Roman CCS White Paper

The Roman Galactic Exoplanet Survey (RGES)

Roman Core Community Survey: *Galactic Bulge Time Domain Survey*

Scientific Categories: *exoplanets and exoplanet formation*

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Abstract:

The primary Science Objective of the Galactic Bulge Time Domain Survey (GBTDS) of the Nancy Grace Roman Space Telescope (Roman) to *Carry out a statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater.* We refer to the component of the GBTDS survey that will achieve this goal as the Roman Galactic Exoplanet Survey (RGES). We review the Level-1 Science

Requirements of the microlensing exoplanet survey and explain how the choice of survey parameters impacts the ability to meet these requirements. For fixed survey duration and current estimates for the slew and settle times, most survey parameters needed to meet the yield science requirements are fairly tightly constrained, with little margin. Decreased slew and settle times or longer survey durations will allow for more flexibility to accommodate other science. To this end, new GBTDS simulations are needed to optimize the RGES survey strategy, verify that Level 1 science requirements will be met with this strategy, and evaluate the impacts of the GBTDS observing strategy modifications that could be selected to enhance non-exoplanet microlensing science on the ability for the GBTDS to meet these requirements. We argue that compressed timeline for the development of the GBTDS observing strategy is very challenging, and will likely harm, rather than enhance, general investigator science.

The Roman Galactic Exoplanet Survey with Roman is needed to complete the statistical census of exoplanets in the Galaxy

With the discovery of the first planets orbiting other stars, or exoplanets, it became clear that some planetary systems looked very unlike our own (Wolszczan & Frail 1992, Mayor & Queloz 1995), thereby indicating that our established theory of the how our system formed was incorrect or at best incomplete. With the discovery of hundreds of additional exoplanets, it became clear that exoplanetary systems were not only ubiquitous, but incredibly diverse in their architectures. The best hope of understanding the physical mechanisms that lead this observed diversity of exoplanets is to measure the demographics of exoplanets, i.e., the properties and architectures of exoplanetary systems over a broad range of parameter space.

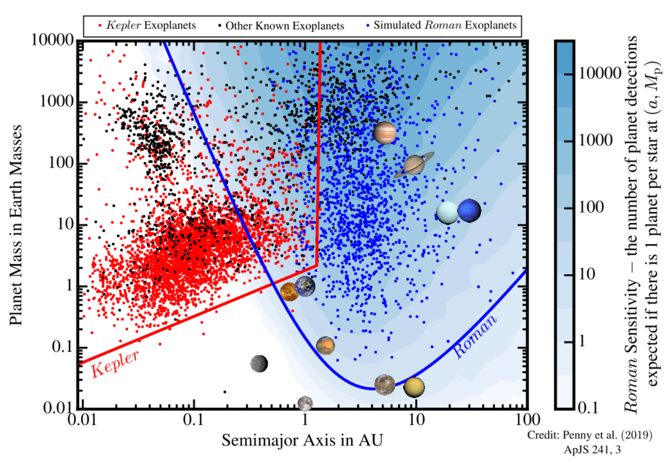

Figure 1. Comparison of the Roman sensitivity to that of Kepler Red line and dots: Kepler detection limit and Kepler planets. Blue line and dots: Roman detection limit and simulated detections with RGES. Black dots: other known exoplanets. Images: Solar system bodies, including Ganymede, Titan, and the Moon at the semimajor axis of their hosts. From Penny et al. 2019.

The first large-scale statistical survey for exoplanets was completed by the Kepler Space Telescope (Borucki et al 2010). Kepler discovered thousands of exoplanets and revolutionized our understanding of exoplanet demographics. However, although Kepler was sensitive to planets as small as the Earth, it was unable to detect planets with orbits wider than roughly 1 AU. Furthermore, the host stars that were surveyed by Kepler are relatively close to the sun and so have ensemble properties that are fairly similar to that of the local solar neighborhood. Thus, Kepler was not able to probe the demographics of planets throughout the Galaxy.

Microlensing is potentially sensitive to planets with mass as low as that of Ganymede, and semimajor axes with semimajor axes $\gtrsim$1au, including very wide separation and free-floating planets. A properly designed microlensing survey with Roman is therefore extremely complementary to that of Kepler, as shown in Figure 1. When combined with Kepler, a microlensing survey with Roman will be sensitive to all planets with masses/radii greater than that of Earth over all semimajor axes. This will provide the ultimate ground truth empirical dataset with which to test and refine theories of planet formation.

Thus, the primary Science Objective of the Galactic Bulge Time Domain Survey (GBTDS) of the Nancy Grace Roman Space Telescope (Roman) is to *Carry out a statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater.* We refer to the component of the GBTDS survey that will achieve this goal as the Roman Galactic Exoplanet Survey (RGES). This science was mandated by the 2010 and 2020 Decadal Surveys and is at least as compelling as when Roman was selected by the 2010 Decadal Survey. **This science cannot be achieved with any other proposed exoplanet detection method, nor can it be achieved by any ground microlensing survey[1], or indeed any space-based mission with parameters that are significantly different than Roman.**

As highlighted in the white paper call, "The primary requirement driving the definition of Roman's Core Community Surveys is to maximize the science performed with Roman's infrared surveys." However, the process of maximizing the science performed by GBTDS must be done with "the consideration that they must provide observations that will fulfill Roman's requirements in […] exoplanet demographics." Therefore, one of the primary goals of this white paper is to explain how the choice of survey parameters impacts the yield of planets and the ability to measure the host star masses, and thus the ability to meet the RGES Level-1 Science Requirements. We aim to provide the community guidance to be able to qualitatively assess the impact of changes from the optimal RGES survey that will enable or enhance other science from the GBTDS. We also advocate for additional detailed simulations to make quantitative assessments of the impact of different survey strategies on the microlensing exoplanet science.

