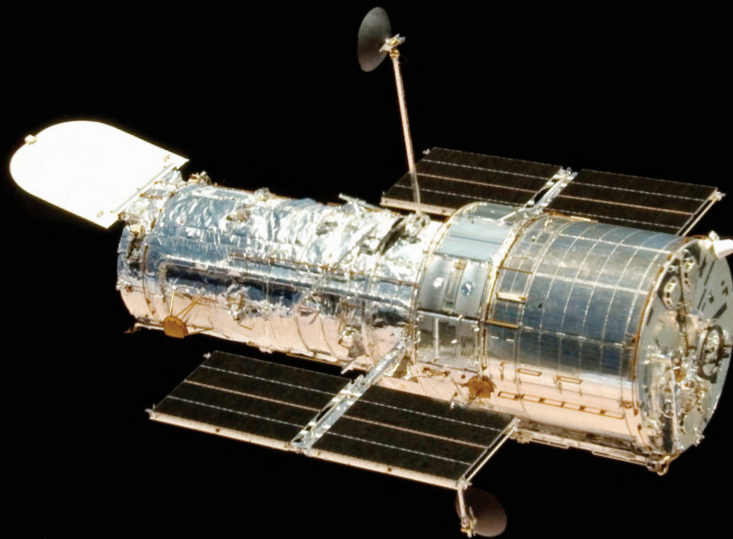
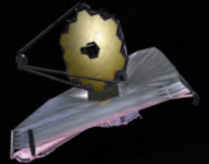
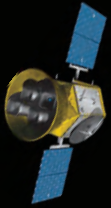


Optimal Strategies for Hubble Space Telescope Follow up of TESS-discovered Exoplanets

HST-TESS Advisory Committee



2019

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1 Introduction

The next few years offer unique opportunities and challenges for the studies of extrasolar planets: the community has begun to reap the scientific benefits of the exoplanet hunter satellite TESS and JWST will soon open new windows on select transiting exoplanets. The impetus behind TESS is to find small exoplanets whose atmospheres can be characterized in detail via transit spectroscopy – i.e., they are nearby and orbit bright stars. One of JWST’s four science themes is “Planets & Life”, mainly through understanding planetary atmospheres via transmission spectroscopy. However, a major knowledge gap separates TESS planet candidates from planets suitable for JWST observations – and HST plays multiple fundamental and unique roles in bridging this gap.

At the same time, HST — our premier resource for exoplanet characterization — is aging and remains one of the most oversubscribed observatories, limiting the community’s ability to carry out pre-JWST studies of exoplanets, which are required for characterization and reconnaissance. Given the flow of targets through the three missions and the dependencies between observations, the scientific yield of the TESS-HST-JWST synergy will strongly depend on the science strategy adopted for HST.

In order to identify the optimal approach to maximize the combined science yield of the TESS–HST–JWST synergy, the HST-TESS Advisory Committee was constituted. This report summarizes the committee’s findings and recommendations, as well as the scientific and programmatic context. The committee was constituted in April 2019 and delivered its final report in November 2019. The committee has solicited input from the community via multiple channels, interviewed topical experts, and studied all important facets of the scientific opportunities and challenges. The committee has identified a major programmatic challenge in the TESS-HST-JWST synergy, driven by the timescale required to mature planet candidate into well-understood JWST targets, and by the availability of JWST and the aging of HST.

The report is organized as follows: Section 2 provides the executive summary, followed by the committee’s charter (Section 3), an overview of the state-of-the-art transiting exoplanet science with HST (Section 4), the overview of the predicted small planet discoveries by TESS (Section 5), followed by programmatic considerations (Section 6), and an overview of the TESS planet candidate verification process (Section 7). Section 8 then reviews the community input received. Finally, the scientific opportunities (Section 9) and challenges (Section 10) are discussed.

Finally, in Section 11 the key findings of the committee are provided, followed by the committee’s recommendations (Section 12), and comments on available and required resources (Section 13). Additional information is provided in the Appendix.

2 Executive Summary

With the number of known planets doubling every two years, the field of extrasolar planets is in the midst of an exciting exponential growth. Not only is the sample of planets growing rapidly, but also the number of small nearby planets suitable for detailed characterization is set to increase. HST and JWST are set to provide revolutionary and uniquely sensitive observations for these small worlds: observations will help decipher the nature, properties, diversity, and evolution of small planets ($R_p < 4R_{Earth}$), mainly super-Earth and sub-Neptune worlds.

However, the path leading from a planet candidate to a JWST-characterized world is long and complex: prioritizing the targets for JWST and fully interpreting JWST observations often requires precursor HST observations of the planet and its host star. In turn, HST observations require verified and characterized planet candidates (e.g., mass constraints), but with HST aging and TESS candidates requiring a lengthy follow-up and verification process, the ultimate combined scientific gain from the TESS-HST-JWST observations will sensitively depend on the observing strategy followed. As a representative example, we estimate that the extension of the current approach will lead, by the end of 2025, to only 10–20 TESS discoveries observed with HST and *only* 2–4 of these observed with JWST. In comparison, if a key science project is implemented on HST in 2020, it would increase the number of HST-characterized targets to 27–32 and the JWST-characterized targets to 20 planets.

The key findings of the committee are as follows:

The greatest impact of TESS will be to dramatically increase the number of small planets well-suited for detailed characterization via HST and JWST. HST and JWST will play critical and unique roles in characterizing these planets. HST and JWST observations of Super-Earth and sub-Neptune planets are likely to yield the largest scientific gains, as these planets are currently poorly understood but will soon be amenable to high quality observations.

However, efficient selection of targets of in-depth HST and JWST studies requires verification of the targets through ground-based studies followed by HST reconnaissance observations and system-level characterization. Bottlenecks in this multi-stage process include radial velocity follow-up observations (typically 1.5–2 years), delays due to the proposal and review cycles, and the scheduling of the observations. The combined timescale of the steps require to advance planet candidates to HST and JWST targets, and the inherent astrophysical risks, in addition to the lifetime and health of spacecrafts involved leads to a programmatic challenge: How can a statistically meaningful number of small planets ideal for JWST observations be identified, verified, characterized, and explored with HST quickly enough to enable their systematic JWST study?

It is highly likely that, ultimately, the science gain from the TESS–HST–JWST synergy will be determined by (a) how efficiently the important planetary targets can be ushered through the validation–characterization–reconnaissance–proposal process; and (b) whether the combined sample of JWST-observed planets allows addressing population-level questions.

The committee recommends the following actions:

1. A Small Planets Key Project opportunity for the community to propose a large, multi-cycle, community-driven treasury project to answer population-level questions on small exoplanets. This project should be managed efficiently, should be fully transparent, and should involve the community. Community input should be used inform the scope of the project and should

be used to keep the project up-to-date. The project should aim to maximize the *joint* impact of the TESS-HST-JWST synergy.

2. In order to maximize the use of the information gained from the program, as much of the Small Planets Key Project as possible should be completed and analyzed by the JWST Cycle-2 deadline, and the program should be completed by the JWST Cycle-3 deadline.
3. The leadership of the Small Planets Key Project should be supported to interface with the broader community to ensure that the most suitable set of targets are prioritized for verification and characterization with HST.
4. The priority of the Small Planets Key Project should be sub-Neptunes and super-Earths well-suited for characterization, whether they are discovered by TESS or other surveys.
5. The TAC should prioritize thoroughly vetted planets.
6. To accommodate efficient and timely follow-up of new exoplanet discoveries, HST proposals should be able to propose compelling targets, for which detailed characterization (e.g., mass measurements) is not available at the time of submission, if the proposers make a compelling case that the required data will be available. Such proposals should be considered for conditional acceptance, pending a review by experts to ascertain that the necessary characterization has been completed.
7. STScI should enable an organized repository for open-source data reduction, analysis, and modeling tools to facilitate the involvement of the broadest possible community.

Comments on resources:

The committee has explored the resource needs for two rate-limiting processes: (a) the follow-up, verification, and characterization of TESS planet candidates required to identifying the select set of planets well-suited for HST and JWST follow-up studies; and (b) the timely execution and analysis of HST observations obtained as part of the recommended Small Planets Key Project.

TESS candidate follow up: the TFOP community – which mostly consist of volunteers funded independently of the TESS and HST projects – is well-coordinated and efficient in obtaining coordinated photometric, high-resolution imaging, and radial velocity follow-up observations of TESS planet candidates. Multiple experts and the committee agreed that the limiting step in this process is the time required for obtaining sufficient radial velocity coverage. The time required is primarily set by object observability and the orbital motions of the targets; *it is not foreseen that the process can be significantly accelerated*. The general challenge of speeding up the planet confirmation and characterization process further motivates increasing the efficiency of the HST follow-up observations to accelerate the overall workflow.

HST Small Planets Key Project: The resource needs of this community-driven program should be overall similar to large, multi-cycle Treasury programs, with two differences. Firstly, given the importance of timely reduction and analysis and how challenging these will be for some of the targets, we recommend that the program is supported at a level that enables two or more subgroups to carry out these tasks independently and in parallel. The timely release of the data to the community will be essential for maximizing the community’s ability to formulate the most relevant

HST and JWST proposals. Secondly, support should include roles and responsibilities to interface with the exoplanet community to ensure full transparency of the program’s execution.

Software Repository: HST observations of small exoplanets (in transit and in emission) are technically challenging and require data reduction and analysis methods beyond the standard STScI-provided data reduction pipelines. However, given the time-constrained workflow between TESS, HST, and JWST, it is imperative that HST observations of TESS-discovered exoplanets are reduced and analyzed in a timely manner and with highly reliable tools; such an approach will ensure that JWST and additional HST observations are targeting the ideal planets and obtain the most constraining data possible. In order to address the data reduction and analysis needs, we recommend that STScI establishes a repository for community-provided data reduction, analysis, and modeling tools. A good basis for this may be expanding the Exoplanet Characterization Toolkit ([ExoCTK](#)).

3 Charter of the Committee

Context: NASA's Transiting Exoplanet Survey Satellite (TESS) started science operations in July 2018 and is now well into its 2-year prime mission. TESS observations have already led to the discovery of a wide range of planetary systems, including hot Jupiters, super-Earths, sub-Neptunes and potential terrestrial analogues. Those planets will be prime targets for observation with the James Webb Space Telescope. HST will play a crucial role in refining the JWST target list by providing initial characterization of selected exoplanets; those observations will require significant investment of resources, time and effort, and require an appropriate level of planning.

After consultation with the Space Telescope Users Committee, the Space Telescope Science Institute's Director, Ken Sembach, has decided to constitute an Advisory Committee to provide counsel on how HST can best support TESS follow-up for JWST. Committee members will be drawn from the science community.

Charter

The HST-TESS Advisory Committee is charged with providing guidance on optimal strategies for maximizing the scientific return from HST observations of TESS targets.

In particular, the Advisory Committee should address the following tasks:

- 1) Solicit input from the community on how HST can capitalize on the discoveries made by TESS;
- 2) Identify specific science themes and/or exoplanet types that should receive particular attention;
- 3) Provide advice on the optimal timing for substantive follow-up observations and suggest mechanisms for enabling those observations;
- 4) Comment on the appropriate scale of resources likely required to support those programs.

The committee will summarize their conclusions in a report to the Director and presentations to the STUC by the fall of 2019.

Constituted in: April 2019

4 Transiting Exoplanet Science with HST

This section will highlight a few exoplanet observations that illustrate the diversity of HST transiting exoplanet science and the types of science questions that have been addressed.

