The TEMPO Survey: Probing Planet & Satellite Formation with the Nancy Grace Roman Space Telescope

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We propose the Transiting Exosatellites, Moons, and Planets in Orion (TEMPO) Survey, a panchromatic time-domain survey of low-mass sources centered on the Orion Nebula Cluster, and capable of detecting newly-formed planets, satellites[1], and moons. TEMPO promises transformational science in the fields of planet and satellite formation, and will extend the IMF below the brown dwarf regime, however, it requires preparatory activities to significantly enhance the science goals. We, therefore, support the selection of a Roman Early-Definition Astrophysics Survey, as this will enable detailed optimization of the cadence/readout/downlink survey strategies in collaboration with the Roman WFI team, thereby maximizing the planet/satellite yield. Early selection also offers the time required to organize simultaneous panchromatic observations with other observatories, enhancing transit detection capabilities unlocking valuable ancillary science—such as investigations of flare temperatures; stellar activity; astrometric measurements; dust extinction curves and maps of the nebulae—including proplyds, globules, and pillars; dust properties in young dipper stars; and binary functions in young clusters.

[1] We use "satellite" as a catch-all term to refer to objects orbiting brown dwarfs and IPMOs, which may not necessarily fit into classifications of planets or moons. This follows the precedent established in the literature (14; 18).

Science Cases Enabled: The Transiting Exosatellites, Moons, and Planets in Orion (TEMPO) survey is a panchromatic time-series investigation of low-mass objects with the unprecedented capability of detecting newly-formed planets, satellites, and moons. The TEMPO field is centered on the young (1-3 Myr), nearby (∼400 pc) Orion Nebula Cluster (ONC)—the densest star-forming region in the solar neighborhood (Fig. 1). The ONC is the ideal environment to search for satellites (i.e. moons, planets, and other companions) in orbit around isolated planetary-mass objects (IPMOs; also known as "free-floating planets")[2], brown dwarfs (BDs), and stars via the transit method (16).

The primary goal of TEMPO is detecting sub-Earth-sized satellites orbiting planetary-mass-objects and BDs (Fig. 2). We estimate that TEMPO will yield dozens of such objects—even after accounting for the transit detection challenges due to young host variability. We estimate that we will be able to monitor ∼1500 IPMO and BD targets (19), detecting **up to 120 IPMO and BD exosatellites, of which ∼10% will orbit planetary-mass objects**, depending on the unknown occurrence rate of these objects (15). Various groups have predicted different occurrence rates and orbital properties for moons orbiting IPMOs and BDs (11); **TEMPO will provide the first constraints on satellite formation models outside the solar system** (Fig. 3).

TEMPO will also yield the discovery of numerous (up to 150) newly-formed planets (1-3 Myr) orbiting low-mass stars. Young planets are critical observational touchstones, bridging the gap between protoplanetary disks imaged by ALMA and the mature planetary systems detected by Kepler and TESS. Small planets around young stars are challenging to detect with current instruments. The large TEMPO sample will probe the formation of hydrogen-helium envelopes around Mars-mass planets (10; 23), help constrain mass/loss scenarios (20), and test theories of planet migration at the youngest-ages yet.

