Roman Early-Definition Astrophysics Survey Opportunity

(1) Survey Name

The Roman Globular Cluster Time-Domain Survey: Probing the Oldest Stars and Exoplanets in the Milky Way

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(4) Do you support the selection of a Roman Early-Definition Astrophysics Survey

We support the selection of a Roman Early-Definition Astrophysics Survey. The Roman Wide Field Instrument will enable unprecedented investigations of stars and planets in our galaxy, enabled by its wide field of view, high spatial resolution and sensitivity. We propose an early-definition time-domain survey of a globular cluster, which would enable preparatory activities that will maximize the scientific return of both core-mission Roman surveys and future community programs through (i) the optimization of crowded-field photometry pipelines for the Roman microlensing campaign (including saturated star photometry), (ii) preparatory ground-based spectroscopy of key astrophysical probes in globular clusters and (iii) starting a time baseline for proper motion measurements and dynamical phenomena in globular clusters that will enable a wide range of science cases across stellar astrophysics and exoplanet science.

(5) Science investigations enabled by the survey

Galactic astronomy has been revolutionized over the past decade by space-based time-series photometry from Kepler/K2 and TESS, enabling the detection of thousands of transiting exoplanets and the systematic application of asteroseismology to age-date stellar populations. However, Kepler/K2 and TESS only sample local stellar populations and their large pixel sizes (4” for Kepler/K2, 25” for TESS) severely limit observations in crowded fields that contain the most ancient stellar populations of the Milky Way.

Globular clusters (GCs) are excellent laboratories for exoplanet formation and stellar physics. Planet occurrence is predicted to depend on stellar metallicity [1], crowding [2] and age [3], all of which can be uniquely controlled in GCs. Discoveries of planets transiting serendipitous nearby thick disc stars [4,5] have recently demonstrated that planets exist around ~>10 Gyr old stars, but the small sample size has prevented the disentanglement of which effects dominate planet formation at old ages. GCs also present long-standing challenges for stellar physics that could be addressed with asteroseismology, such as the discovery of multiple stellar populations, possibly linked to second-generation star formation through massive interacting binaries or AGB stars [6]. Previous attempts to detect transiting planets in GCs were limited by small samples due to HST’s limited FOV [7,8] and the K2 Mission only yielded a handful of asteroseismic detections due to limited pixel resolution [9]. GCs probe a distinctly different population than the Galactic bulge and are therefore currently not covered in any Roman core-science programs.

The unique wide FOV and spatial resolution of Roman will enable the first systematic discovery of transiting exoplanets and oscillating red giants in a globular cluster. Roman’s FOV is exquisitely matched to bright GCs in the Milky Way (Fig. 1, left), with a density in the cluster core comparable to Kepler (2-4 stars per 100 pixels). Simulations assuming Kepler-like planet occurrence rates [10] predict that a Roman time-domain survey would detect ~1000 transiting exoplanets in a GC, a two orders of magnitude higher sensitivity compared to previous surveys with HST [7]. Critically, Roman will for the first time be sensitive to warm sub-Neptune-sized planets in GCs (Fig. 2), which more frequently form around metal-poor stars than hot Jupiters [1]. The survey will yield the first census of oldest planets in the galaxy, allowing investigations into long-standing problems such as the effects of age on atmospheric mass-loss [11] and the dependence of planet occurrence on the distance from the cluster core [2].

A Roman time-domain survey will simultaneously enable the first systematic application of asteroseismology to red giants in a globular cluster. Simulations predict that a 30-day survey will detect oscillations in over 2000 red giants, ranging from the base of the RGB to the red clump (Fig. 3, [12]), which is an increase of two orders of magnitude over previous yields from K2 [9]. The detections will allow precise mass and age measurements that will unambiguously discern between proposed mechanisms for the formation of multiple stellar populations in GCs, and provide a fundamental calibration of the asteroseismic mass scale for metal-poor stars. Ancillary science cases include studies of the metallicity dependence of stellar convection through observations of granulation [13] and the discovery of eclipsing binaries, which will provide near-model independent masses and radii to test stellar models of metal-poor stars, including interior processes such mixing and the efficiency of convective energy transport [14].

In summary, a Roman Globular Cluster time-domain survey would enable a treasure trove of data impacting a broad range of science cases across stellar astrophysics and exoplanet science. The expected impact will be akin to the time-domain revolution initiated by the Kepler Mission, but for the first time focusing on the oldest stars and exoplanets in the Milky Way.