4.1 Atmospheric Abundances and Aerosols

Both the Space Telescope Imaging Spectrograph (STIS) and the Wide Field Camera 3 (WFC3) have become workhorses for measuring both emission and transmission spectra (e.g., [Sing et al., 2016](#)). The identification of water (e.g., [Deming et al., 2013](#); [Kreidberg et al., 2015](#); [Tsiaras et al., 2018](#)) and sodium (e.g., [Nikolov et al., 2018](#)) have become routine via the detection of the 1.4-micron water feature in WFC3 and the 0.6-micron sodium doublet in STIS, respectively. The sample of WFC3 transmission spectra is now large enough for initial studies on statistical trends to be performed (e.g., [Fu et al., 2017](#)). Constraining the abundances of atoms and molecules to within an order-of-magnitude remains a challenge for many targets (upcoming review by Barstow & Heng 2019) due to degeneracies associated with clouds/hazes and the “normalisation degeneracy” ([Benneke & Seager, 2012](#); [Griffith, 2014](#); [Heng & Kitzmann, 2017](#)). However, combining information from high-precision datasets of emission spectra, transmission spectra, and phase curves have allowed us to measure water abundance to within a factor of 5 for the best targets ([Stevenson et al., 2014](#); [Kreidberg et al., 2014a](#)).

Surveys of transmission spectra of hot Jupiters with STIS and WFC3 have revealed a range of cloud and haze (collectively, aerosol) properties (e.g., [Sing et al., 2016](#)): some planets show relatively clear atmospheres with strong molecular and atomic features while others show muted or sloped spectra without detectable features. Some smaller planets (Neptunes and sub-Neptunes) have also been observed with WFC3 and/or STIS. The highest precision of these measurements is for GJ 1214b ([Kreidberg et al., 2014b](#)), revealing a featureless spectrum from 1.1 to 1.7 μm . Some trends appear in the current dataset of Neptunes/sub-Neptunes: the lowest temperature planets ($T_{\text{eq}} < 850 \text{ K}$) appear to have the most aerosol opacity, consistent with an organic methane-derived haze ([Crossfield & Kreidberg, 2017](#); [Fortney et al., 2013](#); [Morley et al., 2015](#)).

Identifying the composition of clouds spectroscopically is challenging with the current wavelength coverage of STIS and WFC3, and requires the detection of absorption features longwards of 10 micron (e.g., [Lee et al., 2014](#)). In some cases (e.g., WASP-76b), the aerosol particle size may be constrained (e.g., [Fisher & Heng, 2018](#)), but the interpretation is degenerate with the absence or presence of other absorbers (e.g. [Tsiaras et al., 2018](#)).

There is an active debate about emission spectra and its implications for the absence or presence of a temperature inversion (e.g., [Evans et al., 2017](#)). WFC3 emission spectra of over a dozen ‘hot’ ($1200 \text{ K} < T_{\text{eq}} < 2300 \text{ K}$) and ‘ultra-hot’ ($T_{\text{eq}} > 2300 \text{ K}$) Jupiters show a variety of behavior, including water absorption (e.g., WASP-43b), water emission (e.g., WASP-103b), or isothermal; condensation of optical absorbers like TiO likely shapes their temperature structures, while dissociation of species like water at high temperatures removes water vapor absorption, replacing those features with continuum absorption from H^- (for the atmospheric theory of ultra hot jupiters see [Bell & Cowan 2018](#); [Parmentier et al. 2018](#); [Arcangeli et al. 2018](#); [Kitzmann et al. 2018](#); [Lothringer et al. 2018](#)).

For small, cool planets orbiting nearby M stars, using WFC3 transmission spectra to identify the presence of water in sub-Neptunes is possible, as has been done for habitable-zone sub-Neptune K2-18b ([Benneke et al., 2019](#); [Tsiaras et al., 2019](#)). However, high mean molecular mass atmo-

spheres (e.g., N_2 , CO_2) remain out of reach with HST, requiring a sensitivity beyond that of WFC3 (e.g., [de Wit et al., 2018](#)).

4.2 Atmospheric Circulation

Thermal phase curves of a short-period planet constrain its atmospheric circulation—specifically the transport of energy from the dayside to the nightside of a synchronously-rotating planet (for a recent review, see [Parmentier & Crossfield, 2018](#)). Many short-period exoplanets are hot enough to emit most of their radiation in the NIR and are hence amenable to observations with HST/WFC3/G141. While the Spitzer Space Telescope has measured many more phase curves than Hubble, HST phase curves have two advantages: 1) the NIR coincides with the peak dayside emission of many hot Jupiters, and 2) Hubble enables *spectroscopic* phase curves.

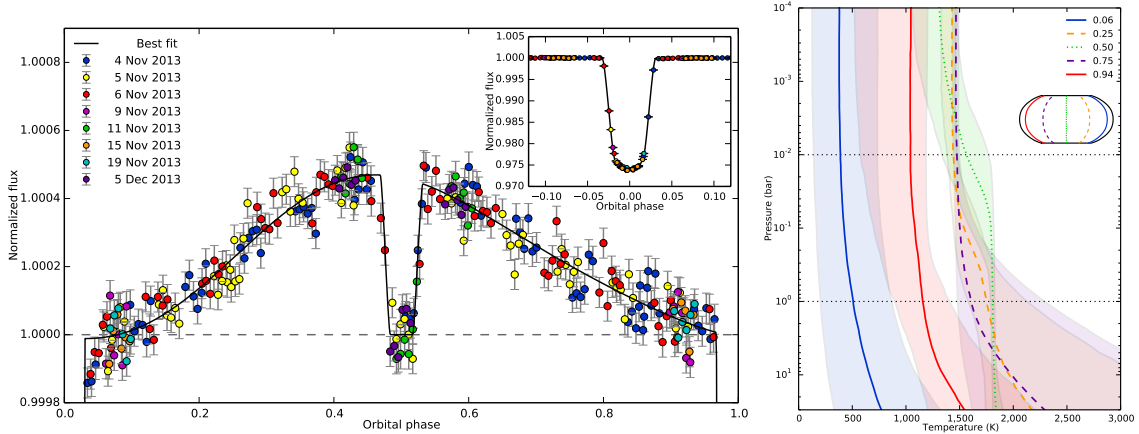


Figure 1: *Left*: Phase-folded white light phase curve of WASP-43b (from [Stevenson et al., 2014](#)). Since HST cannot continuously monitor the planet throughout a planetary orbit, it is necessary to phase fold multi-epoch observations. *Right*: Temperature-pressure profiles of WASP-43b at four planetary longitudes (also from [Stevenson et al., 2014](#)). On their own, HST/WFC3/G141 data constrain the T-P profile over two decades in pressure; subsequent *Spitzer* phase curves further refined the temperature structure in both longitude and altitude ([Stevenson et al., 2017](#)).

To date, HST phase curves have been published for the hot Jupiters WASP-43b ([Stevenson et al. \(2014\)](#)), WASP-103b ([Kreidberg et al., 2018](#)), and WASP-18b ([Arcangeli et al., 2019](#)). Multiband *Spitzer* photometric phase curves were interpreted as probing heat transport as a function of height (e.g., [Knutson et al., 2012](#)), but studying the temperature-pressure profile as a function of longitude can really be said to have started with *Hubble* phase curves. In particular, the change in water vapor opacity throughout the G141 band allows one to simultaneously constrain atmospheric temperature over two decades in pressure (right panel of Fig. 1). Rotational phase curves of brown dwarfs have also been undertaken with HST/WFC3/G141 (e.g., [Buenzli et al., 2015](#)), likewise enabling mapping the clouds and cloud variability in these atmospheres (for a review, see [Artigau, 2018](#)).

HST has offered us a glimpse of what exoplanet characterization will be like in the era of JWST, but the reduction and interpretation of these phase curves has not been without problems. *Hubble*’s low Earth orbit makes it impossible to obtain continuous measurements throughout a planet’s orbit. Full-orbit phase curves are therefore stitched together (left panel of Fig. 1), which requires a model of telescope and detector systematics, and this has improved with time. Moreover, the effect of planetary reflected light is now included in the analysis of HST/WFC3 eclipses

and phase curves, since it can be significant at these wavelengths (Keating & Cowan, 2017). The interpretation of the phase curves of WASP-43b, for example, has evolved from the initial surprisingly large day-to-night temperature contrast to a scenario more in line with other hot Jupiters (cf. Stevenson et al., 2014; Louden & Kreidberg, 2018; Mendonça et al., 2018; Keating et al., 2019).

4.3 Atmospheric Escape

The upper atmospheric layers of exoplanets are exposed to X-ray and extreme-UV (EUV) stellar irradiation. In the case of exoplanets orbiting close to their host star, the high levels of X-ray and EUV irradiation can drive hydrodynamic outflows and loss to space (see e.g. Ehrenreich et al., 2015). Understanding atmospheric escape processes in exoplanets is key for understanding their evolution. In addition, the identification of chemical elements escaping from an exoplanet’s atmosphere provides information about the bulk composition of their lower atmospheric layers (see e.g. Lecavelier Des Etangs, 2007).

Most of what is known to date about atmospheric escape on exoplanets is based on HST UV transit observations. HST observations have detected escaping H I in Lyman- α , C II, O I, and Mg I (Vidal-Madjar et al., 2003, 2004, 2013; Ben Jaffel et al., 2007; Ben-Jaffel, 2008; Linsky et al., 2010). Most recently, Sing et al. (2019) reported the detection of escaping Fe II and Mg II in the atmosphere of a hot Jupiter via near-UV observations with HST STIS (see Figure 2).

The discovery of escaping He I at 1.08 μm with HST WFC3 (Spake et al., 2018) opened a new window to study atmospheric escape in the infrared, which can also be done with large ground-based telescopes (see e.g. Allart et al., 2018, 2019; Nortmann et al., 2018; Alonso-Floriano et al., 2019). However, for most elements, the best lines for detection are in the UV, and HST observations will be at the forefront of atmospheric escape studies for years to come.

4.4 Host Star Characterization

Host stars of transiting exoplanets often have a profound influence on the formation and evolution of the planets and their atmospheres, and can influence the interpretation of HST observations. FUV and NUV-driven photochemistry may also give rise to false biosignatures (e.g., O₂: Luger & Barnes, 2015). Energetic ultraviolet photons (extreme UV and far-UV) impact atmospheric loss processes and can profoundly shape atmospheric chemistry (e.g., Segura et al., 2003; Hu et al., 2012; Hu & Seager, 2014). Due to its broad wavelength coverage — especially in the ultraviolet — and high photometric stability, HST has played essential roles in characterizing the transiting exoplanet host stars.

Ultraviolet spectra: HST’s STIS and COS instruments have provided fundamentally important and often unique data on the UV spectra of stellar host stars, obtained both for individual stars and as a result of multiple large programs (MUSCLES and Mega-MUSCLES, FUMES, France et al. 2016; Pineda et al. 2018). For example, observations of Ly α line intensity for TRAPPIST-1, in combination with GALEX observations of old stars, could be used to model the EUV levels of the star for a variety of activity levels (Peacock et al., 2019).

