Design of the Roman Galactic Exoplanet Survey (RGES)

Matthew Penny
Louisiana State University

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Overview

- RGES Survey Requirements & Motivation
- Microlensing Surveys Order of Magnitude

More in depth version of this talk at:
https://www.youtube.com/watch?v=5dn7QEviU74&list=PLIbTYGsIVYthWRS14eCEK8SK9IO7cYsf&index=15
1. Measure the mass function of cold exoplanets with masses \( > 1 \, M_{\text{Earth}} \) and semimajor axes \( \geq 1 \, \text{AU} \) to better than \( \sim 10\% \) per decade*.

2. Measure the frequency of Mars-mass embryos to \( \sim 15\% \).

3. Measure the frequency of free floating planetary-mass objects in the Galaxy over nearly six orders of magnitude in mass. If there is one \( M_{\text{Earth}} \) free-floating planet per star, measure this frequency to \( \sim 20\% \).

4. Estimate the mass and distance to the host stars and planets to better than \( \sim 20\% \) for the majority of the detected systems.

5. Estimate \( n_{\text{Earth}} \) via extrapolation from larger and longer-period planets.

*Assumes a fiducial mass function.
Failed Cores?

- Only a sub-dominant fraction of systems have gas giant planets
- A Larger Fraction host super-Earths/mini-Neptunes, but only ~1/2
- Planet formation is ubiquitous, so could the remainder of systems be teeming with planetary cores that failed to grow?
Roman’s Mass Measurements

Combination of large numbers of detections, plus accurate physical parameters can yield spectacular clarity

Howard+2011

High-accuracy $R_*$

Fulton+2017

Suzuki+2016

Chambers 2018
Completing the Census of Exoplanets

Penny et al. (2018) submitted


Planet Mass in Earth Masses

Semimajor Axis in AU

Kepler

Simulated WFIRST Exoplanets

Other Known Exoplanets

Kepler Exoplanets

WFIRST Sensitivity [log scale]
Predicted *Roman* Mass Function

\[
\frac{d^2 N}{d(M_p/M_\oplus) d(a/AU)} \text{ [dex}^{-2}] = \frac{1}{C} \exp\left(-\frac{M_p/M_\oplus}{V}\right)
\]

- Shvartzvald et al. (2016)
- Fiducial mass function
- Clanton & Gaudi (2016)
- Suzuki et al. (2016)
- *WFIRST* mock
Back of the Envelope Survey

• Goal: 10% precision requires detecting ~100 Earths
Back of the Envelope Survey

- Goal: Detect ~100 Earths
- Detection Efficiency: 0.01* (Bennett & Rhie 1998) *with continuous observations

Back of the Envelope Survey

- **Goal:** Detect ~100 Earths
- **Detection Efficiency:** 0.01 (Bennett & Rhie 1996)
  - \(\rightarrow\) ~10,000 microlensing events
- **Event rates:**
Event rate $\Gamma$

$\Gamma = \text{Area swept out by all Einstein rings per year} \times \text{Source stars per deg}^2$

$\sim \text{mas} \times 5 \text{ mas/year} \times (10^8 \text{ lenses}) \times (10^6-10^8 \text{ sources/deg}^2) \sim 40-4000 \text{ / deg}^2 \text{/year}$

Event rate per star $\sim \text{few} \times 10^{-5}$
Back of the Envelope Survey

- Goal: Detect ~100 Earths
- Detection Efficiency: 0.01 (Bennett & Rhie 1996)
  → ~10,000 microlensing events
- Event rates: $5 \times 10^{-5}$ per star per year
  → Monitor 200 million star years
Back of the Envelope Survey

- 200 million star years
  - Ground based imaging (e.g., OGLE)
    - 5 million stars / deg$^2$ (detected)
    - 1.4 deg$^2$ imager
    - 28 fields for 1 year, 3 fields for 10 years
      - For continuous observations (24 hrs/day, 365 days/year)
    - 500 fields for 1 year, 18 fields for 10 years
      - ~Accounting for seasons and night/day cycles
Space-based survey

- 2.4m telescope @ 1.5 um
- ~0.15” FWHM
- ~1/50 arcsec$^2$ disk
- ~100m stars/deg$^2$= 6 /arcsec$^2$

$\Rightarrow$ Need ~2 deg$^2$ years
Back of the Envelope Survey

- Observational Timescales:

  - Planets around stars

<table>
<thead>
<tr>
<th>Lens Type</th>
<th>$M_\ell [M_\odot]$</th>
<th>$D_\ell [\text{kpc}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Black hole</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>C Dwarf</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>M Dwarf</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>M Dwarf</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Brown Dwarf</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Neptune</td>
<td>$3 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>$3 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>$3 \times 10^{-7}$</td>
<td></td>
</tr>
</tbody>
</table>
Back of the Envelope Survey

- Observational Timescales:
  - Source diameter crossing time

<table>
<thead>
<tr>
<th>Radius ($R_{\text{sun}}$)</th>
<th>Diameter crossing time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (Red giant)</td>
<td>22</td>
</tr>
<tr>
<td>1 (G dwarf)</td>
<td>2.2</td>
</tr>
<tr>
<td>0.3 (M dwarf)</td>
<td>0.7</td>
</tr>
</tbody>
</table>