The RGES Level 1 Science Requirements and Survey Requirements

To ensure that the primary RGES Science Objective is achieved, the Roman Microlensing Science Investigation Team worked with the Roman Project to define the following Level 1 Microlensing Science Requirements

- EML 2.0.1: Roman shall be capable of measuring the mass function of exoplanets with masses in the range 1 $M_{\oplus}$< m < 30 M_{Jup} and orbital semi-major axes $\gtrsim$1 au to better than 15% per decade in mass.
- EML 2.0.2: Roman shall be capable of measuring the frequency of bound exoplanets with masses in the range 0.1 $M_{\oplus}$< m < 0.3 $M_{\oplus}$ to better than 25%.
- EML 2.0.3: Roman shall be capable of determining the masses of, and distances to, host stars of 40% of the detected planets with a precision of 20% or better.

[1] We note that, although ground-based microlensing surveys have discovered nearly 200 planets, and may discover as many as 400 by the beginning of the Roman Prime mission, Roman will still increase the sample by roughly a factor of 4. More importantly, Roman is sensitive to regions of parameter space that are simply inaccessible to ground-based surveys, including potentially habitable planets, very low-mass planets, low-mass free-floating planets, wide separation planets, and giant satellites. Furthermore, a large fraction of the Roman planet detections will have host and planet mass measurements, which are currently extremely expensive or impossible to measure for exoplanet systems detected from the ground.

- EML 2.0.4: Roman shall be capable of measuring the frequency of free floating planetary-mass objects in the Galaxy from Mars to 10 Jupiter masses. If there is one $M_{\oplus}$ free-floating planet per star, measure this frequency to better than 25%.
- EML 2.0.5: Roman shall be capable of estimating $\eta_{\oplus}$ (the frequency of planets orbiting FGK stars with mass ratio and estimated projected semimajor axis within 20% of the Earth-Sun system) to a precision of 0.2 dex via extrapolation from larger and longer-period planets[2].

Note that four of these requirements (EML 2.01, 2.02, 2.04, and 2.05) are on the yield of various types of exoplanets. Once the optimal survey strategy is set (see below), the total yield is approximately linearly proportional to the total survey duration. However, meeting EML 2.0.3 is a more complicated function of the survey strategy, and more work is needed to ensure that this requirement can be met. We discuss this in more detail below and in Appendix A.

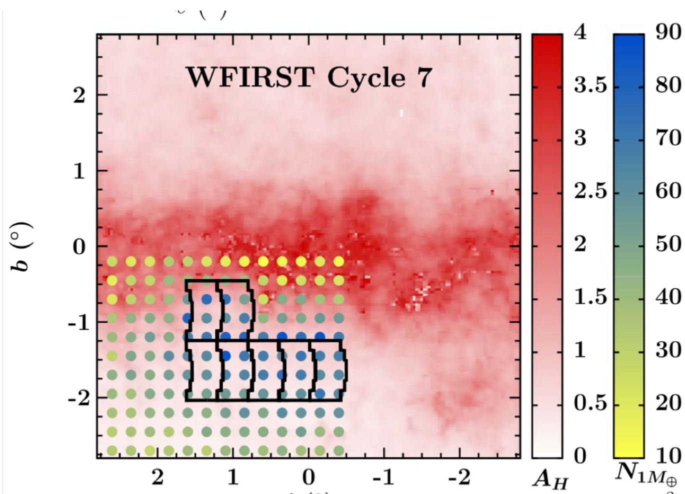

Figure 2. Nominal field placements for the WFIRST/Roman Cycle 7 parameters that maximize the yield. These are plotted over a map of H-band extinction map of Gonzalez et al. 2012). Colored dots show the detection rate of 1 $M_{\oplus}$ planets per square degree as a function of position for the Cycle 7 design. Additional criteria for field selection are discussed in Appendix B.

Survey Requirements for Meeting the Yield Science Requirements

It is possible to make order-of-magnitude estimates of the survey requirements needed to meet the yield science requirements above by considering the requirements to detect roughly 100 Earth-mass planets, since this will also lead to the detection of large number of other types of planets and will essentially guarantee that the four yield requirements are met. These are:

- Monitor ~100s of millions of stars towards the central bulge continuously on a time scale of ~10 minutes for a ~year[3].
  - The microlensing event rate toward central bulge ~few $\times 10^{-5}$/year/star
  - With sufficiently precise ($\lesssim 1\%$) relative photometry, the detection probability for Earth-mass planets ~1%.
  - The minimum duration of features in microlensing planet perturbations, which are set by the crossing time of the source (and not the mass ratio of the planet) are ~30 minutes.

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[2] Given the 2020 decadal survey's recommendation for development of the Habitable Worlds Observatory, and the failure of reaction wheels that prematurely terminated Kepler's extended prime mission, it seems likely that NASA may prefer that GBTDS exceed the EML 2.0.5 requirement by a significant margin.

[3] Given that the surface density of stars with $F146_{AB} < 22$ for which Roman can obtain the requisite photometry to detect Earth mass planets $\backsim 40 \times 10^6$ stars/deg^2 near the Galactic center, this can also be written as a constraint that ~600 deg^2-days are observed.

- Relative photometry of a few %.
  - The typical deviations due to Earth-mass planets are 1 – 10%.
- Resolve main sequence source stars for smallest planets.
  - Unrelated stars blended with the microlensing source lead to larger statistic and systematic noise.

Given certain fixed observatory parameters, including the overall photon collection rate in the wide F146 filter, the spacecraft slew and settle times, the duration, and the times of year of the bulge seasons, the survey parameters can be optimized to meet (and exceed) the yield survey requirements.

A crucial point is that, **for a fixed survey duration and current estimates for the slew and settle times, the majority of survey parameters needed to meet the yield science requirements are fairly tightly constrained, with little margin**. However, changes in many of these parameters can be partially compensated for by increasing the total survey duration, or by reductions in the estimated the slew and settle times. First, a minimum cadence of ~15 minutes is required to detect and characterize planetary perturbations to microlensing events and measure lens-source proper motions. This cadence corresponds to the Nyquist sampling of the crossing time of the smallest sources, which is roughly 30 minutes. This sets the timescale for the shortest microlensing features and the source crossing time, which must be resolved to measure source-lens proper motions, which is important for microlens mass measurements, as described in the next section. Given this cadence, and the fixed observatory parameters mentioned above, the only additional parameters that can be adjusted are the number and location of the target fields, since once the target fields are specified, the exposure time is a set by the slew and settle time (assuming equal exposure times per field). To maximize the yield, fields should be chosen that maximum microlensing event rates. Such fields are generally those that balance the event rate with the near-IR extinction, and for Roman are somewhat closer to the Galactic center than ground-based fields. See Figure 2. Consideration of the optimal field locations for the exoplanet yield science requirements may be at tension with the field locations preferred by the mass measurement requirement. We discuss this in the next section.