TEMPO enables a wide variety of ancillary science including: (A) An ensemble of near-infrared extinction curves to chart grain size evolution as a function of column density, connecting the protostellar cloud grain size distribution to that in the diffuse media. Detailed stellar modeling coupled with the known distance to Orion offers measurement of the absolute extinction law. The true steepness of the NIR extinction law remains a major uncertainty in the Galactic extinction curve (12). **(B)** The detection of a large number of dipper stars—young stars exhibiting flux dips in light curves lasting 0.5-2 days with depths up to 50%. Dippers are thought to result from protoplanetary disk material falling onto the star. If true, the dips will be shallower in the bands probed here than in simultaneous optical observations; something we can test and use to probe disk material properties. **(C)** A variability study of very-low-mass objects, including a search for flares, rotation periods, accretion, and asteroseismic signatures. Few rotation periods are known for very-low-mass sources; TEMPO will increase this number by an order of magnitude, providing rotation period measurements for a large number of substellar objects with well-defined ages, ranging from planetary-mass to BDs. This will extend gyrochronology into the substellar regime. These measurements will trace the angular momentum evolution of substellar objects as a function of mass at young ages, testing the "Universal Spin-Mass Relation" (22). **(D)** A map of the dense star-forming dusty gas including the pillars, proplyds, and globules that are shaped by stellar feedback by young stars and are actively undergoing star and planet formation (13). The density maps will help test star formation models and determine how feedback shapes the ISM, drives turbulence, and may trigger star formation in star-forming environments (3; 17). **(E)** A population of faint wide-separation and free-floating directly-imaged exoplanets. The full co-added TEMPO images will be sensitive to Neptune-mass free-floating companions, and more massive objects near bright stars after image processing using advanced PSF subtraction techniques (24). The population of free-floating planets and BDs will map the low-mass tail of the initial mass function (IMF) and test models of planet ejection. **(F)** Deep extragalactic observations with a limiting AB mag of F213 = 29.7. Two of the H4RGs in our field of view have almost no extinction, and will yield deep observations in an equatorial field in an RA range with few other competing extragalactic deep fields. These sources will be ideal for follow-up with upcoming $20-30$-meter telescopes in both hemispheres. **(G)** Eclipsing binary stars will allow precise mass and radius measurements, necessary for testing pre-main sequence (PMS) evolutionary models and providing critical constraints on radius inflation mechanisms among young, low-mass stars. **(H)** Wide binary companions at separations as close as ≈30 AU (6), providing a crucial test of the universality of the binary function in young clusters (8). **(I)** Proper motion measurements will enable a detailed analysis of stellar dynamics within the cluster, including the detection of young runaway stars (9).

The TEMPO survey will offer the astronomical community a broad and robust collection of time series observations with far-reaching theoretical implications that span a wide range of astrophysical subdomains. The long temporal baseline afforded by the Early-Definition Astrophysics Survey paired with Roman's unprecedented resolution and field of view offers a novel opportunity to probe newly-formed exosatellites, planets, BDs, and low-mass stars and to test models of moon and planet formation, stellar evolution, and the IMF.

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[2] Previous surveys of the ONC identified possible co-moving companions. This survey was designed to achieve an astrometric baseline sufficient to identify additional co-movers/directly imaged exoplanets, which will be monitored for transiting exomoons.

Observational Outline: Roman's large field of view (FOV), high angular resolution, and infrared wavelength capabilities make it the only instrument capable of anchoring the proposed TEMPO survey. The FOV permits the monitoring of thousands of young sources and the removal of systematic effects by ensemble analysis (25), enabling a highly precise time-domain study (Fig. 1). We propose to observe a single FOV for a total of 700 hours (split over two sub-observations), taking continuous 18-s, WFI/F213 K-band (1.95-2.3 μm) exposures for the full survey duration (except during data downlink). Our most valuable transit hosts—BDs and IPMOs—range between F213 = 16-23 mag_{AB}. We, therefore, optimize observations for precision photometry in this regime. We propose to use 18-s exposures, each consisting of 6 samples "up the ramp" to mitigate read noise for our faint transit hosts. The saturation magnitude for 18-s exposures in F213 is 14.9 mag_{AB}, but by downloading or onboard processing the sub-reads (see preparatory activities) and selectively ignoring reads after which a saturated pixel reaches the full-well depth, we can mitigate saturation effects and increase our effective saturation brightness to the 12.55 mag_{AB} limit for a single 2.5-s read, corresponding to 1.9 $M_{\odot}$ stars in Orion. These observational parameters also allow us to efficiently monitor low-mass ONC stars ($<$ 16 mag_{AB}) for transits, while searching for planets, seismic oscillations, dippers, and other phenomena in massive stars, providing overlap between TEMPO planet detections and the population of known planets discovered by Kepler and TESS.

To establish co-moving companion memberships with proper motion measurements, we propose to observe the FOV for an observation window of 15 days in year one and an additional 15 days in year two. Many of the sources monitored will be discovered by our program, so a one-year baseline to measure proper motions for assessing cluster membership is key for our survey. In addition to allowing the detection of bright IPMOs for transit monitoring, co-adding each 15-day set of observations and measuring proper motions will allow for the detection of very faint IPMOs, with sub-Neptune masses, providing a comprehensive view of the IMF and a probe of planet ejection. Assuming orbital periods of several days, we expect to detect multiple transits of each IPMO/BD satellite during the 15-day$\times$2 observing windows. This is essential for disentangling the effects of variability from transit signals—shown to be the main obstacle for detecting transits (16). In cases where a single transit is detected in each 15-day set of observations, experience from K2 and TESS will help constrain orbital parameters (2) and allow efficient transit confirmation with ground-based telescopes or JWST. The large gap in observations will help vet transiting candidates—transits are strictly periodic, while stellar variability is expected to evolve, particularly between the observing windows one year apart.