(6) Observational outline of the survey

We propose to use the Roman wide-field instrument to perform a time-domain survey of a globular cluster in the Milky Way. We expect an instrument setup similar to the microlensing survey, with a ~1 minute cadence in either the F146 or a more narrow filter, resulting in unsaturated photometry approximately around the cluster turn-off (Fig. 1, right). Simulations with 1-minute cadence yield a limiting magnitude for the detection of Neptune-sized planets of F149 ~ 18 mag, while Jupiter-sized planets can be detected down to at least F149 ~ 20 mag (Fig. 2). Asteroseismology of red giants can be performed on saturated photometry following [12] and is expected to yield detections down to F149 ~ 14.5 mag (Fig. 3). A 30-day survey would allow the detection of warm Neptune-sized planets (periods ~> 10 days) and provide sufficient S/N to perform asteroseismology of stars down to the base of the red-giant branch. We estimate that the minimum useful length for a Roman GC survey would be 15 days, allowing the detection of hot Neptunes and Jupiters, and asteroseismic measurements in red-clump stars.

Roman is uniquely suited to perform a time-domain survey of a GC. Transit missions such as Kepler/K2, TESS, CHEOPS and PLATO have poor spatial resolution and the ~100 times smaller FOV of HST and JWST are insufficient to perform such a survey. **Roman's wide-field, spatial resolution and sensitivity make it the only instrument capable of systematically discovering transiting exoplanets and stellar oscillations in a globular cluster in the coming decades.**

(7) Specific preparatory activities enabled by early definition

Testing crowded-field photometry pipelines: The selection of a GC would allow early testing of photometry pipelines in crowded fields that are critical for the success of the microlensing survey, including investigations of proposed techniques to perform photometry of bright stars using unsaturated pixels in the wings of the PSF [9]. Testing these pipelines is particularly important for producing microlensing alerts on a short timescale, since such alerts will not be a standard Roman data product and thus will need to be produced by the community.

Ground-based spectroscopy: Detailed chemical abundances from high-resolution spectroscopy are critical to complement asteroseismic observables to derive masses and ages [15]. Preparatory observations using multi-object spectrographs such as SDSS/APOGEE and GALAH/HERMES require long lead times to cover the large FOV of a globular cluster, and would strongly benefit from early selection to provide necessary spectroscopic information to maximize the science return. Preparatory spectroscopy (as opposed to follow-up spectroscopy, as done for Kepler and TESS) would also provide an unbiased spectroscopic selection function to investigate poorly understood processes such as the suppression of oscillations in close binaries [16].

Proper motions: Roman is expected to provide excellent astrometry [12], including proper motions for cluster membership well beyond the Gaia sensitivity limit (H~> 20 mag, Fig. 1) and over a much wider field of view than HST. Deep imaging provided by a globular cluster time-domain survey would provide an astrometry epoch down to the low mass and brown dwarf regime of the selected globular cluster, eventually allowing a wide range of science investigations including an unprecedented GC membership census, constraints on the low-mass initial mass function and investigations into stellar mass segregation in GCs [19].

Baseline for dynamical phenomena: Early selection would enable sensitivity to long-term dynamical phenomena for subsequent GC observations, including transit/eclipse timing variations that allow the discovery of companions (including circumbinary planets), probes of tidal dissipation and planetary/stellar engulfment through the observations of orbital decay [18], as well as transient phenomena such as sudden dimmings due to circumstellar dust rings [20].