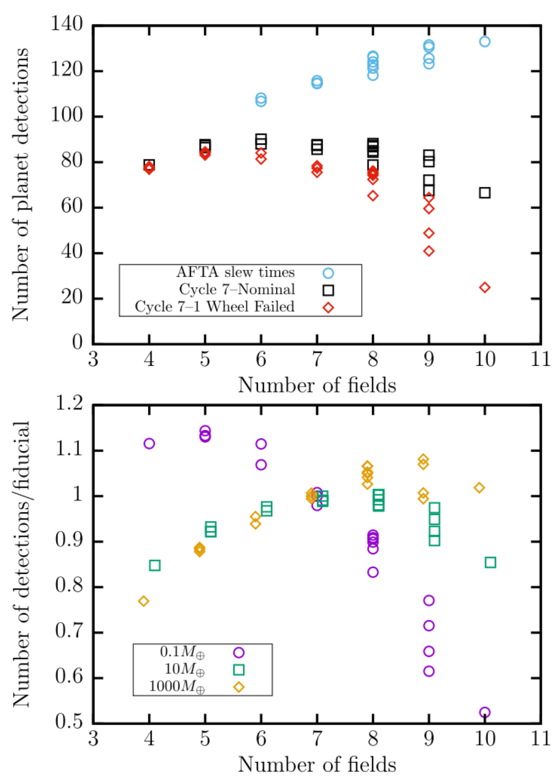

Figure 3. Top: 1 $M_\oplus$ planet yield as a function of the number of fields for simulations of the Cycle 7 design, the Cycle 7 design with a failed reaction wheel, and the overly optimistic AFTA slew times. Several possible layouts are considered for each number of fields. Bottom: planet yield relative to the adopted field layout (see Figure 2) as a function of the number of fields for the nominal Cycle 7 slew times and for 0.1, 10, and 1000 $M_\oplus$ planets. Different numbers of fields would maximize the yield for different planet masses.

Given a set of fields with locations that are ranked in order of decreasing event rate, the final parameter to be optimized is the number of fields. To an order of magnitude, the optimal number of fields is roughly that where the open-shutter time is ~50%. In detail, however, this depends on the planet mass (see Figure 3). For the Cycle 7 slew and settle times, the number of fields that optimizes the yield of $\sim M_\oplus$ planets has a soft maximum at 5-8 fields, with a weak dependance on the precise field locations. For lower-mass planets, the optimal number of fields is smaller, whereas for larger mass planets, it is larger. Once the slew-and-settle times are better constrained, the number of fields will need to be reoptimized, focusing on the yield of planets that are difficult or impossible to detect from the ground. Once the number and location of the fields are optimized, the total yield depends, to a good approximation, on the total survey duration.

We have optimized the survey parameters for the yield of $M_\oplus$ planets using the Cycle 7 observatory parameters (average slew and settle time of ~83 seconds. The resulting 7 field locations with a total area of 1.97 deg^2 are shown in Figure 2. These fields will be repeatedly and continuously monitored at 15-minute cadence in the broad (1-2 μm) W146 filter during seasons of 62 days each when the bulge is visible from Roman. Six seasons will be spread out over the five-year prime mission for a total survey duration of ~370 days. With the current best estimates of the astrophysical and observatory parameters, such a survey strategy meets the level-1 exoplanet survey science yield requirements with essentially no margin. Increasing the season length to 72 days or increasing the number of seasons to 7 would provide a 16% margin.

Survey Requirements for Meeting the Microlens Mass Science Requirement

The Roman Project had planned to work with the Microlensing Science Investigation Team (MicroSIT) to verify that the DRM could meet the exoplanet microlensing mass measurement Level 1 requirement (EML 2.0.3) in 2020. But after the COVID-19 pandemic began, the Project sought no further help from the MicroSIT on this issue before the Science Investigation Teams ended in late 2021. This is now a top priority for the yet to be selected Exoplanet Microlensing Project Infrastructure Team.

To requirements to measure the masses and distances to the host stars of microlensing events are

- Resolve unrelated stars for lens flux measurements.
    - This enables the lens-source relative proper motion to be measured and compared to light curve model predictions to verify the identification of the lens star that hosts the microlens planetary system.
    - This enables the measurement of the flux from the lens and the source, modulo the existence of flux from bound companions to the source and lens.
- Longest possible time baseline between the first and last season.
    - This improves the precision of the proper motion measurements of the lens and source, which in turn can both improve the measurement of the lens and source fluxes and help to break degeneracies and measure the mass and distance to the lens.
- Paired spring+fall fields
    - Needed to measure the parallaxes of the lenses and sources.
- Longest possible observing seasons to maximize the precision of the timescale and microlensing parallax measurements.
    - The most accurate measurement of the microlensing timescale is achieved with observations of the 'wings' of the primary event, along with a robust measurement of the time of peak magnification.

    - Microlensing parallax effects manifest themselves over the entire duration of the primary microlensing event, and thus full coverage of the event is needed to obtain the most precise parallax measurements possible.
- Periodic measurements in two or more additional filters (at lower cadence that the primary filter) to measure the colors of the lens and source.
    - This enables the measurement of the extinction to the source and the angular diameter of the source, which is needed to break degeneracies and measure the masses of the planet and host and the distance to the planetary system.
    - Observations in filters near the red and blue edges of the wide F146 are needed in order to help define the PSF models for stars of different colors to be used in the GBTDS photometry/astrometry pipeline.

