Roman CCS White Paper

Contiguity is Key: The length of the Roman Galactic Bulge Time Domain Survey seasons should be maximized

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

Scientific Categories: *exoplanets and exoplanet formation; stellar physics and stellar types; stellar populations and the interstellar medium*

Additional scientific keywords: gravitational microlensing; exoplanet transits; asteroseismology

Submitting Author:
Name: Matthew Penny
Affiliation: Louisiana State University
Email: penny1@lsu.edu

List of contributing authors (including affiliation and email): N/A

Abstract

The Roman Galactic Bulge Time Domain Survey (GBTDS) aims to study the demographics of cold exoplanets by observing microlensing events caused by bound and free-floating planets. The short duration of the planetary signatures has contributed to driving requirements on Roman's survey speed to enable high cadence observations over a wide field. Conversely, the typically months long duration of the microlensing events of host stars has driven the requirement that Roman be able to observe fields near the ecliptic plane continuously for at least 60 days (Baseline and Threshold Science Requirements 4). Here we argue that the duration of GBTDS observing seasons be maximized to as far beyond 60 days as allowed by safety limits on the mission hardware, which based on design goals is likely to be ~72 days or more. At fixed total GBTDS survey time, this will increase the fraction of microlensing planets with mass and distance measurements, increase the number of multi-planet microlensing detections, increase the range of periods for which transiting planets can be detected without period ambiguity, and improve asteroseismic measurements.

Introduction

The primary goal of the Roman GBTDS is to measure the demographics of cold exoplanets by detecting them in microlensing lightcurves and measuring their masses and distances with the Roman survey data. The microlensing lightcurve will typically yield the mass ratio of a planet to its star, and the ratio of projected separation of the planet from its star to the radius of Einstein ring. As the planet host stars will typically range in mass from ~0.1–1 M_{Sun}, without a mass measurement, the properties of a planet are uncertain to an order of magnitude. Measuring the mass of the planet and its host are critically important for interpreting the planet population with clarity, and for understanding how host mass affects the occurrence rate of cold planets. In microlensing, a mass measurement also yields a distance measurement to the lens/planet host, enabling the measurement of Galactic exoplanet demographics over different stellar populations.

The mass and distance of a microlens can be determined in two principal ways: by detecting parallax and finite source effects in the microlensing lightcurve, or by detecting the light of a luminous lens separated from the source either before or after the microlensing event. We will show how, for both methods, the duration of Roman's GBTDS seasons will impact mass and distance measurements through measurements of the microlens timescale t_E, the time taken for the microlensed source to move by 1 Einstein radius.

From a single observatory, microlens parallax is detected via the impact of the observatory's orbital acceleration on the apparent path of the microlensed source through the magnification pattern of the lens. It appears as a subtle modulation to the lightcurve that is maximized approximately 1 t_E from the peak of the event in each wing of the lightcurve due to the competing effects of a lengthening time baseline over which acceleration away from rectilinear motion can act versus a decline in the magnification gradient encountered by the source further away from the lens. (Bachelet & Penny 2019) found that Roman's photometric precision was sufficient to enable orbital parallax measurements and useful upper limits for a many of Roman's microlensing events.

Finite source effects are used to estimate the angular Einstein ring radius θ_E. Doing so involves equating two ratios

$$\frac{\theta_*}{\theta_E} = \frac{t_*}{t_E},$$

where θ_* is the angular source radius, estimated from the color and brightness of the source star, and t_* is the time taken for the source to cross its radius, which is estimated from the finite source effects in the microlensing magnification. Rearranging the equation yields θ_E in terms of three observables, with t_E being one of them. Measurements of both parallax and finite source effects will therefore be affected by the duration of the GBTDS seasons.

The second method for estimating masses constructs two relationships between the mass and distance of the lens and solves for mass and distance where they intersect. The first mass-distance relation is derived from the observed brightness of the lens using a mass-luminosity relation or an isochrone. The second mass-distance relation uses the relative proper motion between lens and source μ_{rel}, estimated from their separation some time before or after the microlensing event, and the microlens timescale, to infer $\theta_E = \mu_{rel} t_E$, which means that again the microlensing timescale enters the mass and distance estimate.

The Quantitative Impact of Shorter Seasons on Cold Exoplanet Demographics

For this white paper we have conducted simulations of the same Roman survey as simulated by (Penny et al. 2019), i.e., six 72-day seasons, and also simulated the same events observed with six 62-day seasons and six 50-day seasons, centered on the same times. We have used the same gulls simulator as (Penny et al. 2019) to simulate single stellar lenses and compute detection rates and measurement uncertainties on microlensing parameters using the Fisher matrix. We estimated the statistics of the change in measurement uncertainties for the microlens timescale t_E, which impacts all mass measurements, for the source flux fraction f_s, which impacts estimation of θ_* and θ_E, and the two components[1] of microlens parallax $\pi_{E,N}$ and $\pi_{E,E}$. For t_E and f_s we considered how the uncertainty would change only for events where the quantity was measured with a fractional error of at least 3σ in a 72-d season simulation. For parallax, we considered events where either component was measured to a fractional precision of 3σ or both components were measured with an absolute precision of 0.1 or better. Propagation of these errors to masses and distances is complicated for both methods due to intermediate steps in each, but in both cases, it is possible for one or more of the lightcurve parameters to be the dominant source of uncertainty.