Stellar activity and contamination: Stellar activity impacts the interpretation of observed transmission spectra in two ways: by influencing the star’s effective emitting area (i.e., offsetting spectra taken at different epochs) and through the transit light source effect (Rackham et al., 2018), the contamination of the planetary transmission spectrum by stellar features that do not cancel out

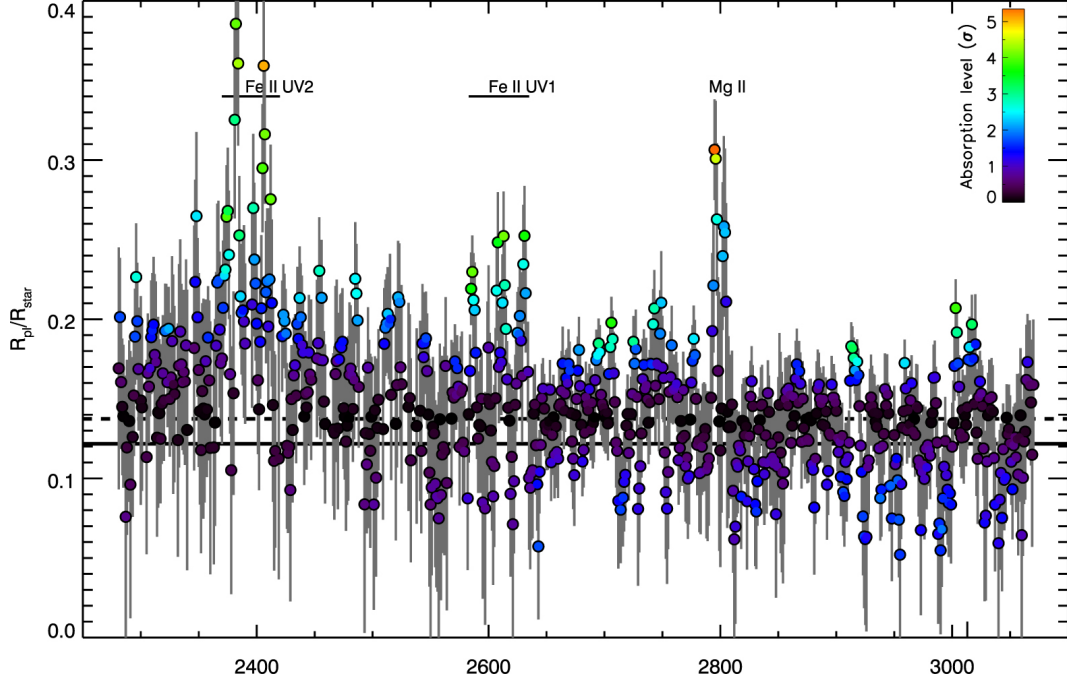


Figure 2: Detection of Fe II and Mg II atmospheric escape from the upper atmosphere of the hot jupiter WASP-121b as observed by HST STIS during a transit of the planet. Figure reproduced from [Sing et al. \(2019\)](#).

when in-transit spectra are divided by out-of-transit ones. For the former effect, multi-epoch and multi-instrument spectra have been combined to provide visual-near-infrared transmission spectra of transiting planets (e.g., [Pont et al., 2013](#); [Sing et al., 2016](#)). HST’s sensitivity and spectrophotometric stability enabled the spectral characterization and modeling of starspots (occulted by planets during their transits, e.g., [Sing et al. 2011](#)).

5 Small Planet Discoveries: TESS and Beyond

The Transiting Exoplanet Survey Satellite (TESS) is searching for transiting planets around the brightest stars in the sky. By providing continuous, precise photometry over 27 days for 85% of the sky, TESS is expected to nearly complete the census of transiting planets on short-period orbits (< 10 days) orbiting nearby stars ([Ricker et al., 2014](#)).

Although TESS will make important and unique contributions to a broad range of scientific questions, in terms of extrasolar planets it is widely anticipated that TESS’s key contribution will be the identification of and mass-measurements for ~ 50 small ($R_p < 4 R_{\text{Earth}}$) planets around bright stars. It is expected that this sample will provide, possibly for decades, the vast majority of the small planet targets that are best-suited for in-depth characterization.

5.1 Predicted Yield and Validation

Several simulations were performed before TESS’s launch using as reference the statistics for small planets discovered by the Kepler mission. Those simulations estimated a yield of a few hundred planets with sizes smaller than $2 R_{\text{Earth}}$ orbiting around bright stars ([Sullivan et al., 2015](#);

Barclay et al., 2018). After TESS’s launch in April 2018, Huang et al. (2018) revised those predictions using an updated photometric noise model based on real data, improved stellar parameters based on Gaia mission Data Release 2 (Stassun et al., 2019), improved simulations of multi-planet systems, a realistic method of selecting targets for 2-minute exposures, and a more realistic geometric distortion model to determine the sky region that falls on TESS CCDs. The new Huang et al. (2018) simulations predict that TESS’s primary mission will discover about 3,500 planets Neptune-size and smaller, half of which will orbit stars with TESS magnitudes brighter than 12.

Once planet candidates are identified, there is a detailed follow-up validation process to establish whether the candidates are bonafide planets or false positives. This validation process includes ground-based photometric follow up to find further transits and rule out binaries in neighboring stars not resolved by TESS, reconnaissance spectroscopy to rule out binaries and characterize the star spectroscopically, AO imaging to identify unresolved stellar companions, and precision radial velocities to measure planetary masses. The wide range and number of resources required for validating candidates are organized via the TESS Follow-up Observing Program (TFOP). See more detail information about TFOP at <https://tess.mit.edu/followup/> and in the answers provided by Dr. S. Quinn on behalf of TFOP (see Section 8.3).

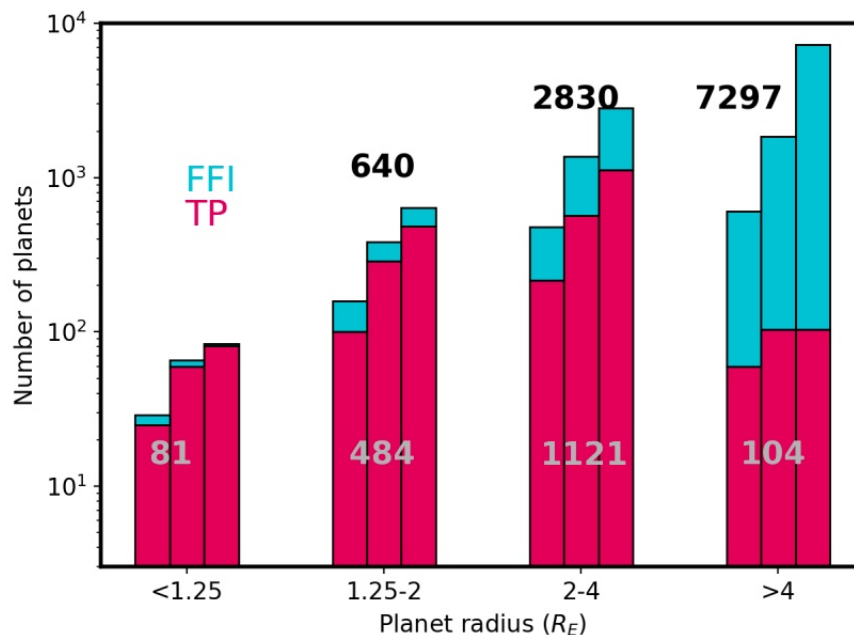


Figure 3: Expected yield of planets in the TESS 2-year primary mission. The three different bins represent stars brighter than TESS magnitude of 10, 12, and 15 mag. Red represents planets discovered in target pixels, and cyan represents planets discovered in full frame images (FFIs) only. The numbers labeled on top of each planet category shows the total number of planets expected around stars with $T < 15$ mag. Grey numbers represent the planets discovered in target pixels only. Figure reproduced from Huang et al. (2018).

5.2 Level 1 Science Requirement Sample

The primary goal of TFOP is to facilitate the achievement of TESS’s Level 1 Science Requirement, which is to measure the masses of 50 transiting planets with radii smaller than $4R_{\text{Earth}}$. As

of September 2019, TESS has identified over 1000 objects of interest (TOIs), 29 of which have been confirmed as planets; about 20 have radii smaller than $4R_{\text{Earth}}$. These numbers are frequently updated at <https://tess.mit.edu/publications/>.

5.3 Small Planets Ideal for HST/JWST Follow up

The planets best suited for satisfying TESS’s Level 1 Science Requirement also tend to be excellent targets for atmospheric follow-up. Generally speaking, the most precise atmosphere characterization is possible for systems with relatively bright host stars and large planet-to-star radius ratios. These systems are also ideal targets for radial velocity follow-up. Formally, the signal-to-noise for spectral features is quantified by the Transmission Spectrum Metric (Kempton et al., 2018). In practice, most of the best target sub-Neptunes have host stars with H-band magnitudes brighter than 10 and late spectral type (K or M stars).

To ensure that these promising targets are promptly vetted, the TESS Atmosphere Characterization Working Group is coordinating with the TESS Follow-up Observing Program (TFOP) to flag the targets for validation and mass measurements. From the first half of the TESS mission, there are over 60 sub-Neptunes that have reached a validation status of VPC (Verified Planet Candidate), indicating that the event has been verified to occur on target by follow-up transit observations and that there are no other obvious or Gaia DR2 stars contaminating the follow-up aperture. Nine of these also have mass measurements, indicating that for the most favorable targets it is possible to measure the planet mass in a single observing season. Much additional radial velocity follow-up is currently underway.

6 Programmatical Considerations

6.1 Types of Proposal Opportunities

The exoplanet community – as well as the broader astrophysical community – can propose for HST observations through regular GO proposal opportunities (which allow for small, medium, and large programs; SNAP, theory/archival and treasury programs); through mid-cycle proposal calls (which allow up to 10 orbit long programs to address questions that could not have been proposed in the preceding GO call); through Target-of-Opportunity programs (for newly discovered targets and observations of time-critical nature); and through Director’s Discretionary programs.

6.2 Lessons from Large HST Transiting Exoplanet Programs

Time has been awarded to 195 exoplanet-related programs in HST Cycles 20 through 27, including 149 proposals through the regular TAC process, 32 mid-cycle proposals and 14 DD proposals. The overall success rate through the TAC is 19.1%, slightly lower than average; however, exoplanet science constitutes 27% of the submitted and accepted mid-cycle proposals.

Ninety-six of the accepted proposals focus on transits or eclipses. Figure 4 shows the size distribution of the latter programs, which encompass 2291 orbits and include 23 mid-cycle programs; the median program size is 10 orbits, with 5 programs awarded between 100 and 150 orbits and the largest program, PanCET, awarded 498 orbits. The strict timing constraints for transit and eclipse observations complicate scheduling, but almost 60% of programs are completed within the same cycle when time was awarded and 73% are completed within 1.5 years. In general, larger programs will take longer, with the PanCET program spanning 3 years, but in a few instances

scheduling collisions with other HST programs can significantly delay the execution of even 10–15 orbit programs.

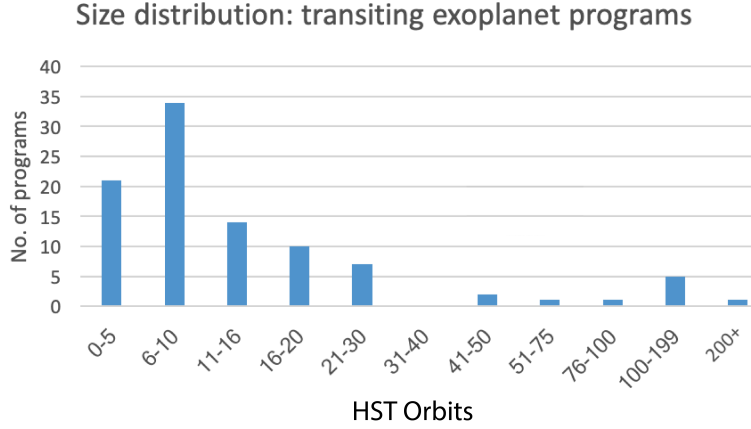


Figure 4: Size distribution of HST exoplanet programs.

Both STScI and the science community have become quite experienced and sophisticated in the design and execution of exoplanet transit observations. Mature and well understood observing protocols and data analysis techniques have been developed although additional efforts to disseminate these more broadly would be desirable. Multi-orbit exoplanet transit observations pose two distinct constraints on the HST scheduling process. First, sequencing a set of observations reduces the number of scheduling opportunities (especially for STIS/MAMA observations due to SAA restrictions). Second, it is not practical to plan observations with tight time constraints more than ~ 10 weeks in advance due to uncertainties in the HST orbital ephemeris. Thus observers generally will have to accept a greater degree of uncertainty in the scheduling of their observations and increased challenges in scheduling coincident observations with other facilities.