Details about the methods for determining the masses and distances to Roman's planetary microlens systems, an explanation of what measurements these methods require, and a discussion of how the viability of these methods depend on the survey parameters, are provided in Appendix A.

While some of the survey parameters needed to ensure that the EML 2.0.3 Level-1 Science Requirement is met have been determined, while other have not.

- *Determined:* The aperture of Roman ensures that essentially all physically unrelated stars are resolved in the F146 filter, even in the most crowded potential target fields.
- *Determined:* The optimal placement of seasons within the 5-year prime mission is the first three available seasons and the last three available seasons, such that there are 3 fall seasons and 3 spring seasons. If additional seasons are needed to meet the survey yield requirements, or are desirable for other reasons, simulations will need to be done to optimize the choice of these additional seasons.
- *To be determined:* The length of the observing seasons needed to robustly measure the microlensing event timescale and parallax, which are needed to measurement the host and planet mass, has not been determined. Given that the median duration of microlensing events is ~40 days, it is likely that seasons that are significantly shorter than that allowed by the field-of-regard (72 days) may degrade the accuracy of the mass measurements. Intra-season observations from the ground may be beneficial; this may in turn influence the placement of the target fields, as the ground-based observations may be done in the optical, where the extinction is higher. This impact of the length of the observing seasons is discussed in more detail in the next section.
- *To be determined:* The choice and cadence of the observations in the additional filters will impact the accuracy of color measurements of the lens and source, the accuracy of lens-source proper motion measurements via color-dependent centroid shifts, and the ability to break microlensing model degeneracies. Additional discussion about the choice and cadence of additional filters, and their interdependence on the field locations, can be found in Appendix B.

In summary, additional simulations need to be performed to determine the optimal survey parameters needed to meet the EML 2.0.3 Level-1 Science Requirement. There are also few examples of mass and distance measurement attempts for events in the higher extinction parts of the provisional GBTDS fields shown in Figure 2. So this simulation effort would benefit from additional Hubble Space Telescope observations of events in these higher extinction regions. These optimal parameters may impact the overall planet yield and thus the ability to meet the other Level-1 Science requirements, and thus cannot be determined in isolation.

Importance of Cadence and Observing Season Durations

Both the duration of the GBTDS observing seasons and the observing cadence have strong impacts on the ability to characterize the exoplanet microlens systems found by Roman. Long duration observing seasons are needed for the following reasons:

- The event duration (or Einstein radius crossing time, t_E) plays an important role in determining the mass and distance to a planetary microlensing event, and events with long durations are most sensitive to planetary signals. Many planets have been discovered with $t_E > 100$ days, but Roman's GBTDS seasons are nominally limited to ≤ 72 days.
- The measurement of the microlensing parallax, π_E, due to the orbital motion of the observatory about the Sun, enables precise exoplanetary system mass measurements, even in cases where the planetary host star is too faint to detect. The precision of π_E measurements is very sensitive to the observing season duration.
- Long duration observing seasons improve the sensitivity to the detection of multi-planet systems and multiple star systems with planets.

The first few years of the Roman mission potentially provide an opportunity for observing seasons longer than 72 days. The maximum observing season duration of 72 days has been set due to the need to power the observatory when the Sun is not shining directly on the solar panels at the end of the mission. Solar panel efficiency is expected to degrade with time, so the Roman solar panels must be designed to have the capacity to power the observatory for Galactic bulge seasons longer than 72 days early in the mission. However, there are also thermal issues that must be considered before the Roman Project would approve longer early observing seasons.

Because of the importance of long duration observing seasons the Microlensing Planet Finder (MPF) mission concept (Bennett et al. 2010a), which was combined with two other mission concepts by the Astro2010 decadal survey, planned 270 day observing seasons. MPF was a much smaller telescope than Roman, with an aperture of 1.1m vs. Roman's 2.4m. This difference may have implications for the GBTDS observing cadence. The original analysis that led to the selection of the nominal 15 minute observing cadence was done for MPF.

A high observing cadence (observing each GBTDS field every 15 minutes or less) is needed.

- High cadence sampling provides more sensitivity to low-mass planets that cannot be detected by any other means. This includes planets down to sub-Earth masses in or near the outer habitable zone for solar type stars.
- The microlensing light curve signals of planets often resolve the finite angular size of the source stars, and this is quite frequently the case for the lowest mass planets. The 15-minute cadence is designed to provide adequate sampling so that the source radius crossing time, t_*, that describes the finite source effects can be measured. The source radius crossing time enables the lens-source relative proper motion, $\mu_{rel} = \theta_*/t_*$, and the angular Einstein radius, $\theta_E = \theta_* t_E/t_*$, to be determined. ($\theta_*$ is the angular source radius determined from the extinction-corrected source magnitude and color.) θ_E is needed for most exoplanet mass measurement methods, and μ_{rel} provides a means to definitively identify the planetary host stars.

The Impact of Possible Modifications to the Optimal RGES Strategy

So far, we have focused on the survey requirements needed to optimize the RGES Survey, e.g., to meet the Roman Level-1 Science Requirements EML 2.0.1-2.0.5. This was motivated by a desire to provide a set of baseline survey parameters for the Roman GBTDS from which extensions and modifications can be considered that would enable a broad range of additional science, with the understanding that "the primary requirement driving the definition of Roman's Core Community Surveys is to maximize the science performed with Roman's infrared surveys."

