Eta-Earth with the Hubble Space Telescope

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☒ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☒ (Theme D) A specific concept for a large-scale ($\sim$500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary:

Over the next couple of decades, NASA is embarking on an ambitious goal to image nearby terrestrial worlds in the habitable zone. Current estimates for the occurrence of terrestrial-size planets orbiting sun-like stars (eta-Earth) are not well constrained, ranging from 0.05 to 1 from the *Kepler* mission [1]. The wide range of eta-Earth estimates leads to a comparably wide range in the number of nearby stars with detectable and characterizable Earth-like planets; a critical parameter for the design and expectations of NASA's Habitable Worlds Observatory (HWO) [2, 3]. In order to reduce the current uncertainty in eta-Earth by a factor of two, we recommend an HST program ($\sim$600 orbits spread over multiple years) in order to confirm *Kepler*'s candidate terrestrial-size planets orbiting in the habitable zone of Solar-type stars (THZ) that most influence measuring eta-Earth. This program will provide the first confirmed THZ planets orbiting GK dwarf stars, the most accurate and precise legacy estimate of eta-Earth for the coming decade, reduce the uncertainty in HWO expected returns by a factor of two, and enable joint analysis of future missions such as *PLATO*, *Earth 2.0 Telescope* (ET2), and *Roman Space Telescope* (RST). These observations directly respond to the 2020 Decadal Survey that identified 'Pathways to Habitable Worlds' as one of the most scientifically compelling and highest priority areas of research to undertake during the next decade. Additionally, eta-Earth measurements will advance planet formation theory by providing observational constraints on the final outcomes of disk evolution, planetesimal growth, migration, and dynamical interactions [4, 5, 6, 7, 8].

Anticipated Science Objectives: The *Kepler* mission provided a statistically significant population THZ candidates (Figure 1; 15 planet candidates with $R_{\rm p}$<2.3 $R_\oplus$ and $P_{\rm orb}$>290 day). Unfortunately, we cannot take full scientific advantage of *Kepler*'s THZ candidates because their false alarm contamination rate is high, causing the leading systematic error in measuring eta-Earth [9, 10, 11, 12]. *HST* can confirm or deny the existence for *Kepler*'s THZ candidates with a single transit visit; *HST* provides ∼2 times higher SNR per transit than *Kepler*. Following up 13 of the candidates reduces the false alarm induced systematic error below the Poisson error for measuring eta-Earth, and an **overall reduction in the total eta-Earth uncertainty by half**. The visit duration requires a comparable duration both before and after the transit event while accounting for a 2σ ephemeris uncertainty; The visit duration accommodates TTVs as 99.3% of KOIs have TTV amplitudes <1 transit duration [13]. The 13 candidate sample and visit duration estimates yield a ∼ 600 orbit multi-year *HST* program and is expected to **yield 4-9 planet confirmations**. The *PLATO* [14, 15], ET2 [16], and RST [17] missions are not predicted to yield a significantly larger sample of THZ candidates than *Kepler*, and this program would enable a joint refined estimate of eta-Earth. This program would profoundly impact the planning for NASA's HWO (Figure 2) by **reducing the astrophysical uncertainty in direct imaging mission yields by half**.

Urgency: The *Kepler* THZ candidates are being lost due to ephemeris drift at a rate of 5% increase to the target visit duration every 2 years.

Risk/Feasibility: The recovery of Kepler-62f using *HST*/UVIS (Figure 3) demonstrates that this program will succeed. For *Kepler*'s THZ candidates, *HST* provides a median SNR=8.5 (5<SNR<12) detection from a single transit (median depth=260 ppm; 75<depth<800 ppm). Due to the long transit durations (∼10hr), programmatic, single-orbit gaps do not impact detection. The observations of Kepler-62f demonstrate that UVIS spatial scanning observations during SAA passages and enhanced cosmic ray rates do not impact detection.

Timeliness: An *HST* program dedicated to reducing uncertainty on eta-Earth directly addresses SCI-04, -05, -06, and -12 of the 2023 Exoplanet Exploration Program 'Science Gap List' [18].

Cannot be accomplished in the normal GO cycle: Accurately and precisely measuring eta-Earth requires observing many candidates detected homogeneously using a pipeline with known search completeness. The program is too large (600 orbits) to be accomplished in a single GO cycle.