6.3 Timeline for HST and JWST Proposals and Observations

JWST is scheduled for launch on March 30 2021. Launch will be followed by a 6 month commissioning period, so, under this scenario, science observations will begin on October 1 2021, coincident with the start of HST Cycle 29. The JWST Cycle 1 GO proposal schedule is now finalized: the Call for proposals will be issued on January 23 2020, with the proposal deadline on May 1 2020 and the TAC meeting scheduled for the last week of July and first week of August. To accommodate this, the HST Cycle 28 schedule has been advanced by ~ 6 weeks, with the Call for Proposals issued on November 20 2019, the proposal deadline on March 1 2020 and the TAC meeting during the week of May 15.

The proposal schedule for future cycles is not yet determined for either telescope, but the JWST Cycle 2 deadline will likely be 13 months after launch. As a possible scenario, the HST schedule for Cycle 29 could return to a mid-April proposal deadline and a mid-June TAC; the JWST Cycle 2 GO deadline would fall in late April/early May 2022 for a March 30 2021 launch, with the HST Cycle 30 schedule pulled forward to match the Cycle 28 cadence. Both HST and JWST will follow annual proposal cycles. HST will continue to offer mid-cycle proposal opportunities.

6.4 Impact of Possible Single-Gyro Operations

The entry of HST into a Reduced Gyro Mode (RGM) will reduce the scientific productivity of HST by ~ 25 percent, preclude several existing science observing strategies, reduce synergies with other observatories, and decrease the likelihood of responding to time critical events. For exoplanet observations, the primary science implications of running HST in RGM include reduced observing efficiency, target availability, limitations on the maximum spatial scan rates, and reduced ability to carry out simultaneous observations with other observatories (including JWST). Currently HST has three remaining operating gyros (from its initial complement of six following Servicing Mission 4). Each of these remaining gyros has an engineering enhancement expected to considerably prolong their lifespans although such estimates have large degree of uncertainty. It is therefore difficult to provide any meaningful estimate of the time when HST will switch from Three to Reduced Gyro Mode. It is possible that this could occur tomorrow or not for five or more years in the future.

Operations in RGM will reduce the number of scheduled science orbits per week by $\sim 15\%$ and reduce the field of regard from 82% to $\sim 40\%$ of the sky. This field will likely have some but a limited overlap with the JWST field of regard (the actual overlap may be less than 20% of the sky at any given instant). However, HST will still be able to observe the entire sky over the course of the year but with shorter and fewer scheduling opportunities. Thus it will be more difficult to schedule for repeated transit observations (especially for longer period targets). Also, as gyro guiding with spatial scans permits moving at 8 arc seconds per second versus 5 arc seconds per second under FGS control, WFC3 Grism observations of the very brightest targets ($HAB < 4$) becomes impossible. For serpentine scans, the rate restriction is 1 arc second per second thus limiting observations further by ~ 2 magnitudes. In addition, roll angle constraints will make the avoidance of nearby bright confusing stars for WFC3/IR spectroscopy more difficult to schedule.

7 From Candidates to Characterized Planets

TESS is identifying thousands of Targets of interests (TOIs), only a small fraction of which will eventually be confirmed as bona fide extrasolar planets, mainly through the efforts of the TESS Follow-up Observing Program (TFOP). An even smaller fraction of these planets will have reliable mass determination, and just a fraction of these will be followed up by HST and JWST. To maximize the science output of HST and JWST follow-up observations of TESS-discovered exoplanets, it is important to understand the complex, multi-stage, and lossy pipeline that delivers the targets for these observations.

Figure 5 illustrates the key steps in the process that targets follow from identified as TOIs to HST/JWST follow-up observations and characterization.

The TESS mission's Science Processing and Operations Center (SPOC) processes all spacecraft data. TESS Targets of Interest (TICs) are identified based on pipeline reduction and identifiers are assigned to individual objects of interest, primarily transiting exoplanet candidates. The planet candidates are passed on the TESS Follow-up Observing Program (TFOP), which coordinates a global network of astronomers who carry out follow-up observations to clarify the nature of the candidates. Candidates are prioritized, but it is ultimately up to the individual TFOP members to determine how they utilize their telescope time to follow up the candidates. TFOP observations include ground-based high-precision time-resolved photometry of predicted transits; high-resolution imaging (to identify possible background objects); host star characterization; low- and high-precision radial velocity follow up (to eliminate astrophysical false positives and to confirm

planetary nature); and space-based high-precision photometry.

The path of planet candidates through the identification, verification, and characterization process is important for the science yield of the HST-TESS-JWST synergy, as this pipeline is the primary source of the targets for HST and, ultimately, JWST. The progress of planet candidates through the pipeline is, in most relevant cases, set by the timescale of the precision radial velocity observations, as all other steps require only one or a few observations, whereas PRV studies typically require observations collected over a year or more.

The typical duration of the verification and basic characterization steps – pre-requisites for compelling HST proposals – is about 2 years from the initial identification of the candidates. This timescale must be considered in the context of two other facts that (a) most JWST proposals will require pre-cursor HST observations; and (b) the typical time span between the definition of an HST proposal for time-constrained observations to receiving the data is about 1.5–2 years (and longer for Large programs).

Thus, currently the typical time span between the discovery of a planet candidate through verification, characterization, an HST proposal, and HST observations to the point where it can be proposed for JWST is approximately *four years*. This already long process is further extended if the initial HST proposal is not successful or if the time-constrained observations cannot be scheduled promptly; furthermore, for many of the targets in the pipeline the precision radial velocity or HST observations may show that these are, in fact, not ideal targets for JWST observations.

This combined timescale and inherent astrophysical risks lead to a programmatic challenge: how can a statistically meaningful number of small planets ideal for JWST observations be identified, verified, characterized, and explored with HST quickly enough to enable their systematic JWST study?

8 Community and Expert Input

The charter of our committee included soliciting input from the community on how HST can capitalize on the discoveries made by TESS. The committee solicited input via four channels: through an online survey, a call for white papers, by interviewing experts, and by receiving informal comments in person and via electronic communications. Our committee members have attend most of the major exoplanet-focused conferences during the work of the committee, including the TESS Conference in Boston, MA; the Exoclines meeting in Oxford, UK; the Extreme Solar Systems IV meeting in Iceland, IS. The following subsections summarize the community input received by our committee.

8.1 Online Survey

Our committee has issued a call for information to the exoplanet community on May 15, 2019, with responses to be provided by an anonymous Online Survey. The window for responses was July 3–July 16, 2019. The survey contained 9 questions and a free comment box. In addition, five optional questions were included to establish the demographics and expertise of the participants. The questions of the online survey are provided in Appendix C.

Forty-one responses have been received to the online survey, with a total of approximately 430 individual comments and answers. The committee has reviewed the responses and sought for patterns in the answers (e.g., consensus on specific questions) as well as for particularly insightful individual comments.

TESS Exoplanets: From First Identification to JWST Characterization

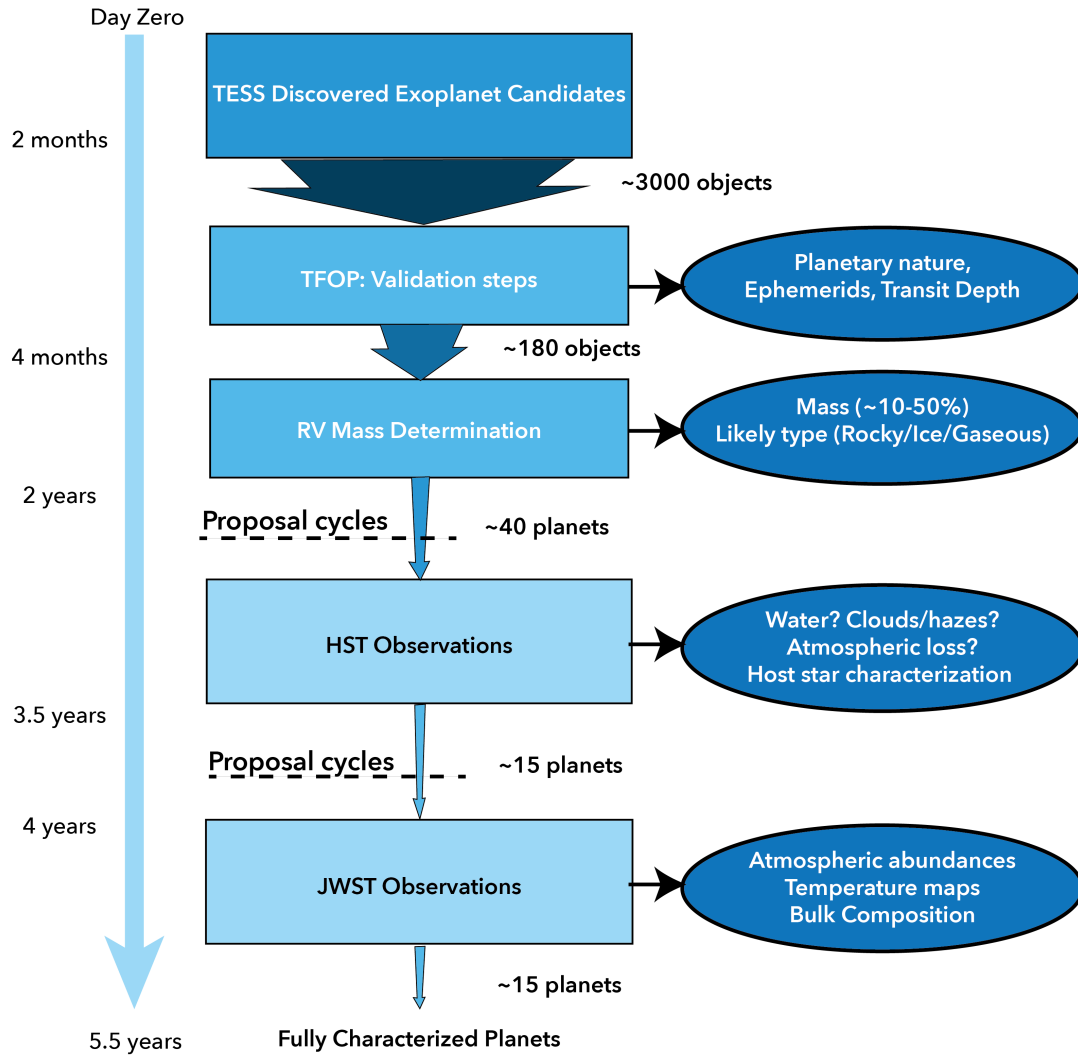


Figure 5: The process of identifying, verifying, and characterizing TESS-discovered exoplanets. .

Answers to the online survey were submitted both by researchers working on exoplanet-related fields and by researchers working on other fields. The committee has identified significant differences in the responses provided by these two groups of responders. While the committee has carefully considered input from both groups, in cases where systematic differences were obvious the committee has considered responses from exoplanet researchers to be more representative to the needs of the exoplanet community.

In the following we highlight the key conclusions our committee has drawn from the online survey.

1) Opinions differed on whether the current time allocation model is overall satisfactory. The majority of the exoplanet researchers who responded felt that that changes must be made to enhance the efficiency of follow-up of TESS discoveries. (Question 7).

2) The most important TESS discoveries will be small (Earth-sized) planets around nearby bright stars, suitable for follow-up spectroscopy (strong consensus).

3) HST/JWST follow-up observations will be the most important for the characterization of TESS-discovered small planets, including the determination of atmospheric composition, measurements of atmospheric escape rates, the nature of small planets, and the presence or absence of clouds in their atmospheres.

4) The highest priority TESS-discovered planets for follow-up are: (1) low-density super-earths/neptunes; (2) multi-planet systems, (3) planets for which very detailed information can be gained. Gas giants should receive lower priority than smaller HZ planets. (*Question 3*)

5) The most important HST observations are (in no particular order): UV spectral characterization (spectrum and stellar activity); exploratory observations (pre-cursor to JWST follow-up) to assess stellar contamination, atmospheric cloudiness.