There are several different possible modifications of the RGES survey strategy that can be considered, each of which will have different impacts on the ability of the GBTDS to meet its Level-1 Science Requirements. These include (but are not limited to):

- Changing the total survey duration while keeping the other survey parameters (cadence, filters, field locations, or choice and duration of the survey seasons) fixed. To first order, this will only change the yield of exoplanets by an amount that is linearly proportional to the survey duration. Examples include:
    - Periodic, low-cadence observations of fields that are disjoint from the main GBTDS fields.
    - Observations that comprise a majority of one or more of the primary GBTDS seasons.
- Changing the cadence of the survey while keeping the other survey parameters fixed. Shortening the cadence would increase the yield of lower-mass planets while decreasing the yield of higher mass planets. Lengthening the cadence would impact the ability to obtain proper motion measurements through finite source effects. Examples include:
    - Decreasing or increasing the number of contiguous fields.
    - Including non-contiguous fields.
- Changing the field locations while keeping the other survey parameters fixed. The optimal field locations of the RGES survey are chosen to maximize the event rate while minimizing the impact of extinction. Shifting the fields to those with lower average microlensing event rate would decrease the yield, and vice versa. Shifting to fields with higher dust extinction could reduce the fraction of planetary microlensing events with reliable mass measurements. Secondary effects include changing the relative disk/bulge lens population and changing the signal-to-noise ratio per epoch due to the effects of greater or lesser extinction. Examples include:
    - Shifting the fields to lower Galactic latitude to have greater overlap with fields that are accessible to ground-based optical observations. This may also increase our efficiency at determining masses and distances of the planetary microlens systems, helping to meet science requirement EML 2.0.3. It would certainly increase our confidence in meeting this requirement.
- Changing the choice and cadence of the secondary filters. The impact of such trades is unclear, as simulations have not been performed that access the impact of different filter choices on the ability to meet the Level-1 science requirements. Dramatic changes from the optimal RGES design would almost certainly lead to decreased yield and/or accuracy of the mass measurements. Examples include:
    - Observations in one or more secondary filters with a cadence approaching that of the observations in the primary survey filter.
- Changing the choice of the survey seasons. The optimal choice for the survey seasons for RGES is the first three and last three seasons. A survey where the seasons are more condensed will have (to first order) the same yield, but the accuracy of the host and planet mass measurements will be degraded. Examples include:
    - A survey encompassing the first six available bulge seasons.

- Changing the duration of the survey seasons. The total yield is directly linearly proportional to the total survey duration, and thus if the total survey duration in changed to compensate for the change in the length of the observing seasons, there will be no impact on the yield. However, there is a secondary effect that shorter observing seasons will lead to poorer mass measurements, as discussed above. Examples include:
  - A GBTDS that encompasses all 10 available observing seasons, with each season lasting 43 days. Such a survey would need to share some time with the SNe surveys.

For most, but not all, of the modifications considered above, the impact of changing the survey parameters from the optimal RGES parameters can be compensated for by increasing or decreasing the total survey duration. However, the above arguments are purely qualitative, and thus detailed survey simulations are needed to address the precise impact of specific survey design choices. In addition, it is also possible to envision changing two or more of the survey parameters. The impact of such a survey strategy will also need to be determined through detailed simulations. This motivates the need for a fast, flexible, and user-friendly GBTDS survey simulator, which will presumably be developed by the Microlensing PIT.

Conclusions

Our primary conclusions are as follows:

For fixed survey duration and current estimates for the slew and settle times, most survey parameters needed to meet the yield science requirements are fairly tightly constrained, with little margin. However, if the true slew and settle times are shorter than the Cycle 7 estimates, and/or if the total survey duration is increased by increasing the length of individual seasons and/or adding additional seasons, changes in many of these parameters away from the those that are optimal for the microlensing exoplanet science can likely accommodated while still meeting the Level-1 Science requirements.

New GBTDS simulations are needed to optimize the RGES survey strategy, verify that Level 1 science requirements will be met with this strategy, and evaluate the impacts of the GBTDS observing strategy modifications that could be selected to enhance non-exoplanet microlensing science on the ability for the GBTDS to meet its Level-1 Science Requirements. These new simulations will need to include the following:

- Variations in the number and locations of the GBTDS survey fields.
- Variations in the observing cadence and exposure times in both the wide F146 filter and the narrower band filters at the red (F213) and blue (F062 or F087) edges of the F146 filter sensitivity. The precision of the source radius crossing time (t_*) measurements will be important for determining the fraction of planetary microlensing events with accurate mass and distance determinations.
- A realistic accounting microlensing of parallax (π_E) measurements with realistic measurement uncertainties, including the effects of the length of the GBTDS observing seasons.
- An investigation of the selection of either F062 or F087 as the GBTDS short wavelength filter and the trade-off between this filter selection and the optimal field locations.

The compressed timeline for the development of the GBTDS observing strategy is very challenging. Developing the optimal GBTDS observing strategy that enables the broadest possible science return will be a complicated, multi-step process that will likely require several iterations. Once the full range of viable science applications of the GBTDS is identified, simulation tools need to be developed that can evaluate the return for different GBTDS strategies for all these applications. Crucially, these simulations must adopt consistent assumptions about the observatory and data properties, as well as the properties of the Universe (e.g., star counts, Galactic structure, etc.). The application of these tools must be coordinated to identify survey strategies that optimize, to the extent possible, the full science returns. To do so, metrics will need to be developed that can be used to access the return of each science area. Finally, this process will need to be repeated as additional information becomes available, e.g., new slew and settle times.

Appendix A: Microlens Mass and Distance Measurements

A key strength of a space-based exoplanet microlensing survey is the ability of a space-based survey to determine host star and planet masses for the majority of exoplanets detected (Bennett et al. 2007). This helped persuade the Astro2010 decadal survey to include such a survey (now known as the Galactic Bulge Time Domain Survey or GBTDS) as one of two primary science drivers for the Nancy Grace Roman Space Telescope (formerly WFIRST). The Astro2010 Electromagnetic Observations from Space panel stated "Importantly, a space-based microlensing survey can determine the planetary masses and projected separations in physical units and can frequently detect the light emitted by the host star imaging to accomplish this." This capability is captured in Roman's level 1 science requirement EML 2.0.3: "RST shall be capable of determining the masses of, and distances to, host stars of 40% of the detected planets with a precision of 20% or better." A number of methods will be employed to determine the lens masses and distance. Most of these can be expressed in terms of mass-distance relations, and as displayed in Figure 4, it is often possible to have redundant methods that can confirm these measurements (Batista et al. 2015, Gaudi et al. 2008, Bennett et al. 2010b, 2015).