Simultaneous multi-wavelength observations alongside Roman enhances our primary science (mitigating stellar variability using color dependence) and enables additional numerous investigations (e.g., stellar activity/flares/variability, dippers, dust extinction properties). We will obtain simultaneous ground-based multiband light curves with telescopes such as the Rubin Observatory/LSST and time-resolved multi-object spectroscopy with the WIYN-Hydra spectrograph.

Preparatory Activities Enabled by Early Definition: An early definition designation of the TEMPO survey permits preparatory activities that would enhance the success of this pivotal investigation, potentially doubling the yields of transiting exomoons and planets. A space-based transit survey using infrared detectors has never been attempted, which enables TEMPO's revolutionary science but also introduces unknowns that require time to carefully address. Moreover, our science goals are significantly enhanced by simultaneous observations at other wavelengths, which will require significant lead-time to organize.

Data Management/Downlink Strategy and Onboard Processing: Currently, the biggest uncertainty in the design of our program is the tradeoff between data downlink rate, saturation/brightness limit, and photometric precision. Because Roman uses a sample-up-the-ramp strategy to non-destructively read out its H4RG infrared detectors, it should be possible to extract unsaturated photometry from stars that are brighter than the nominal detector saturation limit by reconstructing shorter exposures from the intermediate readouts. However, this strategy greatly increases the data volume that must be downlinked (or alternatively processed on-board). We contacted the Roman helpdesk and learned that final decisions on the data downlink frequency and rates have not yet been made. Early selection of TEMPO will allow us to work with the Roman team to explore and optimize the survey data handling and assess the potential of downloading intermediate data reads or performing tailored on-board processing to analyze bright stars.

Simultaneous Panchromatic Observations: Early selection of TEMPO will give us time to organize simultaneous ground-based observations in different wavelengths, which will significantly enhance the survey's science output. Simultaneous ground-based observations from large telescopes like the Rubin Observatory to allow for use of panchromatic light curves. Young stars, brown dwarfs, and IPMOs are known to have high levels of photometric variability, which can be difficult to distinguish from planet/satellite transits in achromatic light curves, but color information can break this degeneracy. As demonstrated in (16), host variability is the biggest obstacle for detections of exosatellites transiting IPMOs and BDs. For our yield calculations, we assume that transits with depths $< 0.2\%$ will not be detectable. Without this obstacle, we could **double the number of detectable exoplanets transiting BDs—detecting up to 200 BD exoplanets** and almost all the additional exosatellites would be **sub-Earths**, another unexplored regime. BDs in Orion are bright enough in the red optical (15-18 Vega mags in *y* band at 3 Myrs for 15-75 M_J) for Rubin to measure precise light curves.