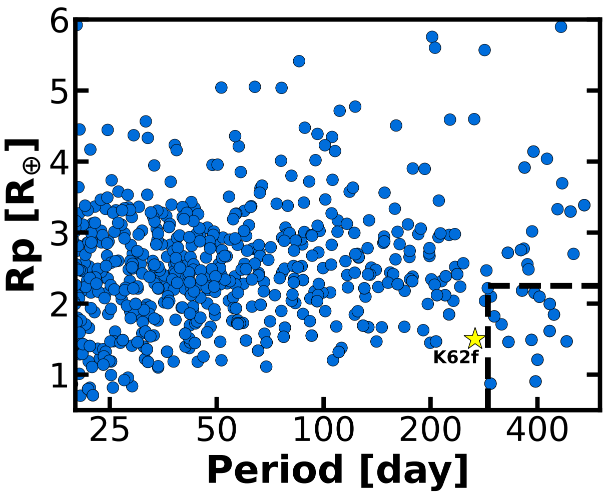

Figure 1: The *Kepler* DR25 planet candidate catalog for the GK dwarf stellar sample (circles) [19]. The star symbol shows properties of Kepler-62f recovered by *HST* (see Figure 3), and the dash line shows the selection region of *Kepler*'s THZ candidates ($R_{\rm p}$<2.3 $R_\oplus$; $P_{\rm orb}$>290 day).

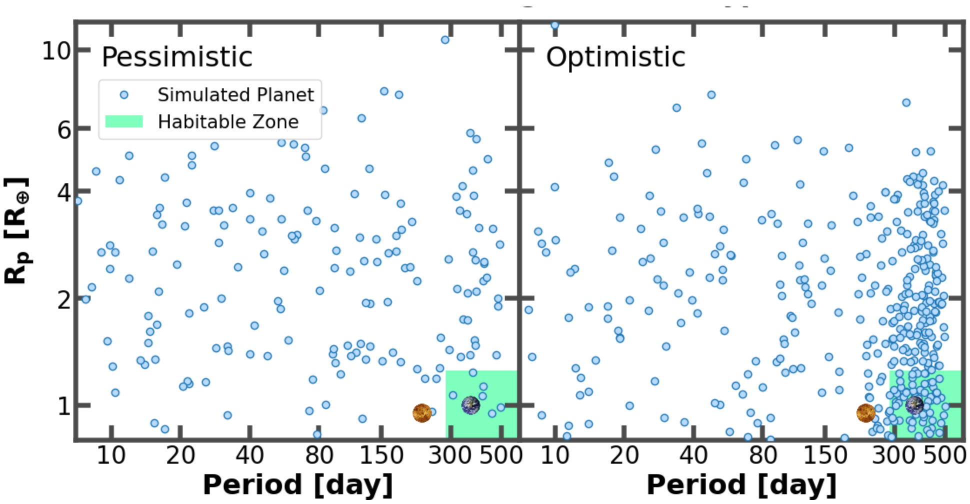

Figure 2: Simulated planetary content of the 100 closest GK dwarf stars based on the *Kepler* DR25 planet candidate catalog after correcting for survey incompleteness at the upper and lower systematic uncertainty for eta-Earth. The right panel assumes an optimistic THZ planet abundance, and the left panel assumes a pessimistic THZ planet abundance. Without additional follow up *HST* observations we cannot distinguish which THZ planetary abundance universe we live in. Large symbols represent Earth and Venus.

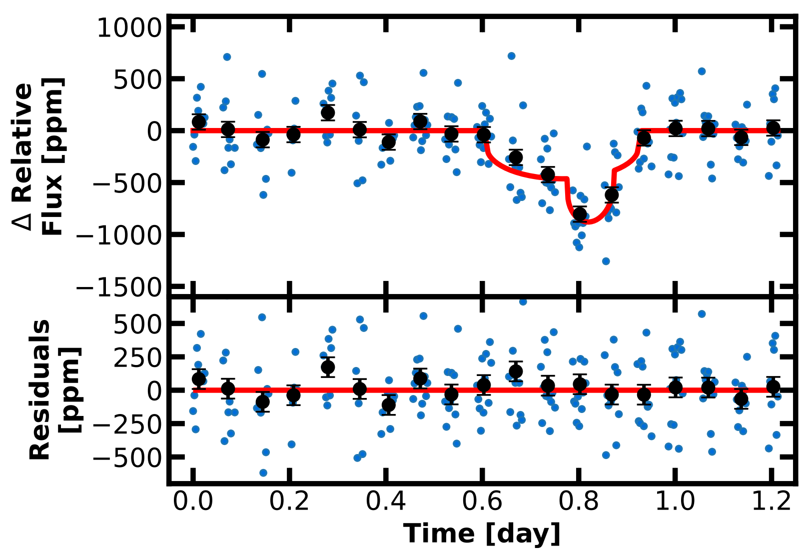

Figure 3: *HST* observations (GO:15129) of Kepler-62f and a simultaneous transit of the shorter duration planet Kepler-62b (blue points). Limb-darkened transit model (red line) from a simultaneous fit to *Kepler* and *HST* data. These observations demonstrate the capability for *HST* to recover *Kepler* candidates by providing Poisson-limited, 75 ppm, orbit-to-orbit stability (*HST* orbit average observations – black points) using the UVIS F350LP filter with spatial scanning.

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