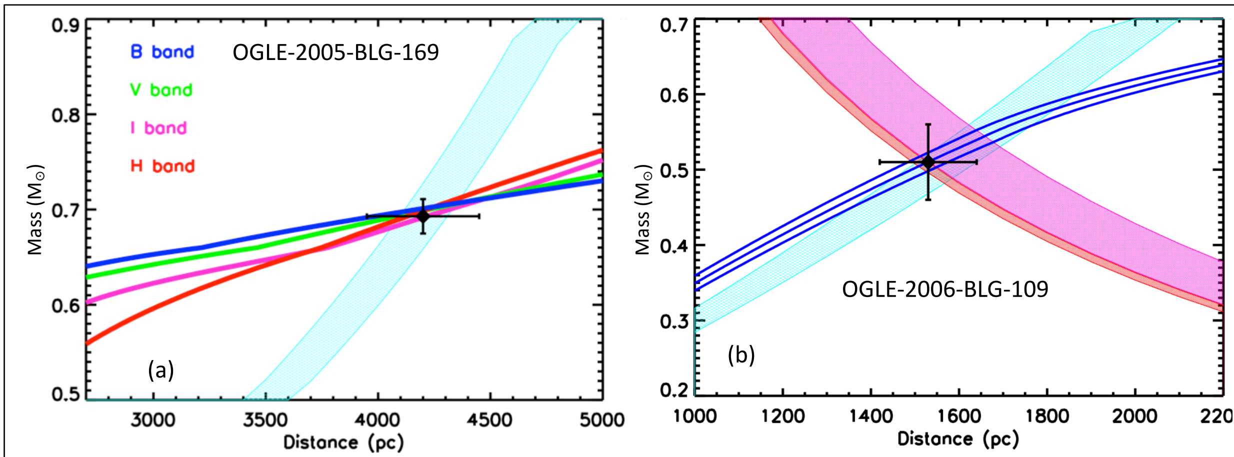

Figure 4: Mass-distance relations for 2 planetary microlens systems, (a) OGLE-2005-BLG-169, a $0.69M_\odot$ host and a planet of $14M_\oplus$ determined by a light curve angular Einstein radius (θ_E) measurement (cyan) and host star brightness measurements in the BVIH passbands, and (b) OGLE-2006-BLG-109, a $0.51M_\odot$ host with planets of $230M_\oplus$ and $86M_\oplus$ determined from a θ_E measurement (cyan), an H-band brightness measurement (blue), and a microlensing parallax (π_E) measurement (red, orange and magenta).

These methods can be used to constrain the masses and distances of the planetary microlens systems discovered by Roman:

1. Measurement of the angular Einstein radius, θ_E, indicated by the cyan shaded regions in Figure 4, can be determined from the Einstein radius and source radius crossing times, t_E and t_*, from the light curve model and the angular source radius, θ_*, which can be determined from the source magnitude and color, $\theta_E = \theta_* t_E/t_*$ (Kervella et al. 2004; Boyajian et al. 2014; Adams et al. 2018). Measurement of the lens-source relative proper motion, μ_{rel}, will also yield $\theta_E = \mu_{rel} t_E$.
2. Measurement of the extinction-corrected lens star brightness in a single passband yields a mass-distance relation when combined with a mass-luminosity relation, and measurements in multiple passbands can yield redundant constraints, as shown in Figure 4(a). Upper limits on the lens brightness can also be used to identify stellar remnant exoplanet host stars (Blackman et al. 2021) in combination with measurements of the angular Einstein radius and microlensing parallax.
3. Measurement of the amplitude of the microlensing parallax vector, π_E, from the microlensing light curve model yields a mass-distance relation as indicated by the red curve and orange and magenta shaded regions in Figure 4(b). Microlensing parallax effects are detectable due to the orbital motion of the observer or the observations from two telescopes separated by ~1 AU (for stellar mass lenses) or ~0.01 AU (for planetary mass lenses). It is often the case that only one component of the 2-dimensional $\boldsymbol{\pi}_E$ vector can be measured precisely, but a measurement of the lens-source relative proper motion vector, $\boldsymbol{\mu}_{rel}$, will provide a precise determination of $\boldsymbol{\pi}_E$ because $\boldsymbol{\pi}_E \parallel \boldsymbol{\mu}_{rel}$ (Bhattacharya et al. 2018; Bennett et al. 2020).

The measurement of the lens-source relative proper motion, $\boldsymbol{\mu}_{rel}$, is an important ingredient of the mass and distance measurement process. The length of this 2-dimensional vector is given by $\mu_{rel} = \theta_*/ t_*$, so it can be determined from the light curve models when the extinction corrected magnitude and color of the source can be determined and finite source effects are detected. (Finite source effects are found in most planetary light curve features due to low-mass planets.) The full 2-dimensional $\boldsymbol{\mu}_{rel}$ vector can be measured directly from the Roman images, which will usually be able to detect the lens-source separation a few years before or after a microlensing event. For most microlensing events detected in the Roman GBTDS images, the lens and source stars will not ever be directly resolved during the duration of the prime mission, but the lens-source separation can be measured through the color-dependence centroid-shift and image elongation methods (Bennett et al. 2006, 2007). The precision necessary to make these measurements with small lens-source separations has been demonstrated with HST imaging (Bennett et al. 2006, Dong et al. 2009, Bhattacharya et al. 2017) and confirmed with later Keck adaptive optics imaging (Bennett et al. 2020; Bhattacharya et al. 2023). The signals of these effects are time dependent, scaling as Δt and Δt^2, respectively, where Δt is the interval between the first and last observations of the lens-source system. We expect that the **GBTDS survey will need to use the first and last Galactic bulge observing seasons for Roman to meet its level-1 science requirement for exoplanet mass measurements** because of the importance relative proper motion measurements for the microlens mass and distance determinations. Furthermore, it is highly desirable that the GBTDS will include the first and last spring and fall observing seasons. The telescope orientation will rotate by 180° between seasons, and this means that the fields observed in the spring and fall will not completely overlap and that image field distortions could make astrometric comparisons between spring and fall observations more challenging.

