenger Astronomy”*

**TESS’s torrent of exciting new discoveries has commenced...**
TESS Extended Mission: Best is Yet to Come...

- NB: Log Scale on Y-axis

- TESS Extended Mission (2020-2022)
  - Should **double** number of planets
    - 4,518 in Primary
    - 9494 in Extended
  - 3x as many Earth-sized planets
  - Many more planets in HZ

T. Barclay
Sky Coverage for Primary & Extended Missions

Primary Mission
Sky Coverage for Primary & Extended Missions

Primary Mission

Extended Mission