6) There was a diversity of opinions and no consensus on the need for new program category. Answers ranged from suggesting new programs for Target-of-opportunity-type observations; for exoplanet statistical surveys that allow large, uniform set of observations; for individual planets, a JWST ERS-type program, to establishing a separate panel within the time allocation committee for exoplanets. Some participants indicated that there is no need for new programs. Suggestions also included greater flexibility in target selection (after the approval of the program); but others warned that generic targets should not be allowed and review should be restricted to fully vetted targets. Fast turn-around proposals, similar to Gemini's such program, as well as modifications of the existing mid-cycle program have been also proposed. *If a new program is required, what is your recommendation?*

7) The majority of the participants felt that the current cadence of the proposal submission–time allocation–observations cadence is satisfactory. Some participants warned that exoplanet science should not be distinguished from other fields where discoveries are made. Some argued for a special call for newly-discovered exoplanets (or other new discoveries). Concern was raised that Target-Of-Opportunity programs do not allow for exoplanet targets, driving the community to propose targets individually given what is known by the proposal deadline, eventually leading to a hodgepodge science program emerging from a random set of individual targets proposed in many small programs, hampering efforts to think and propose strategically.

Additional Comments: A handful of participants were concerned about access to TESS discoveries. Multiple participants indicated concern that major HST time allocations to exoplanet characterization may limit telescope time available to other important, non-exoplanet topics.

8.2 White Papers

Our committee has issued a Call for White Papers on May 15, 2019. We received six white papers in response to the call. The modest number of white papers submitted may be due to the fact that our committee's work overlapped with the launch of the Astro2020 Decadal Survey, which also solicited white papers from the community for multiple purposes in a similar time window. Although the number of white papers received was not high, the authors did successfully communicate multiple important and complex messages that would have been difficult to convey without the white paper opportunity.

The individual white papers are available through the committee’s public website (see Appendix A). **In the following we provide a very brief summary of each white paper and not an endorsement of the white papers message by the committee.** The arguments laid down in the white papers have been considered carefully by the committee and have influenced the high-level findings and our recommendations.

White paper #1 offers a metric to prioritize TESS-discovered exoplanets for HST follow-up observations. WP1 argues for the use of the Earth Similarity Confidence metric, derived from probabilistic assessment of the planets’ similarity to Earth (Earth Similarity Indices). These metrics use probability distribution functions to represent the key observable properties of exoplanets and to compare these to Earth’s properties.

White paper #2 argues for the importance of debris disks surrounding white dwarfs as excellent probes of the composition of extrasolar minor bodies. TESS will observe about $\sim 1,700$ white dwarfs and it is expected to discover multiple systems in which debris will introduce transit-like features. WP2 argues for the importance of HST/COS follow-up of the circum-WD gas ring to derive elemental inventories of the disrupted asteroids. Some of these follow-up observations will be time-critical, as the recently disrupted objects may evolve rapidly. WP2 also makes a case for the importance of JWST mineralogical studies (infrared emission bands), especially in combination with HST ultraviolet data, as this potent combination will provide elemental abundances as well as dust stoichiometry.

White paper #3 focuses on HST’s importance and potential for improving our understanding of atmospheric evolution. In particular, WP3 highlights atmospheric loss as a key, but poorly understood mechanism. WP3 points out the unique power of HST UV observations for atmospheric escape studies. It highlights the important classes of planets for which such studies have not yet been carried out: 1) mini-Neptunes and super-Earths; and 2) young planets. TESS is likely to identify excellent targets in these categories and HST will play a unique role in constraining stellar XUV flux (through extrapolation from the observable EUV emission). WP3 argues for HST UV transit observations of sub-neptunes/super-Earths and close-in planets to intermediate-mass main sequence stars.

White paper #4 focuses on the importance of exoplanet masses to provide context for atmospheric characterization. Mass is one of the most fundamental properties of planets and impacts the interpretation of most other measurements. On one hand, accurate mass measurements would be desirable for all planets *before* scarce HST or JWST time is expended on their characterization. WP4 explores the question *How precisely must the planet’s mass be known in order to interpret HST transmission spectra?* In terms of exoplanet transmission spectroscopy, a key impact of the mass uncertainty is the uncertainties it introduces into atmospheric retrievals through the uncertain atmospheric scale height (Batalha et al., 2017). The authors assess atmospheric retrieval results as a function of the error in the atmospheric scale height, driven by the error in the planet’s assumed mass (Batalha et al., 2019). The rule-of-thumb conclusion of that study is that *planets with mass uncertainties of $\lesssim 50\%$ are desired*. The white paper argues that HST time allocation committees should require proposers to demonstrate that the mass of any planet proposed for observations is known to (or will be known to) $\sim 50\%$ accuracy.

White paper #5 explores the exciting possibility that volcanically produced tori could be detected around transiting exoplanets via UV spectroscopy. The white paper argues that planets detected around bright M dwarf stars by TESS will be particularly well-suited targets for searches of such phenomena. The authors further argue that studies of volcanically produced tori could

shed light onto multiple important exoplanetary processes (atmospheric composition and escape, volcanic activity itself, and planetary interior processes).

White paper #6 lays down a vision for a large, strategic TESS follow-up program. It is argued that the ideal follow up of TESS-discovered exoplanets requires a strategic, rather than a piecemeal approach. This is due to the fact that exoplanet observations must be interpreted in a multi-dimensional parameter space. Non-systematic, sparse sampling of a complex, high-dimensional parameter space is unlikely to allow our community to build up a correct and comprehensive picture of the key processes. The authors argue that a large program (preferably supported by Director's Discretionary Time) should be established for systematic survey of exoplanets. The program would be organized around broad scientific goals, potentially with placeholder targets that are replaced as the appropriate new TESS planets are discovered.

8.3 External Experts

The HST-TESS AC has invited multiple experts to discuss specific aspects of the scientific and programmatic context of TESS follow up. The experts have received a list of questions before their interview and typically responded in writing, followed by a 30-50-minute long discussion with the committee. The following is a brief summary of the key points of these interviews.

Dr. Didier Queloz (Chair of CHEOPS GTO Science Program, University of Cambridge). Dr. Queloz provided written input to the questions of the committee and joined the committee's telecon to answer its questions on Aug 12, 2019. The committee was consulting with Dr. Queloz to explore possible synergies between TESS, CHEOPS, and HST and, in particular, whether CHEOPS could provide efficient means to refining transit ephemerids for TESS-discovered planets to enable HST observations. Dr. Queloz informed us that 80% of the observing time on CHEOPS is reserved for and allocated by the CHEOPS Guaranteed Time Observing Program (GTO Team). Within the GTO no significant efforts are foreseen to utilize CHEOPS and HST in a coordinated fashion, although individual teams within the GTO program may propose for HST programs separately.

The target allocation and change process is particularly important to follow-up observations. Dr. Queloz explained that the general procedure of target allocation is similar to those adopted by other observatories: in each cycle first the GTO team can update their targets, then the GTO targets are frozen and the GO programs can propose for targets not on the reserved targets list; once the GO proposals have been ranked and targets are allocated (reserved in the reserved targets list), the GTO team can again swap targets at will (unless they conflict with a reserved GO target). Dr. Queloz stressed that the CHEOPS team has worked extensively to reach out and connect to the broader exoplanet community and, for example, that the CHEOPS team has given talks on all major exoplanet conferences to advertise proposal deadlines and opportunities for collaboration.

Dr. Queloz has also emphasized the limitations of CHEOPS for TESS follow-up, especially now that the TESS extended mission has been approved. There are two primary reasons for this. First, CHEOPS' sky visibility is significantly limited due to its low Earth orbit and by its Sun, Earth, and Moon avoidance angles. In practice, therefore, scheduling targets on timescales shorter than ~ 6 months is challenging and, often, impossible. Second, CHEOPS is scheduled through an observing queue populated by A- and B-ranked proposals. To ensure efficient operations the pool itself is over-filled (by about 30%), i.e., about 30% of the programs in the pool will not be executed. The programs are selected for execution by an algorithm. A-ranked programs are more likely to be scheduled than B-ranked programs, and the completion of programs in progress has

higher priority than starting new programs. Overall, while this scheduling approach is beneficial for the observatory, it does not allow for new follow-up programs – injected mid-cycle – to be executed quickly with high priority.

Dr. Kate Isaak (CHEOPS Project Scientist, ESA). Dr. Isaak has submitted answers to the questions of the committee in writing and joined a committee telecon on Aug 26, 2019 to answer further questions. Dr. Isaak explained that 20% of time on CHEOPS is open for Guest Observer (GO) proposals. This 20% is open to the global community without restrictions —as is for any ESA mission. The CHEOPS Cycle-1 Call for Proposals came out in March 2019 and closed in May, and the Time Allocation Committee met in July 2019. In its first cycle the GO time was not highly oversubscribed.

To help the community, ESA provided an extensive set of planning and proposing tools. Proposers can use these tools to assess whether a target or observation they are considering for CHEOPS is viable. These tools are downloadable, running on local virtual machines. The tools allow users to check for possible conflicts with the reserved targets list, calculate target visibility maps, assess scheduling feasibility, assess magnitude and field crowding limits.

With 80% of CHEOPS' time reserved for Guaranteed Time Observations, it is important that possible target conflicts are assessed and recognized early. Targets are blocked on a coordinate basis, i.e., if a target is on the reserved target list, no other observations are possible. Our committee noted that this may be a concern for following up different planets in the same planetary system (where coordinates are the same, but transit times are different). The GO program does not allow for target change requests (due to staffing limitations). Furthermore, there is no target-of-opportunity program element.

Therefore, Dr. Isaak emphasized, that CHEOPS' Director's Discretionary Time program provides the only opportunity for the community to propose targets outside the regular GO cycles (which may be a typical need for TESS discovery follow-up). Proposals are invited for DD Time as long as they propose for targets that are new or recently declared to be of high scientific interest. An important limitation is that in DD proposals only a single target can be proposed. It is anticipated that CHEOPS follow up of a discovery of particularly interesting target may be proposed by both the GTO team and one or more GO programs. As outside the GO proposal selection period the GTO team can change targets at will, a grace period (24 h) was agreed upon by ESA and the GTO team. Within this grace period GO/DD proposals would take precedent over GTO target change requests submitted for the same target. Given how short this grace period is, in practice, the GO community must prepare proposals in advance, anticipating discoveries, so they can propose in a timely manner.

Dr. Isaak described the CHEOPS scheduling system and the target visibility limitations. Due to these limitations (see also above), CHEOPS is overall not well positioned to be able to carry out efficient follow-up of TESS targets and/or to refine transit ephemerides to support HST follow-up observations.

Dr. Drake Deming (Chair, TESS Atmospheric Characterization Science Working Group, University of Maryland). Dr. Deming – with input from the previous Chair of the ACWG – provided written answers to the questions of the committee and participated in a committee telecon on Sep 16, 2019. *Organization:* The ACWG is an unfunded group of experts that loosely collaborate to aid the atmospheric characterization of TESS-discovered exoplanets. The group is undergoing re-organization, which includes a new charter; the ACWG's current charter is focusing on pre-launch activities and it no longer represents its current goals.