The results are shown in the table and the figure. The results of the simulations are rich and challenging to summarize, but the median uncertainty on all parameters (except possibly f_s) appear to scale roughly as the inverse square of the season duration, though for a significant fraction of events the increase in uncertainty is much more dramatic even reducing the season duration from 72 to 62 days. If we are concerned with the number of mass measurements made, rather than the exact size of their uncertainties, then the fraction of mass measurements lost by shortening a season increases faster than the rate of decrease of the season length. This latter result implies that if time were shaved off individual seasons and added to create a new season, the loss due to the shortening of the season would be worse than the gain of new events by nearly 50% more. We can extrapolate the result in the opposite direction as well, and infer that even longer seasons than 72 days, should they be possible, would provide even greater benefits for mass measurements.

There are a number of caveats to the above analysis. First, it is of a limited simulation conducted for a small area of the bulge, less than the GBTDS area, and with a limited number of events; in particular the parallax estimates are affected by small number statistics. The analysis was performed for single-lens microlensing events rather than planetary microlensing events. While planetary microlensing events have more parameters to fit with the same number of data points, the typically the more complex lightcurve shape caused by caustic structures can provide information to break or constrain some of the degeneracies that affect the smooth, symmetric single lens, and make it easier to measure parallax, t_E, and f_s. Understanding how the additional complexities of planetary microlensing impact the degradation of mass measurement precision with shorter GBTDS seasons will require significantly larger and more computationally expensive simulations in order to properly sample the range of planetary parameter space and lightcurve

---

[1] Microlens parallax is a dimensionless 2-d vector quantity whose magnitude depends on mass and distance, and whose direction is set by the relative proper motion vector between the lens and source.

variety. However, we can assume that due to the similar physics, the approximate scaling relations we have found here are a reasonable expectation for planetary events as well.

Impact on Secondary GBTDS Goals

The length of GBTDS seasons will also affect the other time-domain science that can be conducted with the GBTDS data. The location of planets in a microlensing lightcurve is set by their projected orbital position, so longer coverage of each individual event will maximize the chances of detecting multiple planets. Longer seasons will allow more transiting planets to show two or more transits in a season, and thus will have no period ambiguity. Longer seasons will also produce a cleaner window function for asteroseismology measurements (e.g., (Stello et al. 2022)), enabling frequency of maximum power and mode separations for stars with a wider range of stellar properties.

Summary

One of the key drivers of the Roman GBTDS is to measure masses of planets found via microlensing. We show that, for single lens microlensing events, the uncertainties of microlensing lightcurve parameters that enter into mass determinations scale inversely superlinearly with the season duration. Assuming a similar scaling applies to planetary microlensing events, this implies that the duration of GBTDS seasons should be maximized.

References

Bachelet, E., & Penny, M. 2019, The Astrophysical Journal, 880 (American Astronomical Society), L32

Penny, M. T., Gaudi, B. S., Kerins, E., et al. 2019, The Astrophysical Journal Supplement Series, 241

Stello, D., Saunders, N., Grunblatt, S., et al. 2022, Monthly Notices of the Royal Astronomical Society, 512 (Oxford University Press), 1677

Figures & Tables

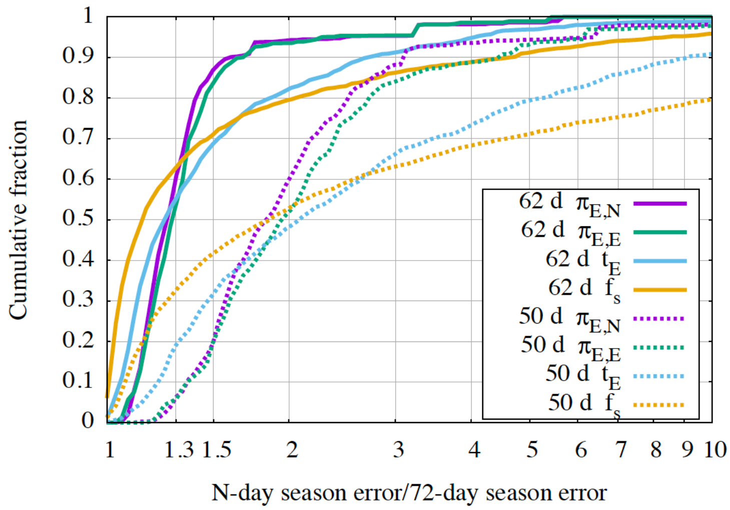

Figure 1. Cumulative distribution of the ratio of uncertainties for microlensing event parameters when observed by Roman in a shorter season versus a 72-day season. Note the x-axis is a log scale. Results are shown for 62- and 50-day seasons. The fractional increase in uncertainty is typically larger than the fractional decrease in season duration. Purple, green, blue, and gold lines show the distributions for the lightcurve parameters $\pi_{E,N}$, $\pi_{E,E}$, t_E, and f_s, respectively. Solid lines show the ratio of uncertainties from 62-day versus 72-day seasons and dashed lines show the ratio of uncertainties from 50-day versus 72-day seasons.

Table 1: Summary statistics for the change in uncertainty distribution

Parameter	Median uncertainty increase	80th percentile uncertainty increase	Fraction of significant measurements lost
72 d → 62 d	Season duration reduction: -14%		
t_E	~1.24x	~1.8x	~20%
f_s	~1.15x	~2.0x	~17%
$\pi_{E,N}$	~1.3x	~1.4x	~23%
$\pi_{E,E}$	~1.3x	~1.5x	
72 d → 50 d	Season duration reduction: -31%		
t_E	~2.1x	~5x	~44%
f_s	~1.8x	~10x	~37%
$\pi_{E,N}$	~1.8x	~2.5x	~42%
$\pi_{E,E}$	~1.9x	~3x	