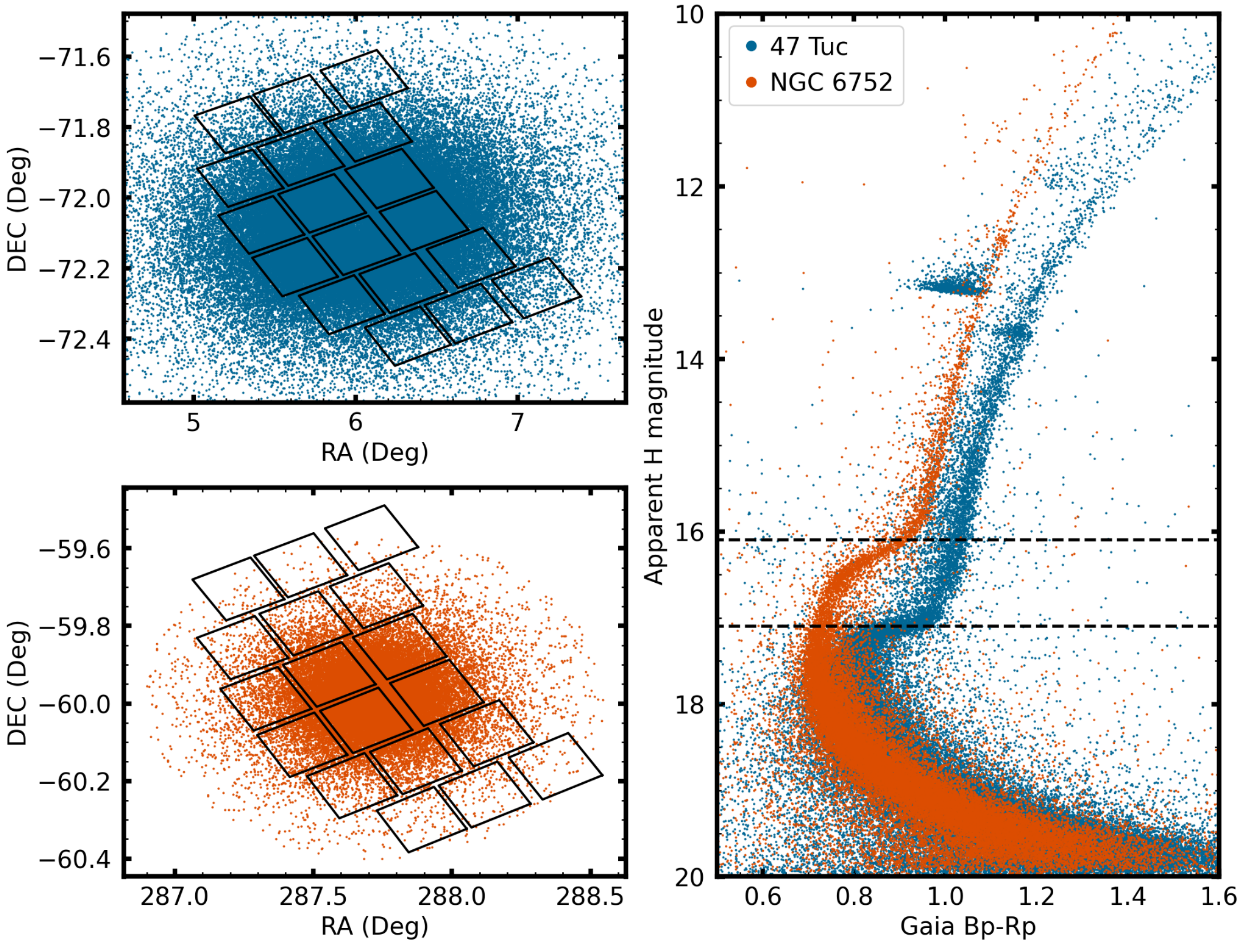

Figure 1: Roman's wide FOV and high spatial resolution is ideally suited to perform precise time-series photometry of nearby globular clusters. *Left panels:* Spatial distribution for Gaia astrometry selected members [17] of the globular clusters 47 Tuc (top; Age ~ 13 Gyr, [Fe/H] ~ -0.8) & NGC6752 (bottom; Age ~ 12 Gyr, [Fe/H] ~ -1.2). The Roman FOV footprint is overlaid in black. *Right panel:* Color-magnitude diagram (2MASS H-band converted to AB magnitudes as a proxy for Roman F149) for both clusters. The cluster turn-off mass is ~0.8 solar masses. Horizontal dashed lines mark the approximate Roman saturation limit for 2 (bottom) and 6 (top) detector reads using the F149 filter.

References:

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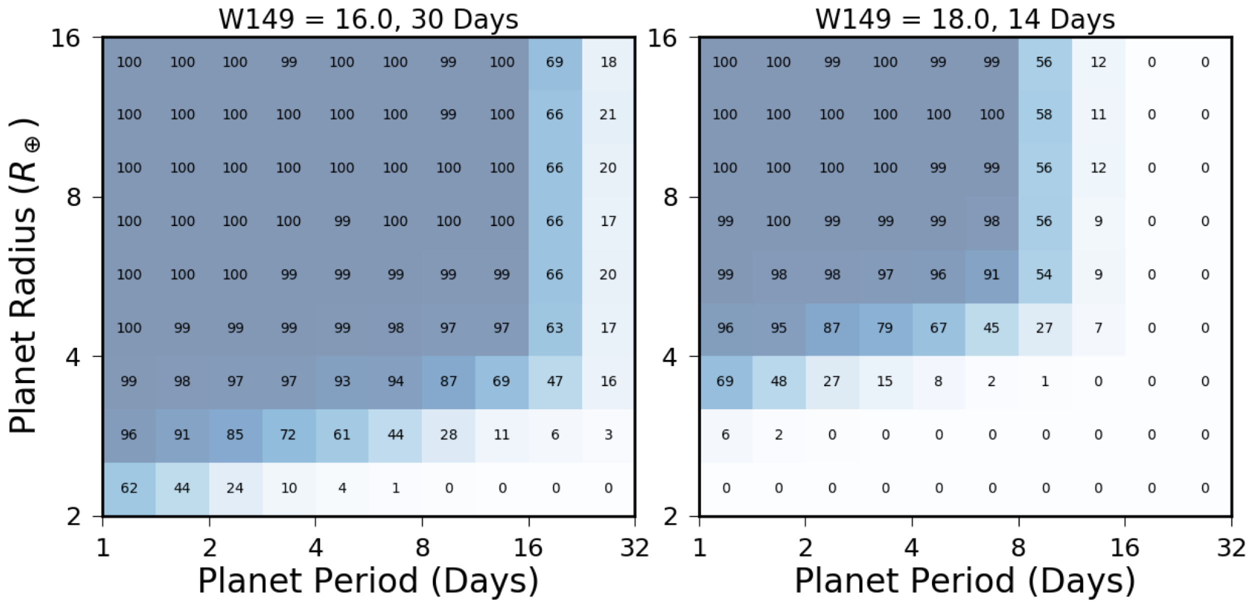

Figure 2: Roman will enable the first discovery of transiting sub-Neptune sized planets in a globular cluster, providing unique insights into exoplanet demographics at old ages. Detectability of transiting planets orbiting a 1 solar-radius star using simulated Roman light curves with 1-minute cadence, assuming 30 days of observations of H~16 mag star (left) and 15 days of observations at H~18 mag (right). Each box marks the percentage of recovered planets for a given planet radius and orbital period. Simulations follow the methodology in [10].

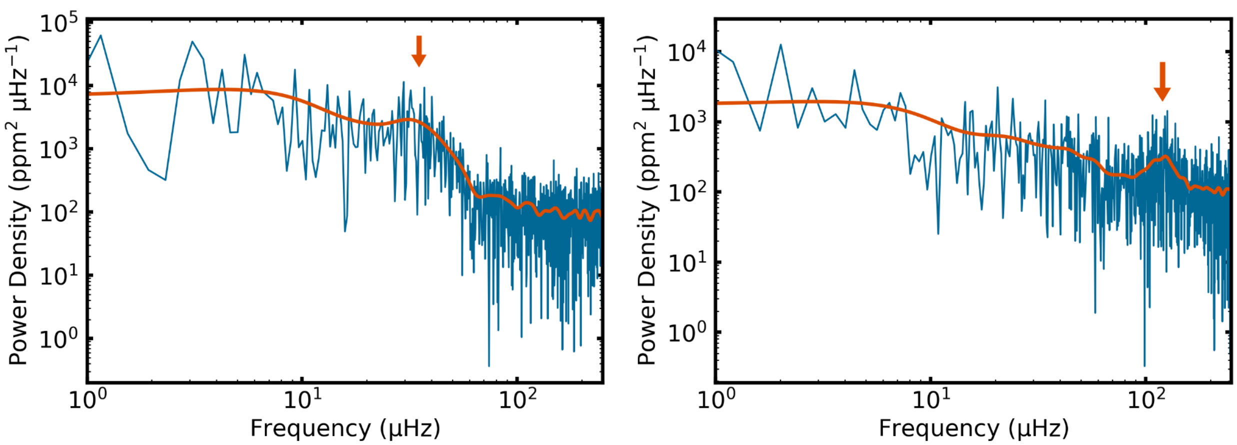

Figure 3: Roman will enable the first large-scale application of asteroseismology in a globular cluster, providing mass measurements that will address long-standing challenges in stellar physics such as the formation of multiple stellar populations in GCs. *Left panel:* Simulated asteroseismic power spectrum of a H~13 mag red clump star assuming 30 days of Roman observations. The red line shows a heavily smoothed version of the power spectrum and the red arrow marks the true frequency of maximum power from stellar oscillations. *Right panel*: Same as left panel but for a H~14.5 mag low-luminosity RGB star. Simulations follow the methodology in [12].