The ACWG is led by a five-member Steering Committee and currently chaired by Dr. Deming. The working level of the ACWG is divided into six tasks, each led by a Task Lead. The tasks primarily support the characterization work required to prioritize targets for atmospheric characterization. *Results and Activities:* At least three refereed papers have emerged from the ACWG’s work (Dragomir et al., 2019; Kempton et al., 2018; Louie et al., 2018). Among the major efforts of the ACWG are two medium-sized proposals submitted to the HST Call for Proposals (Cycles 26 and 27, PI: Kreidberg). Although highly ranked, neither of these proposals have been selected. However, as an unfunded group of volunteers, activity within the ACWG has been uneven. The ACWG is not functioning as a mission-related pipeline; instead, it currently depends on the initiative of the task leads. Membership in the ACWG group and in its steering committee has been a somewhat ad hoc process and concerns have been raised that the group has not been as inclusive as it should be. *Plans:* The ACWG will be restructured to be a more pro-active group rather than simply reacting to HST and JWST cycles; however, lack of resources for the group will make it difficult to sustain coordinated, efficient work. Membership in the ACWG, its task groups, and steering committee will be revisited to ensure good community representation. An HST Treasury proposal, perhaps with an NSF-funded ground-based component would a possible pathway for the ACWG.

Dr. Sam Quinn (Member of TFOP Leadership and sub-group lead). Dr. Quinn provided written answers to the committee’s questions and joined the committee’s meeting on September 23, 2019. Dr. Quinn described the TFOP community as highly efficient and very successful in following up and confirming TESS exoplanet candidates. A large number of telescopes are contributing to TFOP observations and the momentum of the group is not showing a decline, although with TESS switching from the south to the north means that, in part, different facilities and different groups will contribute follow-up observations. The TFOP community is making excellent progress to reach the TESS Level 1 Science Requirement of characterizing masses and radii for 50 small ($R < 4R_{Earth}$) planets. With ~ 25 planets published, the community is already about halfway there. Of the remaining 25 planets, 5-6 already has enough data in hand to determine their masses.

Although almost no one in the TFOP community is funded by the TESS mission, the group is making excellent progress in spite of the resource limitations. The largest possible challenges may be the different structure of the northern photometric follow-up program (lack of LCO), but Dr. Quinn believes that other groups with long photometric heritage (e.g., KELT, KELTFUN, Kepler-CAM, MASCAT, MASCAT-2) will be able to step up. For northern spectroscopy, facilities such as TRACE, FIAS, and PRV will be important for securing precision radial velocity observations.

In terms of the pipeline from TESS candidates to confirmed planets, Dr. Quinn described that – due to the very large TESS pixels – the primary source of astrophysical false positives are nearby eclipsing binaries. The TFOP group has developed an efficient strategy to identify false positives.

The TESS follow-up efforts triggered efficient central coordination between different precision RV projects, as typically – for small planets – no single project has enough data to publish. For example, HARPS-N began collaborating with CARMENES, HARPS, etc. for K2 follow up, and such collaborations have further expanded in the TESS era. Currently there is sufficient excitement (and funding) in the RV teams to support the preparation of multiple proposals in each semesters to continue follow up.

Currently precision radial velocity observations are the limiting factor in the publications; correspondingly, these teams tend to lead most papers. As for how the planet confirmation process

could be accelerated, Dr. Quinn told the committee that TFOP is operating about as efficiently as possible; but purchase of time on precision radial velocity instruments, such as NEID, could help somewhat.

8.4 Informal Input

Informal input has been received by committee members from multiple exoplanet scientists. The following is a brief summary of these informal input.



Dr. Ian Crossfield (MIT) suggesting that a dedicated pool of HST time for TESS follow-up will be very beneficial for preparing for JWST, but it shouldn't be managed by a single person - rather, the community should be allowed to propose for time.

Dr. Brice-Olivier Demory (University of Bern) expressed concerns about the difficulty for the transiting exoplanet community to propose for time on newly-discovered TESS targets and to do it in a way that allows a systematic and comprehensive approach to the target selection. Specifically, the challenges are that planets are being discovered and verified continuously, i.e., target lists in proposals may be superseded by newer and more suitable targets, and, while it is known what type of exoplanets will be found and be most interesting to study, the targets are not always known at the time when the proposals are due. Dr. Demory noted that Target Of Opportunity proposals or an opportunity with a similar flexibility in target choice and timing could be a good solution to the problem. However, TOO proposals currently do not allow transiting exoplanet proposals. Dr. Demory argued that a large-scale, coordinated program – perhaps based on the example of the JWST Early Release Science program – would be very important for the exoplanet community.

Dr. Eliza Kempton (University of Maryland) argued that it is essential that a statistical survey of TESS-discovered exoplanets is executed instead of the current piecemeal approach. However, recent proposals with placeholder targets – in spite of major community support – have been unsuccessful. The problem has been that time allocation panels are reluctant to allocate time for yet-undiscovered planets. This roadblock could be alleviated if the panel had the option to allocate time that is released only once an object with the right parameters is discovered – similarly to the TOO program. Dr. Kempton suggests that allowing transiting exoplanets to be proposed within the TOO program could be a solution.

9 Scientific Opportunities

Considering community input (Section 8) the committee has identified multiple important scientific opportunities for Hubble Space Telescope follow-up observations of TESS-discovered exoplanets. In the following we summarize the scientific opportunities and then briefly discuss these, noting that these opportunities may overlap.

1. *High-quality, in-depth studies of archetype and extreme planets, comprehensive (multi-instrument) study of planets and atmospheres.*
2. *Reconnaissance of Potentially Habitable Planets and their Environment*
3. *Scouting Targets for JWST and Preparatory Observations*
4. *Stellar characterization* 
5. *Large-scale, comparative study* 

6. *Other Discoveries: Exomoons, WD debris, disintegrating planets*

7. Planet candidate verification in unusual circumstances, if impossible from ground

9.1 High-quality, in-depth studies of archetype and extreme planets

TESS will likely reveal planets that are exceptionally well-suited for follow-up observations. Such planets may be scientifically valuable either because they are representative/archetypical or because they are extreme (hottest, least dense, etc.). Characterization of such planets will be particularly important and HST often has the potential to offer unique data on such new discoveries.

9.2 Reconnaissance of Potentially Habitable Planets and their Environment

TESS is discovering Earth-sized exoplanets and super Earths that have potentially temperate atmospheres. It is likely that these rocky exoplanets have thin secondary atmospheres (not dominated by hydrogen or helium) that are regulated by geochemical cycles rather than being a fossil record of the initial conditions of exoplanet formation (e.g., [Gaillard & Scaillet 2014](#)). The low temperatures and high mean molecular weights of these atmospheres means that the pressure scale heights are at least an order of magnitude smaller than for hot gas giants. The spectral features are thus likely to be too small for optical or infrared transmission spectroscopy with HST. The low temperatures render these targets too faint for optical or infrared emission spectroscopy.

Instead, these temperate, rocky exoplanets are better scrutinized with HST’s ultraviolet spectroscopy, a capability that JWST will not have. There are two reasons to pursue ultraviolet spectroscopy. First, it is a probe of “space weather”, star-exoplanet interactions and atmospheric escape (e.g., [Shizgal & Arkos 1996](#); [Yelle et al. 2008](#); [Tian 2009](#)), as has been demonstrated for warm Neptunes (e.g., [Ehrenreich et al. 2015](#)). Second, water photolysis may provide an abiotic mechanism for producing oxygen and ozone on terrestrial exoplanets (e.g., [Wordsworth & Pierrehumbert 2014](#)). The detection of escaping hydrogen via the Lyman-alpha line will provide context for future interpretations of spectral features on these habitable-zone exoplanets. The caveat is that these ultraviolet observations are probing a combination of exoplanetary atmospheric escape and stellar wind protons (e.g., [Holmström et al. 2008](#)). The only star for which the stellar wind is well-characterised is the Sun.

9.3 Comprehensive Studies of Atmospheres

Comprehensive studies of benchmark systems are needed to shape the science questions for the next generation of exoplanet atmosphere observations. Benchmark systems tend to have bright, nearby host stars, enabling high signal-to-noise measurements. Until now, most benchmark objects have been hot Jupiters, but TESS is rapidly completing the census of smaller planets with longer period orbits around the nearest and brightest stars. For these systems, comprehensive, precise spectra should be measured across a broad wavelength range.

Past detailed observations of benchmark systems have been very fruitful. Recent examples from HST observations include the near-IR transmission spectrum of GJ 1214b, which provided a definitive detection of clouds in the atmosphere of a mini-Neptune ([Kreidberg et al., 2014b](#)), a precise measurement of the water abundance for HAT-P-26b, which suggested a diversity in the chemical composition of exoplanet atmospheres ([Wakeford et al., 2017](#)), and the detection of an evaporating helium exosphere in WASP-107b, which opened a new window into observations of

atmospheric escape ([Spake et al., 2018](#)). All of these observations shaped the science questions and observing strategy for exoplanets going forward.

9.4 Scouting Targets for JWST

HST precursor observations are necessary to maximize the value of JWST observations and, sometimes, even to enable their interpretation. We identify the following needs for precursor observations: (a) Verification of the presence (or absence) of a planetary atmosphere. (b) Assessment of the presence and impact of clouds/hazes in the upper atmosphere of the planets, which could negatively impact the information content of transmission spectra. (c) Stellar activity: combining observations of the star-planet system taken at multiple epochs requires an understanding of whether and how the stellar spectrum and effective emitting area has changed between those epochs. As broad wavelength coverage spectrum can only be built up from observations multiple epochs, it is important to develop models for changes in the stellar disk due to stellar activity. (d) Stellar contamination: a second effect of stellar activity is that it contaminates the transit spectra through the transit lightsource effect ([Rackham et al., 2018](#); [Apai et al., 2018](#)). This effect is more important for active stars (such as most M dwarfs, [Zhang et al. 2018](#); [Wakeford et al. 2019](#)), for smaller planets, and for bluer wavelengths ([Rackham et al., 2019](#)).

9.5 Exoplanet Host Star Characterization.

HST can also provide powerful observational data on the properties of exoplanet host stars, which are often essential for the correct interpretation of the evolution and present state of the planetary atmospheres. In particular HST’s unique UV capabilities are valuable in this regard, as the UV spectral regions of host stars is difficult to model and predict, yet they have profound impact on atmospheric loss and atmospheric chemistry.

9.6 Other Discoveries: Exomoons, WD debris, disintegrating planets

The UV capabilities of HST have been used to determine the atomic abundances of rocky debris accreted onto white dwarfs (WDs): the short settling time in the high-gravity of a WD atmosphere should produce pristine atmospheres, yet a large fraction of WDs exhibit “polluted” atmospheres (for a review, see [Farihi, 2016](#)). [Vanderburg et al. \(2015\)](#) used K2 to monitor such a white dwarf, WD 1145+017, and found it to host a disintegrating minor planet.

[Rappaport et al. \(2012\)](#) reported periodic, variable-depth, transits of a star in the *Kepler* field, KIC 12557548. The authors interpreted this as a disintegrating ultra-short period planet (USP). [Croll et al. \(2014\)](#) used a variety of instruments, including HST, to monitor the system and help constrain the mass of the dying world.

The Kepler mission revealed that the star KIC 8462852 occasionally dims, as if transited by a time-varying occulter ([Boyajian et al., 2016](#)). The most mundane explanations involve structure in the ISM, or an intervening object with a large and structured disk ([Wright & Sigurdsson, 2016](#)). The TESS mission could discover other such systems and, if the host stars are bright enough, HST and JWST will likely be able to obtain time-resolved spectroscopy to explore the wavelength-dependent opacity of the occulters, possibly shedding light on their nature.

Hubble has also been used to search for exomoons, in particular by leveraging the high photometric precision of HST/WFC3/G141; results are so far ambiguous ([Teachey & Kipping, 2018](#); [Kreidberg et al., 2019](#); [Teachey et al., 2019](#)). The ideal candidates for moon searches are planets

orbiting bright stars on slightly longer orbits (for orbital stability of the moon). It is therefore possible, but unlikely, that TESS will discover better targets.