Redundancy is needed for accurate exoplanet system mass and distance measurements. There are complications due to both astrophysical and instrumental effects that can lead to systematic errors in the determination of microlens exoplanet system masses and distances. At the time of a microlensing event, the starlight from a stellar microlens will be unresolved from the light from the source star and the starlight from the source and lens stars are likely to remain blended together for years before and after the microlensing event. However, as Koshimoto et al. (2020) investigated in detail, there is a significant probability that starlight from binary companions to the lens and/or source star or even unrelated stars can contribute also be blended with the source star.

Redundant measurements are needed to diagnose such cases. For example, Bhattacharya et al. (2017) found that the relative proper motion of a planetary lens star candidate did not match the $\mu_{\rm rel} = \theta_*/ t_*$ value determined from the light curve for planetary microlensing event MOA-2008-BLG-310. Bennett et al. (2016) found that the brightness of the host star for a planetary microlensing event did not match the prediction of the mass and distance determined from $\mu_{\rm rel}$ and $\pi_{\rm E}$ measurements unless the host was a binary system in a short period orbit. Terry et al. (2021) detected the host star system of another planetary event with K-band adaptive optics observations. Also, the light curve indicates the presence of a 3rd lens body in the system, but the light curve is equally well fit by models with a 2nd planet or a close binary companion to the host star. Observations in bluer passband are needed to distinguish these two possibilities. In contrast, multicolor measurements of OGLE-2005-BLG-169, shown in Figure 4(a) (which assumes a single host star), indicate the same host star mass, confirming the single host star interpretation.

It is possible that the accuracy of the mass and distance measurements will be compromised by systematic measurement errors. The Wide Field Instrument (WFI) of the Roman Space Telescope that will be used for the GBTDS employs 18 Teledyne 4k $\times$ 4k pixel H4RG-10 infrared detectors, which are a new design. In many respects, these detectors are an improvement over previous generations of infrared detectors, but they also have new features that may contribute to systematic photometry or astrometry errors that have not been seen if previous generations of infrared detectors. For example, a number of detectors have been found to have an increase and significant variability in the number and locations of hot pixels that is now thought to be due to contamination by Chlorine atoms that generate photoelectrons if they get trapped in crystal defects in the detectors. Other hot pixels have been classified as "blinkers" because they switch back and forth between different photoelectron emission rates on an unpredictable schedule. It is likely that methods to deal with these and other detector, as yet unknown, imperfections will have to be developed based on the data from the GBTDS survey itself.

Several of the measured light curve parameters that contribute to the mass and distance measurements are susceptible to subtle photometry errors or subtle errors in interpretation. Microlensing parallax, $\boldsymbol{\pi}_{\rm E}$, typically modifies microlensing light curves with low amplitude, long term variations, and a number of published planetary microlensing papers have reported incorrect microlensing parallax values due to systematic photometry errors (Bennett et al. 2008; Koshimoto et al. 2021) and a failure to find the correct light curve model (Udalski et al. 2015; Han et al. 2016). Such errors can be flagged by cases where redundant mass and distance measurements are not consistent with each other. Figure 4(b) shows the example of the two-planet event OGLE-2006-BLG-109 where the mass-distance relations based on $\theta_{\rm E}$, $\pi_{\rm E}$, and the host star H-band magnitude measurements all intersect at the same location in the mass-distance plane, confirming that the mass and distance determination is correct.

The situation is different for planetary microlensing OGLE-2012-BLG-0563. High angular resolution H-band images were taken using adaptive optics with the Subaru telescope before the lens star had a chance to separate from the source, and excess H-band flux corresponding to a star 0.6 mag fainter than the source was detected. Fukui et al. (2015) used this excess flux measurement and the $\theta_{\rm E}$ value from the light curve model to determine the host star mass to be $M = 0.34 M_\odot$, at a distance of ~1.3 kpc, if all of the excess flux was due to the planetary host star, but they also noted that the host could have a significantly lower mass if there was another star blended with the source and host star, such as a companion to the source or host star. They indicated that later high angular resolution follow-up observations should be able to resolve this issue of possible contamination with a star other than the source or host stars.

Keck K-band adaptive optics observations taken in 2018 were able to measure the apparent separation of the source and host stars that were blended together in a clearly elongated image. A 2-star PSF fit to this elongated image indicated a separation of only 60% of the value predicted by the microlensing light curve analysis. This suggested that a 3rd star located between the lens and source might be responsible for reducing the best fit separation for the 2-star fit. Fortunately, HST data for this event was taken in the V and I bands, and these data revealed exactly the same separation as the K-band Keck data for 2-star PSF fits. It was difficult (but perhaps not impossible) to explain this with the 3rd star model, but this suggested another possibility. Both the angular Einstein radius, $\theta_E = \theta_* t_E/t_*$, and the lens-source relative proper motion, $\mu_{rel} = \theta_*/t_*$, have the same dependence on the source radius crossing time, t_*, that is determined by light curve finite source effect. For many planetary events t_* is determined very precisely by sharp caustic crossing features in the light curve, but this event had no caustic crossings. The t_* value was determined by much more subtle cusp approach features, and it was found that systematic photometry errors in one of the one of the data sets managed to reduce the t_* value. With the suspect data set removed, the predicted host-source separation was reduced to the value determined by the 2-star PSF fits in three passbands, V, I, and K. This results now imply a host star mass of $M = 0.84M_\odot$, at a distance of ~5.4 kpc.

Of course, these examples are based on ground-based data, and we anticipate that the Roman GBTDS data will be much better in many respects. However, the systematic errors in the Roman data will need to be discovered in the Roman data itself, redundant ways to determine the masses and distances of microlens systems discovered by Roman are a vital tool for identifying and correcting such systematic errors.

We should also note that the ability of the GBTDS to meet the level-1 exoplanet mass measurement requirement has not been verified for the DRM or the version of the GBTDS presented in Penny et al. (2019) that had 72-day instead of 60-day observing seasons. There had been a plan for the Roman Project to work with the Microlensing Science Investigation Team (MicroSIT) on this starting in early 2020, but this plan was not carried out, apparently due to pandemic related disruptions.