- Need <~15 minute cadence
$M = 2.02M_{\text{Moon}} \quad a = 5.20 \text{ AU} \quad M_\star = 0.29M_\odot \quad \Delta \chi^2 = 710$

$W149$

$Z087$

$W149$ magnitude

Time (days) 0 hr 2 4 6 8 10 12 14 16 18 20

21.55

21.6

21.65

21.7

21.75

21.8

21.85

22

22.2

22.25

22.3

22.35

Penny+2019
Roman RGES

- 2.4 m mirror
- 0.9-2.4 um IR detectors
- 18 4k x 4k H4RGs
- 0.28 deg$^2$ FoV
- 7-9 fields (2-2.6 deg$^2$)
- 15 min cadence
- 0.16” FWHM, 0.11” pix
- 5 year mission,
  ~1 year microlensing
WFIRST Microlensing Masses

Bennett, Anderson & Gaudi (2007)

- After a few years, lens and source star may separate enough to be partially resolved
- Measurements of the lens-source separation and lens flux can be used to solve for the mass and distance to the lens
- Assumes no luminous companions or interloping stars
- Roman requires 20% masses for >50% of events
- Need observations over maximum (~5 year) baseline

e.g., OGLE-2005-BLG-169 (Gould+06)
HST imaging in 2011 (Bennett+15)
Roman: ~1400 cold exoplanets

Penny et al. (2018) submitted

Predicted *Roman* Mass Function

\[ \frac{d^2N}{d(M_p/M_\oplus)d(a/AU)} \text{ [dex}^{-2}] \]

- Shvartzvald et al. (2016)
- Fiducial mass function
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\[ \log(M_p/M_\oplus) \]
Conclusions

• RGES survey designed to collect large statistical sample of cold exoplanets, comparable to Kepler. This is needed to detect fine features in the cold exoplanet mass function that could be signatures of planet formation.

• Survey design driven by requirements to detect and characterize short duration planetary anomalies that occur unpredictably (cadence), the maximum microlensing event rate in the Galaxy (duration), and the need to watch lens and source separate over time (baseline).
Backup slides
WFIRST Microlensing Masses

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Essential Reading: Bennett, Anderson & Gaudi (2007)
WFIRST’s Seasons

- Solar panels restrict range of Sun-spacecraft angle to ~72 deg range
- Can observe bulge for 72 days twice a year
- $6 \times 72 = 432$ days =
Back of the Envelope Survey

• 200 million star years
  - Ground based imaging (e.g., OGLE)
    • 5 million stars / deg$^2$ (detected)
    • 1.4 deg$^2$ imager
    • 15 minute cadence (~2 minutes for exposure + overhead)
    • Need 500 fields for 1 year, 18 fields for 10 years
    • Max 7 fields at necessary cadence
OGLE-IV fields

Credit: K. Ulaczyk, J. Skowron
Limitations of the Ground

- Mass ratio of Earth (for 0.3 Msun) = $10^{-5}$
- OGLE-IV running 6 years, no planets with mass ratio less than few~$10^{-5}$
- Expected: $4 \text{ deg}^2 \times 6 \text{ years} \rightarrow 6 \text{ Earths}$
  - But, calculation was likely optimistic

- KMTNet increases area (12 vs 4 deg$^2$) and time coverage (3 vs 1 site)
  - Expect ~20 Earths in 10 years under same assumptions
Stellar Density

\[ \log(\frac{dN}{dF_{814W}}) \text{ [deg}^{-2} \text{mag}^{-1}] \]

\[ N(<F_{814W}) \text{ [deg}^{-2}] \]

- Ground
- HST
- Besançon model
- OGLE
- Cumulative

\[ F_{814W_{\text{Vega}}} \]
Crowded Fields

- Ground:
  - ~1” seeing
  - ~1 arcsec$^2$ seeing disk
  - 5 million stars/deg$^2$
  - = 0.4 stars/arcsec$^2$
Crowded Fields

- **Space:**
  - 1m telescope @ 1um
  - ~0.25” FWHM
  - ~1/16 arcsec² disk
  - 80 million stars/deg²
  - = 6 stars/arcsec²
Crowded Fields
Space-based survey

- >= 1 m telescope
- 200 million stars → ~2.5 deg$^2$
- 15 minute cadence, ~2 min/field
- → 0.36 deg$^2$ Field of View
- 1 year survey (total time)

- 200 million stars → 10000 events → 100 Earths
Microlensing in the Habitable Zone

- Transits most sensitive to HZ of low-mass hosts
- Microlensing most sensitive to HZ of high-mass hosts
  - but how sensitive?

\[
\frac{a_{\text{HZ}}}{r_E} \approx 0.3 \begin{cases} 
M^{1.5} & M \lesssim 1M_\odot \\
M^{1.75} & M \gtrsim 1M_\odot 
\end{cases}
\]
Habitable Zone planets

\[ M = 0.94M_\oplus \quad a = 1.46 \text{ AU} \quad M_* = 0.95M_\oplus \quad \Delta \chi^2 = 939 \]