10 Challenges

1. *A tension exists between timely follow-up observation of TESS discoveries and the need for proper vetting.* On the one hand, given the need for timely HST–JWST follow-up, it should be possible to propose for follow-up observations of TESS discoveries swiftly. However, given that only a tiny fraction of the exoplanet candidates can be observed by HST and JWST, great care must be taken to ensure that targets are verified planets with well-determined fundamental parameters (mass, radius, density). However, assembling the required contextual information takes time: in most cases radial velocity characterization is setting the timeline, requiring 1–2 years of observations to establish reliable planetary masses. Planets that lack proper long-term monitoring pose a risk due to their uncertain transit times.
2. *A systematic approach is necessary to address population-level questions.* A major goal of exoplanet atmosphere characterization is to search for demographic trends as a function of system properties, such as planet mass, temperature, surface gravity, rotation rate, and host star type (e.g. [Sing et al., 2016](#); [Crossfield & Kreidberg, 2017](#); [Fu et al., 2017](#)). Studying a representative sample of planets will enable comparison with the predictions from planet population synthesis models (e.g. [Fortney et al., 2013](#); [Mordasini et al., 2016](#)), as well as general characterization of atmospheric physics and chemistry, such as which conditions are more likely to form clouds and haze. Such a survey requires a large target list carefully chosen to span the whole parameter space. If instead transit observations are proposed on a case-by-base basis, the resulting sample is often biased toward the highest S/N systems that may not be representative of the population. This issue is particularly challenging for TESS, where exciting new targets are rapidly being discovered and more are expected, but the full sample of planets is not yet complete.
3. *Correct interpretation requires data from multiple instruments, often collected over many transits.* As each of HST’s instruments covers only part of the spectrum that is relevant for exoplanet and host star characterization, re-visits are necessary. And, as data can only be collected during transits, often multiple transits must be observed even with a single instrument to build up sufficient signal-to-noise ratios. For small planets, as many as 12 transits (60 orbits) have been combined in a single instrument mode to increase data quality. Therefore, completing comprehensive observations of even a single target may require observing suitable transits over baselines of a year or longer. As this timescale is in large part set by observing and scheduling constraints, there is no easy solution to accelerate the completion of such programs.
4. *Clouds and hazes may complicate transmission studies of many small planets.* Particulates are present in every planetary (and satellite) atmosphere in the Solar System and there is an abundance of evidence that they are common in warm and hot exoplanetary atmospheres, too. Even modest number density of high-altitude cloud/haze particles can dramatically increase line-of-sight optical depth for transit spectroscopy, weakening or completely obscuring otherwise prominent absorption features. As clouds/hazes represent a modulation of the

transmission spectra, high-precision measurements are required to assess their presence and importance in atmospheres to-be-targeted by JWST. Therefore, sensitivity reconnaissance of targets with HST and/or the 8m-class ground-based telescopes is necessary to prioritize targets.

5. *Stellar activity (primarily spectral changes due to time-evolving spot/faculae coverage) makes it difficult to combine data from multiple epochs.* Transit spectroscopy is a relative measurement method; whenever the disk-integrated stellar spectra are undergoing slight changes – as is common in all but the least active stars – the transit spectra will suffer from wavelength-dependent offsets that are not directly measurable. This problem is further exacerbated every time multi-spectral coverage is built from multi-instrument data obtained at multiple times. Stellar activity can mimic spectral slopes.
6. *Stellar contamination.* For real, non-idealized stars stellar spectral features do not cancel out fully during the removal of the out-of-transit spectrum. The resulting stellar contamination is most important for active host stars and for the small and cool planets. The current state of the art understanding of stellar activity and heterogeneity for non sun-like stars is insufficient to reliably correct for or even characterize the stellar contamination. A better understanding of this effect and strategies for selecting targets that are minimally affected is an important challenge in the characterization of small planets via transmission spectroscopy.
7. *Slow decline in UV efficiency and overall scheduling efficiency.* With the eventual decline of the HST gyroscopes, the observatory may transition to single gyro operations. Should this occur, it would decrease the efficiency of the scheduling of some of the transiting exoplanet observations, and may significantly reduce the shared sky visibility of HST and JWST, making simultaneous observations much more difficult to execute. Furthermore, ongoing slight decline in the sensitivity of the COS detector may limit high signal-to-noise future observations of ultraviolet-faint targets.
8. *With the imminent loss of the Spitzer Space Telescope ~~we will lose~~ the ability to carry out high-precision, continuous photometric monitoring.* This may complicate or limit studies such as disentangling transits of multiple planets in the same system or search for smaller planets in known multiplanet systems. The committee has evaluated whether ESA's CHEOPS mission could fill the gap left by Spitzer but established that due to orbital and scheduling limitations CHEOPS cannot replace Spitzer's capabilities to establish transit times. Furthermore, Spitzer's ability to search for eclipses (in addition to transits) and hence establish eclipse times cannot be replaced by any existing observatories. The TESS extended mission alleviates some of the concerns – by providing additional epochs and an extended baseline – that will help with transit time prediction, but will not fully replace Spitzer's long-term continuous monitoring capability.
9. *Healthy balance between small programs vs. large programs.* Small and medium programs (typically focusing on 1–3 planets) are well-suited to answer well-defined, narrow questions about particularly interesting individual planets. These programs are essential to realizing new ideas, carrying out pathfinder observations, and to study unique objects. These programs focus on objects that are both scientifically important and ideally suited for observational studies. On the other side of the program size spectrum, large programs are important

because they allow comparative studies that can address general, population-level questions. Such large programs have the unique potential to create datasets with long-term legacy value, and enable studies where groups of targets are selected. Such selection contrasts with the ensemble of targets that emerge from small/medium programs, which tend to lack scientifically relevant, but observationally less favorable targets and countersample. Such tension exists in every field HST studies; however, for small transiting exoplanets this tension is even more pronounced as studies of individual targets are exceptionally expensive and the overall number studied is likely to be much smaller than target samples in most other sub-fields of astrophysics.

11 Summary of Key Findings

The key findings of the HST-TESS Advisory Committee are as follows:

1. TESS’s ultimate goal is to identify small planets that are well-suited for atmospheric studies via transmission spectroscopy. HST and JWST are the most powerful facilities for such studies. One of JWST’s four science themes is “Life and Planetary Systems”, prominently featuring the study of small exoplanet’s atmospheres. In short, TESS, HST, and JWST were funded, fully or in part, to work in synergy, the only way to fulfill their potential for exoplanet studies.
2. TESS will identify ~ 50 small ($R < 4 R_{Earth}$) exoplanets orbiting bright stars and ephemerides and masses will be well established for these planets. This sample of planets is going to provide the majority of the ideal small planet targets for HST and JWST atmospheric characterization.
3. HST and JWST offer unique capabilities to characterize this new sample of small planets, likely transforming our view of Super-Earth/Sub-Neptune planets.
4. TESS will likely further expand the sample of known hot Jupiters and hot Saturns. In contrast to the small planet discoveries, however, it is unlikely that TESS will find a large number of hot Jupiters and hot Saturns that are better-suited for follow-up observations than the current sample.
5. Although TESS will likely discover multiple exciting Earth-sized planets in the habitable zones of their host stars, HST’s aperture is too small to meaningfully characterize the atmospheres of nearly all such planets. Medium to large HST programs focusing on single such planets are likely not to yield important insights into the atmospheres (but can provide powerful observations required to characterize their host stars)
6. HST has been fulfilling powerful, unique roles in characterizing transiting exoplanets and their host stars, and it will be well-positioned to extend these to TESS-discovered small planets.
7. **It is highly likely that, ultimately, the science gain from the TESS-HST-JWST synergy will be determined by (a) how efficiently the important planetary targets can be ushered through the validation–characterization–reconnaissance–proposal process;**

and (b) whether the combined sample of JWST-observed planets allows addressing population-level questions.

8. The most important *unique* HST capabilities (prior to JWST) include: (a) UV characterization the host stars and atmospheric escape from the planets. (b) sensitive probe of water absorption present in the atmosphere. (c) comprehensive broad wavelength coverage (from UV to NIR) of the scientifically most interesting planets.
9. The transmission spectra of an unknown fraction of small planets will be limited by the presence of particulates (clouds/hazes) and/or by stellar activity and stellar contamination. Therefore, many compelling JWST proposals will require HST scouting/reconnaissance observations.
10. A major concern is the timeline for validating and characterizing TESS targets, and for proposing these to HST reconnaissance observations, before they can be proposed for JWST.
11. Two key groups made up of unfunded volunteers (TFOP, ACWG) are responsible for transforming TESS planet candidates into vetted and characterized targets for HST and JWST proposals. Nevertheless, TFOP has been operating very efficiently and it is not the rate-limiting step. ACWG did not intend to and did not serve as a community-wide effort to support the preparation of successful HST proposals; but ACWG is re-organizing itself and its roles may change in the future.
12. The slowest part of verifying small planet candidates is the radial velocity follow up (typical timescale 1.5–2 years). The timescale is mainly limited by target visibility and the number of epochs required for RV characterization. It is unlikely that this timescale could be shortened significantly.
13. A large fraction of the exoplanet community expressed concern that without a larger, coordinated effort HST/JWST studies will focus on individual planets that are the most observable/interesting, and a sample built from such observations will fail to address population-level questions. The committee agrees with this concern.
14. Community members raised concerns about the inclusivity of the TESS follow up efforts, and having limited access to information on the candidates. Concerns were expressed that a key program without transparency could further limit community-wide access the information needed to propose for HST and JWST time.
15. If a community-driven large program is implemented, it is essential that the program is managed in a transparent *and* efficient manner.

12 Recommendations

Considering input from the broader community and external experts, the committee makes the following recommendations to maximize the scientific return from HST observations of TESS targets:

1. *A Small Planets Key Project opportunity should be provided for the community to propose a large, multi-cycle, community-driven treasury program to answer population-level questions.* This program should be managed efficiently and should be fully transparent to and involve the community. It should aim to maximize the *joint* impact of the TESS-HST-JWST synergy. Additional considerations for the program are discussed in Section 12.1.
2. *The timeliness of the Small Planets Key Project: In order to maximize the use of the information gained from the program, at least half of the program should be completed and analyzed by JWST Cycle-2 deadline as possible, and the program should be completed by JWST Cycle-3 deadline as much as possible.*
3. *Observations of sub-Neptunes and super-Earths well-suited for characterization should be prioritized,* whether they were discovered by TESS or other surveys. TESS will acquire a near-complete sample of the most accessible planets in this size range for atmosphere follow-up studies. HST observations are crucial for vetting and reconnaissance of this population to prepare for JWST.
4. *The TAC should prioritize thoroughly vetted planets* and should consider the status of planet candidates in the vetting process when considering time allocation recommendations. Specifically, we recommend that planets prioritized for observations should have (a) well-determined orbital periods and transit times; (b) mass measurements (RV or TTV-based) are available to verify the nature of the target. If mass measurements of sufficient precision are not available but the proposers make a compelling case that they will be, proposals should be considered for conditional acceptance, pending a future review by experts to ascertain that the necessary characterization has been completed; (c) surface gravity is sufficiently well known to ascertain detectability of spectral features in a hypothetical, clear atmosphere; (d) proposals should quantify the risks introduced by uncertainties on the planetary and system parameters. If significant uncertainties exist at the time of proposing the program, proposers should identify upper bounds for uncertainties on planet properties that will still ensure successful interpretation.
5. *STScI should ensure that an organized repository exists for open-source data reduction, analysis, and modeling tools to facilitate the involvement of the broadest possible community.* This repository may be built on the existing [ExoCTK](#) platform or hosted by another organization.
6. *STScI should provide support to a group that can interface between TESS, TFOF, and the HST community to ensure that the most suitable set of targets for HST/JWST characterization are prioritized for verification and characterization.* This responsibility could most naturally be assumed by the leadership of the large coordinated small planet observing program, but could also be undertaken by a re-organized TESS ACWG or a similar external group.