One would hope that the soon to be selected exoplanet microlensing survey Project Infrastructure Team (PIT) could work with the Project to accomplish this. Unfortunately, the start of the PIT work has been delayed by more than a year from the expectation at the time the Science Investigation Teams were ended in November 2021. Furthermore, the Project is now asking that the PITs generate their recommendations for the details of the GBTDS by the end of 2024, instead of mid-2026, which was the expectation at the end of the MicroSIT in late 2021. This greatly compressed timeline (3.5 years compressed to slightly more than 1 year), may well have negative implications for the GBTDS science goals other than the exoplanet microlensing survey.

Appendix B: Choice of Additional Filters and Field Locations

The vast majority of the GBTDS observations are expected to be in the wide F146 filter that spans the wavelength range from 0.927—2.000μm in order to maximize the S/N. However, a lower cadence of observations in the narrower band filters is needed for a number of reasons:

- The widths of point spread functions (PSFs) in F146 images will be color dependent, depending on both the intrinsic stellar colors and the Galactic dust extinction, and the photometry/astrometry pipeline that will be used for the GBTDS observations will employ observations using filters near both the short and long wavelength boundaries of the F146 passband to help define the PSF models used by this data reduction pipeline. The long wavelength filter is very likely to be F213 (the Roman-K band), and the short wavelength filter is likely to be either F087 (the Roman-Z band) or F062 (the Roman R-band). The observations with the F146 passband can also contribute to the color measurements to help determine the PSF models, but we have no experience with such a passband, so the use of more conventional passbands lowers the risk of unexpected problems with the GBTDS data reduction pipeline.
- As described above, source star colors are needed to determine the source star angular radius, θ_*, which is used to determine the angular Einstein radius and the lens-source relative proper motion, $\mu_{\rm rel}$, which is used to help verify the identification of the lens (and planetary host) stars. The relations used to relate θ_* to the extinction corrected source star colors are empirical relations using standard passbands, based on observations of nearby stars with direct radius measurements.
- The narrower band filters contribute to the redundancy of the exoplanet system mass and distance measurements that is needed to identify host star binarity and possible systematic errors, as described in the previous section.

Galactic dust extinction plays an important role in the selection of the short wavelength filter to be used for the GBTDS. Color measurements used for the study of known exoplanet microlens systems have largely relied upon light curve observations in the V and I bands, with occasional use of the infrared H and K bands. So, the choice of F062 as the GBTDS short wavelength filter would be the best match to our current experience. Existing simulations of the exoplanet microlensing yield of the GBTDS (Penny et al. 2019; Johnson et al. 2020) have assumed the use of F087 as the short wavelength filter, but this was largely because the F062 filter (like the F213) was added to the Roman WFI filter complement relatively recently. An advantage of the F087 filter over F062 is that dust extinction would be less severe at the slightly longer wavelengths. This would likely enable the selection of GBTDS observing fields to be selected closer to the Galactic plane where the microlensing rate is higher, so that the GBTDS could discover planetary microlens systems at a higher rate. However, one drawback of using F087 as the GBTDS short wavelength filter is that the mass—distance relationship for longer wavelengths becomes nearly parallel to the θ_E mass—distance relationship for nearby lens systems with host stars with mass $\leq 0.5\,M_\odot$. This is evident with the nearly parallel blue (H-band lens magnitude) and cyan (θ_E) mass—distance relations in the lower, left portion of Figure 4(b). On the other hand, nearby lens systems are the ones most likely to yield microlensing parallax (π_E) signals that could compensate for this difficulty. Detailed GBTDS simulations that include all the details needed for exoplanet system mass and distance determinations are need to investigate this issue.

The locations of the provisional GBTDS fields described in the DRM is based on simulations using rather conservative estimates for the Roman spacecraft slew and settle times, and a Galactic model and dust extinction map that have been improved significantly since these provisional GBTDS fields were selected. New simulation code that implements these improvements has been developed. Also, the selection of the GBTDS fields presented in Penny et al. (2019) that were used for the DRM was based criteria that did not include all the science requirements for Roman's exoplanet microlensing survey. In particular, the yield of exoplanet and host star mass measurements was not included in these simulations. New GBTDS simulations are needed to optimize the survey strategy and verify that Level 1 science requirements will be met.

The compressed timeline for the development of the GBTDS observing strategy is very challenging. When Roman's Science Investigation Teams ended in November 2021, it was anticipated that the next iteration of Roman science teams would begin in less than a year, but this selection has been delayed by about a year. In addition, the deadline for detailed observing strategy recommendations now appears to have been advanced from mid-2026 to the end of 2024. The rationale for this change is to make it easier to design general investigator proposals for science beyond the exoplanet microlensing science to be accomplished. However, this change seems more likely to harm, rather than enhance general investigator science.

Our experience to date with mass and distance determinations for exoplanetary microlens systems has been based on events detected with ground-based microlensing surveys using the I-band for most observations, with lower cadence V-band observations to obtain color information. We have little existing data to investigate how the situation would change if we were observing higher extinction fields using a filter like F087 as the shortest wavelength passband. The one example of a planet discovered with an infrared microlensing survey (Shvartzvald et al. 2018) indicates a dramatic failure of mass determination methods, as both the distance to the source star and its extinction corrected color cannot be determined, but this is in a field has dust extinction that is much higher than is likely to be considered for the GBTDS.

To ensure that the GBTDS will meet its exoplanet microlensing level-1 science requirements in the compressed timeline, it is likely that conservative choices for a survey strategy that is not too far from the experience with planetary microlensing events will be favored. This would mean using F062 as the GBTDS short wavelength filter and limiting the GBTDS fields to those with relatively modest dust extinction. The downside of this is that these fields have somewhat lower event rates. Hopefully, these lower event rates can be at least partially compensated by improvements in the telescope slew and settle times over the assumptions used in previous simulations. However, the lower event rates would almost certainly limit the variations from the optimal exoplanet microlensing observing strategy that can be made to enable better non-exoplanet microlensing science. In fact, it is possible, perhaps even likely, that more observing time for the GBTDS than allocated in the DRM will be needed to ensure that Roman's level-1 science requirements will be met.

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