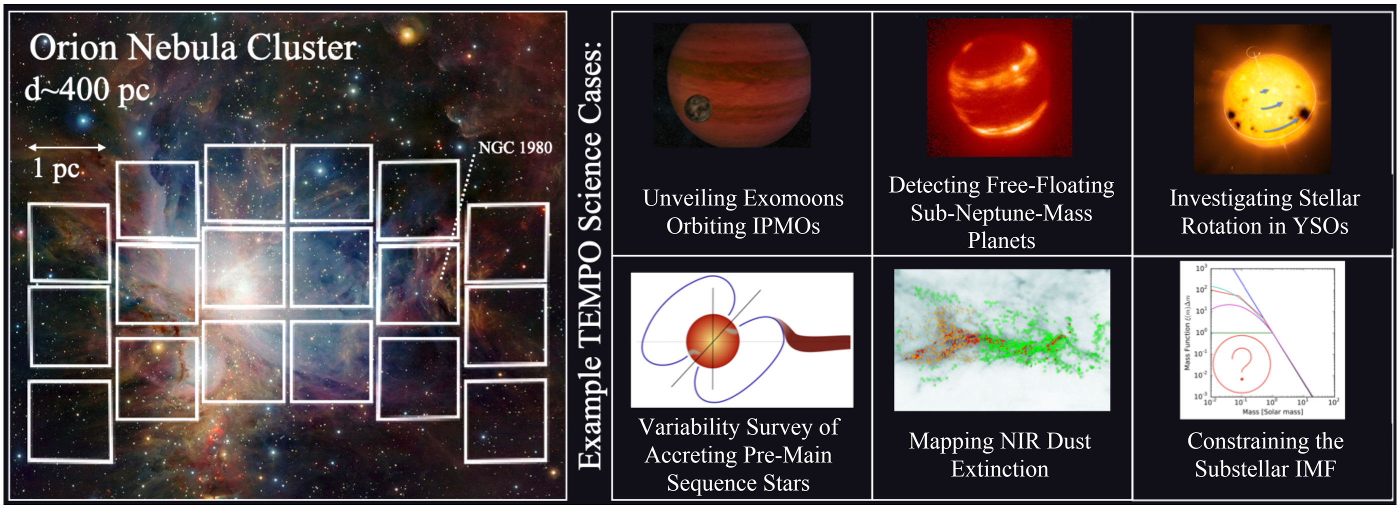

Figure 1: **Left:** FOV for the TEMPO Survey, centered on the Orion Nebula Cluster (1-3 Myrs) and including NGC 1980 (∼5 Myrs). **Right:** Depiction of six ancillary science cases that can be investigated with the data supplied by this survey. We review a larger collection of ancillary science goals in Limbach, Soares-Furtado, et al. in prep.