12.1 The Small Planets Key Project

Addressing many of the practical challenges described in Section 10 requires a large-scale HST program. For example, such a program is required to address population-level questions; to ensure that data are taken homogeneously and consistent for many targets; that targets are selected not

only based on their individual properties but as part of a larger sample; that the data are shared with the greater community, facilitating robust and timely analysis. Such a large, coordinating program can also address the most significant issue, the compressed timeline for the exoplanet discovery–validation–reconnaissance–characterization pipeline.

The committee recommends that STScI follow the model of the original HST Key Projects, such as the H(0) program: science goals for those projects were outlined in the Call for Proposals and the community was invited to submit proposals for their execution; those proposals were reviewed as part of the HST Cycle 1 TAC process (see STScI Newsletter Vol 2 No 3, October 1985).

Recommended Goal: Perform reconnaissance and characterization observations of a sample of sub-Neptunes/super-Earths to enable informed follow-up observations with JWST. The sample should be defined to provide the highest information content *after* the combined HST+JWST follow-up observations. It is likely that observing a larger sample with HST will be necessary to inform the selection.

We recommend the following considerations for the Small Planets Key Project:

1. Should have an overall scope that is comprehensive, allowing to answer population-level questions.
2. Scope and scientific focus of the program should be determined by the community (the proposers and time allocation panel) through peer-review.
3. Should provide a comprehensive characterization (all relevant instruments with appropriate SNR) of the most favorable small planets discovered by TESS and other surveys as early in the JWST mission as possible.
4. Should aim to characterize planetary atmospheres as a function of size and equilibrium temperature.
5. Should focus on mini-neptunes and super-earths, i.e., targets for which HST observations can efficiently yield data with sufficiently high SNR for meaningful constraints.
6. Should be a Treasury program: Results and data are shared with the community immediately and in a transparent manner.
7. All precursor observations for JWST should be completed in a timely manner – JWST proposals should not have to be delayed due to lack of HST vetting.
8. The observations should provide a good basis for assessing the presence of aerosols (i.e., presence/absence of strongly weakened absorption features) and problematic stellar activity.
9. While focusing on HST observations, the program should consider the potential combined science yield from HST *and* JWST.
10. A balanced, healthy program portfolio (small/medium/large programs) should be maintained, i.e., the Small Planets Key Project should not infringe on individual investigator's and small team's ability to propose focus programs.

11. Funding and resources must be available for the Small Planets Key Project science teams for timely and high-quality exploitation of the datasets, including interpretation and publication.
12. Target selection should be driven by broad science questions and not focused on individual planets ideal for observations.
13. The Small Planets Key Project should be managed efficiently and with complete transparency, providing fair and equal opportunity to community members to participate and contribute to the program, and to propose for JWST observations building on Small Planets Key Project data products.
14. Small Planets Key Project should inform the community by the JWST Cycle-2 deadline as much as possible, and should be completed by the JWST Cycle-3 deadline.
15. While it is anticipated that most targets will be TESS discoveries, the Small Planets Key Project should have the potential to include non-TESS-discoveries, if they are superior targets.
16. Community input should inform the scope of the Small Planets Key Project and should be used to keep the program up to date.

Estimated Impact: Although the exact impact of a Small Planets Key Project will depend on when and how it is implemented, we explore here the possible impact of such a program on the number of targets studied jointly by HST and JWST. In Figure 7 we show four representative scenarios for how TESS-discovered planet candidates may progress toward HST–JWST characterization. The extension of the current approach (top panels, optimistic and pessimistic scenarios) is expected to lead, by the end of 2025, to only 2–4 planets characterized jointly by HST and JWST. This small sample is insufficient to address any population-level questions. Such an outcome would fail to make use of the opportunity offered by TESS. In contrast, an HST key project implemented starting from 2021 would be able to reduce or eliminate the bottleneck set by HST time allocation process, boosting the anticipated yield of HST–JWST-characterized TESS discoveries by a factor of 3–5. While this sample is still modest, 11–20 such worlds would be sufficient to answer fundamental population-level questions. They would allow understanding the most compelling worlds TESS is likely to find. We stress here that these examples should be considered as representative scenarios based on the committee’s assessment of the expected yields and bottlenecks in the process. The exact number of planets characterized is, of course, not possible to accurately predict.

Additional comments:

Planets Targeted: The Small Planets Key Project should allow the exoplanet community to determine the best targets to maximize science over the JWST primary mission. It is likely that most of the targets could be drawn from the TESS Level 1 science requirements sample (50 planets with $R_p < 4R_{Earth}$), because this is likely to be the best-characterized, validated, and best-understood consistent sample of small exoplanets transiting bright stars.

Timeline for HST and JWST Follow-up of TESS-discovered Exoplanets

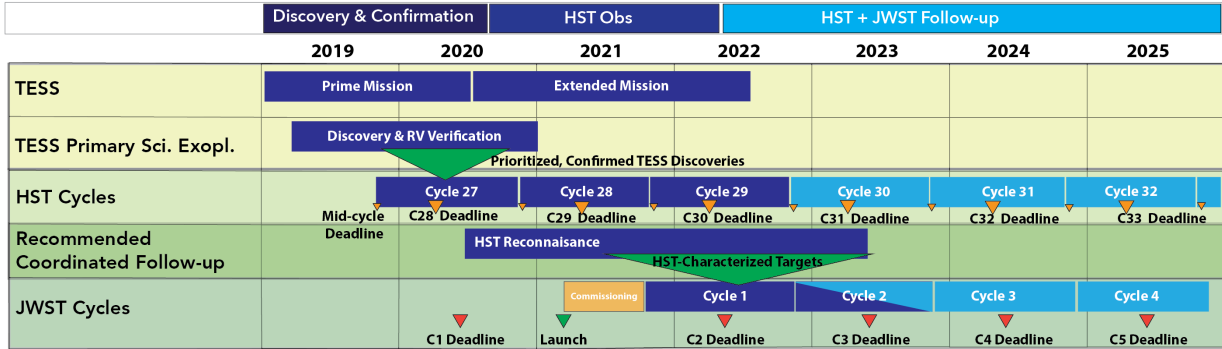


Figure 6: Likely timeline for major TESS, HST, and JWST events, including deadlines and start/end dates for proposal cycles. JWST launch is currently planned for March 2021 and commissioning ends six months after launch.

Possible Representative Scenarios for HST and JWST Follow-up of TESS Discoveries

Year	TESS Candidate	Confirmed & Characterized	HST Prop. Accepted	HST Obs. Complete	JWST Prop. Accepted	JWST Obs. Complete
2019	1300	15	0	0	0	0
2020	1900	20	2	0	0	0
2021	2200	40	4	1	0	0
2022	2300	50	5	3	0	0
2023	2400	60	7	4	1	0
2024	2600	65	9	7	2	1
2025	2600	70	10	10	4	2

Year	TESS Candidate	Confirmed & Characterized	HST Prop. Accepted	HST Obs. Complete	JWST Prop. Accepted	JWST Obs. Complete
2019	1300	25	0	0	0	0
2020	1900	70	3	0	0	0
2021	2200	100	9	2	0	0
2022	2300	130	15	6	1	0
2023	2400	150	21	11	3	1
2024	2600	175	26	15	5	2
2025	2600	200	30	20	8	4

Year	TESS Candidate	Confirmed & Characterized	HST Prop. Accepted	HST Obs. Complete	JWST Prop. Accepted	JWST Obs. Complete
2019	1300	15	0	0	0	0
2020	1900	20	9	2	0	0
2021	2200	40	19	9	4	0
2022	2300	50	23	21	7	3
2023	2400	60	25	23	9	5
2024	2600	65	27	25	17	7
2025	2600	70	29	27	18	11

Year	TESS Candidate	Confirmed & Characterized	HST Prop. Accepted	HST Obs. Complete	JWST Prop. Accepted	JWST Obs. Complete
2019	1300	25	0	0	0	0
2020	1900	70	11	3	0	0
2021	2200	100	24	10	4	0
2022	2300	130	28	19	7	4
2023	2400	150	32	24	13	10
2024	2600	175	36	28	20	13
2025	2600	200	39	32	24	20

Figure 7: Four scenarios and the corresponding cumulative number of targets studied in the TESS-HST-JWST synergy. Values in the table show the number of targets in different stages through the progress toward possible HST-JWST observations. One set of HST observations are assumed to be pre-requisites for JWST follow up. An HST Key Project will expand the bottleneck in the target characterization process and thereby lead to a major increase in the number of small planets with HST and JWST observations.

13 Comments on Resources

13.1 Resources for the Small Planets Key Project

An important component of the Small Planets Key Project is contribution to the characterization and screening of possible targets. This is a program component that is traditionally not supported by the HST Data Analysis grants; however, such support is essential to ensure that HST

time is invested optimally.

13.2 Data Reduction and Analysis Software Libraries

Based on input from multiple experts we conclude that a centralized and comprehensive repository of shared, open source data reduction and analysis software (toolkits, pipelines, etc.) would be a valuable resource to the community. Such a repository would facilitate independent verification of data reduction and analysis efforts, reduce the learning curve for new teams wishing to reduce, analyse, and interpret HST data, and would lead to more robust and reliable results by enabling comparisons of data reduced and analysed via different methods.

The [ExoCTK](#) repository hosted by STScI is a great initiative in this direction and should be further supported, maintained, and expanded to enhance its impact. Jupyter notebooks are particularly well suited to present and share data reduction and analysis methods and have been adopted broadly in other fields as a standard supplement to publications.

The impact of the software repository can be further increased by engaging the exoplanet community in “hackweeks” or “hack sessions”, that focus on providing quick-and-dirty, but functional solutions to challenging problems. STScI may be the ideal host to such hackweeks, which could accelerate the identification and implementation of software solutions to data reduction and analysis challenges.

A Advisory Committee's Public Website

<https://outerspace.stsci.edu/display/HPR/HST-TESS+Advisory+Committee>

B Calls for Community Input

C Online Survey Questionnaire

- Q1 Exoplanet survey priorities: What are the most important exoplanet discoveries you expect from TESS?
- Q2 What is the single most important question HST/JWST follow-up of TESS-discovered exoplanets will likely answer?
- Q3 What type of TESS-discovered planets should be the highest priority for HST and JWST to follow up?
- Q4 What HST observations (follow up of TESS discoveries) would greatly enhance future JWST observations of the same or similar targets?
- Q5 What guidelines would you give to the time allocation panel about what constitutes a viable (confirmed) target for HST follow-up?
- Q6 Are there cases when HST observations should be pre-requisites for JWST follow-up of important TESS-discovered planets?
- Q7 Programmatics: The current HST proposal / time allocation process is ideal for selecting HST proposals for the follow up of TESS-discovered exoplanets. Please use the dropdown menu and select between 1 and 5 with 1 being “Strongly Agree” and 5 being “Strongly disagree.”
- Q8 If a new program type would be required, what would be your recommendations about its format and evaluation criteria?
- Q9 Do you anticipate the need for important HST observations (following up TESS exoplanet discoveries) that must be reviewed, approved, and executed on a cadence that is not compatible with mid-cycle and regular proposals? If so, what would be these observations and what cadence would they require?
- Q10 Please add any other comments you may have.

Questions 11 to 16 are optional. Answers to these questions will be used only to assess the demographics of the responders.

- **Does your work include exoplanet detection and confirmation? Y/N**
- **Q12 Does your work include exoplanet characterization (atmospheres, orbits, other properties)?**
- **Q13 Are you working on other exoplanet-related research?**

- **Q14 Are you working on TESS data or TESS exoplanet discoveries?**
- **Q15 Have you used space-based, time-resolved data in your past research?**
- **Q16 Years since PhD (if you do not have a PhD, enter 0)**

D Demographics of Survey Responders

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