Detection of Terrestrial Extra-Solar Planets via Gravitational Microlensing

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Talk Outline

• What do we need to know to determine the abundance of Earth-like planets?
  – What does Earth-like mean?

• The basics of microlensing

• Microlensing Planet Search Mission Design
  – The proposed GEST mission as an example

• The Scientific Return
  – Simulated planetary light curves
  – planet detection sensitivity
  – Lens star detection
  – What we learn from the planets that are detected

• Why is a Space mission needed for microlensing?
  – Resolve main sequence stars
  – continuous coverage
A Definitive list of Requirements for a habitable or Earth-like planet

- A 1 $M_\oplus$ planet at 1 AU orbiting a G-star?
- How about a 1 $M_\oplus$ planet at 1.5 or 2 AU?
  - with a greenhouse atmosphere
- Is a gas giant at 5 or 10 AU needed, as well?
- Are planets orbiting M-stars more or less habitable than those orbiting G-stars?
- Moons of giant stars?
- Is a large moon important for the development of life?
- Is it possible that life could be based upon NH$_3$ instead of H$_2$O?
- ...
- It seems prudent to design a exoplanet search program that reveals the basic properties of planetary systems rather than focusing too closely on current ideas on habitability.
The Physics of \( \mu \)-lensing

- Foreground “lens” star + planet bend light of “source” star
- Multiple distorted images
  - Total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Peak sensitivity is at 2-3 AU: the Einstein ring radius
Microlensing Rates are Highest Towards the Galactic Bulge

High density of source and lens stars is required.
Mission Design

- ≥ 1m telescope
  - 3 mirror anastigmat
- ~2 sq. deg. FOV
- shutter for camera
- 0.2”/pixel => 6×10^8 pixels
- continuous view of Galactic bulge
  - for 8 months per year
  - 60 degree Sun avoidance
  - 1200km polar or high Earth Orbit
- Images downloaded every 10 minutes
  - 5 Mbits/sec mean data rate
- <0.03” pointing stability
  - maintained >95% of the time

Polar Orbit for GEST MIDEX proposal

Galactic Exoplanet Survey Telescope
Wide FOV CCD Camera

Bulge stars are highly reddened, so Lincoln or LBL IR optimized CCDs improve sensitivity. IR detector arrays might be even better.

**GEST shutter concept – no single point failure mode.**

Focal Plane layout: 32 Labs 3k × 6k CCDs, 10µm pixels; 600 Mpix total
Simulated Planetary Light Curves

- Planetary signals can be very strong
- There are a variety of light curve features to indicate the planetary mass ratio and separation
- Exposures every 10 minutes

\[ M_{\text{lens}} = 0.69M_\oplus \quad M_{\text{planet}} = 0.7M_\oplus \quad M_{\text{moon}} = 0.02M_\oplus \]

\[ \Delta I_{\text{lens}} = -0.1 \quad a = 5 \text{AU} \]
Low S/N visible G-star lenses with typical S/N
Planet Detection Sensitivity Comparison

- most sensitive technique for \( a \geq 1 \text{ AU} \)
  - \( \mu \)-lensing + Kepler gives abundance of Earths at all distances
- "habitable" planets in Mars-like orbits
- Mass sensitivity is \( 1000 \times \) better than \( v_r \)
- Assumes \( 12.5\sigma \) detection threshold
- Sensitivity to all Solar System-like planets
  - Except for Mercury & Pluto

![Exoplanet Discovery Potential Graph](image-url)
Lens Star Identification

- Flat distribution in mass
  - assuming planet mass $\propto$ star mass
- 33% are "visible"
  - within 2 I-mag of source
  - not blended w/ brighter star
  - Solar type (F, G or K) stars are "visible"
- 20% are white, brown dwarfs (not shown)
- Visible lens stars allow determination of stellar type and relative lens-source proper motion
For faint lens stars, separation determination yields a to factor-of-2 accuracy, but the brightest \( \sim 30\% \) of lens stars are detectable. For these stars, we can determine the stellar type and semi-major axis to \( \sim 10\%-20\% \).
Microlensing From the Ground vs. Space

- Target main sequence stars are not resolved from the ground.
- Lens stars cannot be identified from the ground
  - Lens-source proper motion can’t be measured
- Ground surveys can only find events with $a \approx R_E$
  - No measurement of planetary abundance vs. semi-major axis
Simulations use real VLT seeing and cloud data, and realistic sky brightness estimates for the bulge. The lightcurve deviations of detectable $\sim 1 \, M_\oplus$ planets have durations of $\sim 1$ day, so full deviation shapes are not measured from a single observing site - except for unusually short events.
Predicted Ground-Based Results for Terrestrial Planets

**Planet Discoveries**
- 12.5σ detection threshold
- “deviation” region varies by 0.3% or more from stellar lens curve
  - includes “baseline”
- require ≥ 80% of deviation region measured
- Assumes 4 year bulge surveys from LSST & VISTA - very optimistic!
- Lens stars not detected
- Little sensitivity to separation

**Cheap ground based programs are sensitive to “failed Jupiters”**
Space-Based Microlensing
Planetary Results

- Planets detected rapidly - even in ~20 year orbits
- average number of planets per star down to $M_{\text{mars}} = 0.1M_\oplus$
  - Separation, $a$, is known to a factor of 2.
- planetary mass function, $f(\varepsilon=M_{\text{planet}}/M_*, a)$
- for $0.3M_{\text{sun}} \leq M_* \leq 1M_{\text{sun}}$
  - planetary abundance as a function of $M_*$ and distance
  - planetary abundance as a function of separation (known to ~10%)
- abundance of free-floating planets down to $M_{\text{mars}}$
- the ratio of free-floating planets to bound planets.
- Abundance of planet pairs
  - high fraction of pairs => near circular orbits
- Abundance of large moons (?)
- ~50,000 giant planet transits
Space-Based Microlensing Summary

- Straight-forward technique with existing technology
- Low cost – MIDEX level or possible shared mission
- Low-mass planets detected with strong signals
- Sensitive to planetary mass
- Sensitive to a wide range of separations
  - Venus-Neptune
  - Combination with Kepler gives planetary abundance at all separations
- Should be done!