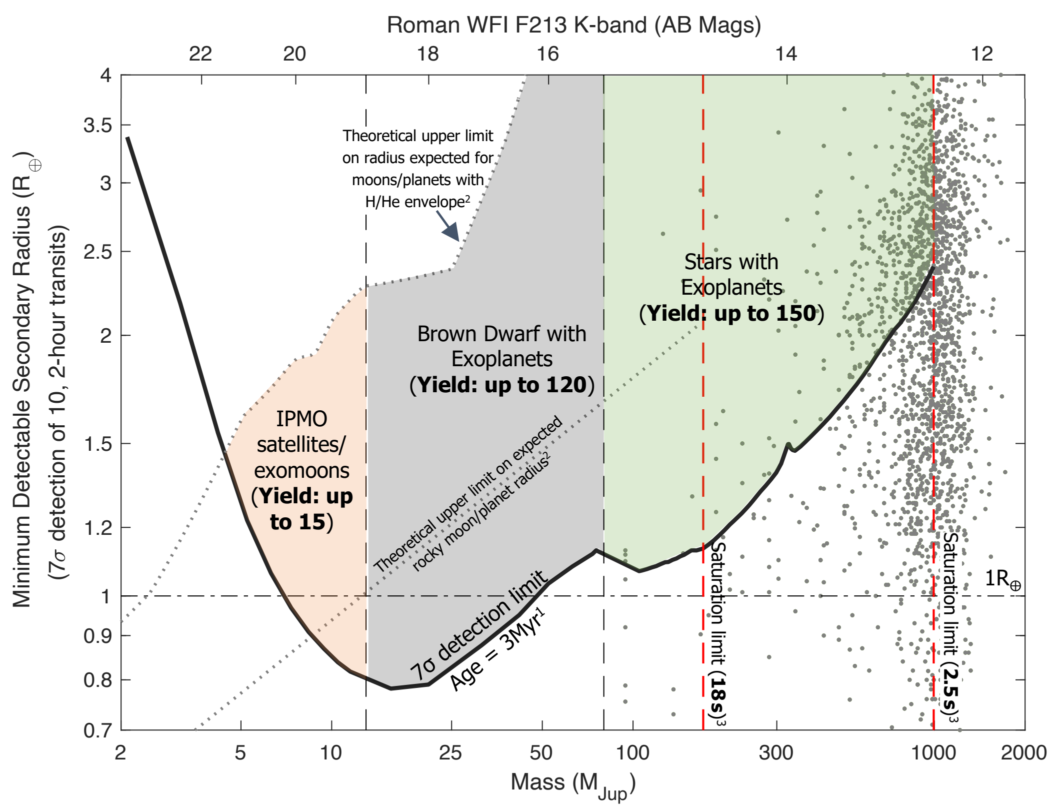

Figure 2: Minimum detectable (7σ) radius of a transiting companion ($R_\oplus$) with observations of 10, 2-hour transit events (y-axis) vs. host mass (bottom x-axis) and ABmag with Roman/WFI F213 filter (top x-axis). Magnitudes correspond to 3 Myr host masses. Estimated companion yield provided in parenthesis based on modeling described in (15). Note that all known exoplanets (black points) overlapping the green region are much older than the exoplanets that will be detected by this survey. Young companions detected with the TEMPO survey are likely to possess H/He envelopes similar to primordial-earth. Several lines of note are shown on the plot: (1) WFI/F213 (K-band) 7σ detection limit based on models from (1; 7; 21) and Roman/WFI SNR tables provided in support of this RFI. (2) The theoretical upper limit (dotted diagonal black-lines) assumes companion mass scales as $M_s \propto 2.5 \times 10^{-4} M_p$ (4) and companion radius scales as $R \propto M^{0.28}$ (5) for rocky worlds (lower dotted line) or worlds with volatile envelopes (upper dotted line), which are expected at young ages down to Mars mass (23). (3) Saturation limit of F213 = 14.9 AB mag (18-s exposures) or 12.55 AB mag (2.5-s reads; 6 reads per exposure) based on the provided Roman RFI saturation tables.

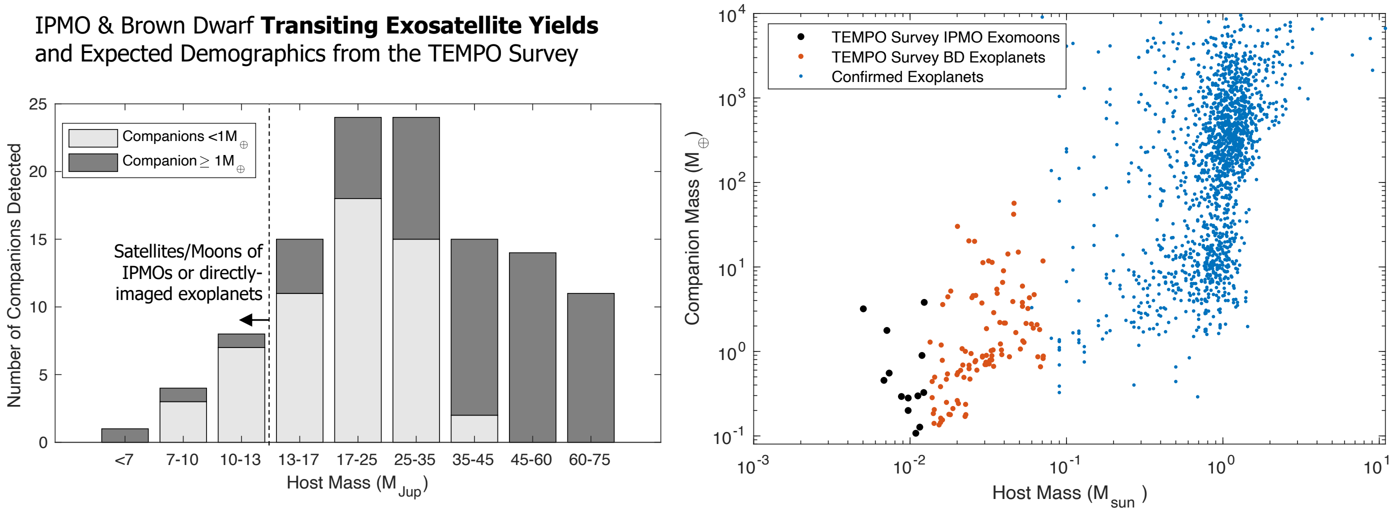

Figure 3: **Left:** Example TEMPO survey distribution of IPMO and BD transiting exosatellite detections for a given set of theoretical models. **Right:** TEMPO IPMO and BD companion demographics compared to known exoplanet population for the example yield calculation. Calculations are based on the detection limits shown in Figure 2 and described in detail in Limbach, Soares-Furtado, et al. in prep. These estimates account for any loss in yields due to anticipated young host variability.

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