Robotic Microlensing Follow-up

Rachel Street

- Discovery and follow-up of microlensing events
- Robotic pros and cons
- Robotic approaches
- Robotic Projects

Sagan Workshop 2011
Requirements for Microlensing Planet Detection

Lensing events require precise alignment
- Rare
- Large sample of stars (e.g., Galactic Bulge)
- Crowded fields, mag range $I \sim 12-20$ mag

→ Ultra-wide-field instrument
  - $<1$ arcsec pixel scale
  - $\sim 1$ m telescope

→ Non-repeating – must get data now!
Requirements for Microlensing Planet Detection

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  - Ultra-wide-field instrument
    <1 arcsec pixel scale
    ~1m telescope
  - Non-repeating – must get data now!
- Timescale $\tau \geq$ days - months, some with fast (mins) variations (anomalies)
  - Dedicated facilities
  - Cadence several visits/field/night

Facilities uncommon, existing surveys single-site
Survey Coverage

- Single ground-based observatory can observe for ~6-12 hrs / night

- No single ground-based survey can continuously monitor lensing events (except polar)

- Survey fields overlap in some places ...non-continuous coverage for much of the season

- Weather losses/technical downtime

  → Follow-up network
Global Microlensing Follow-Up Network

- 100s of microlensing events detected in Galactic Bulge each year by MOA, OGLE
- Online alerts of new events and anomalies

**But...**
- Must select events of interest
- Real time response imperative
- Modeling binary events non-trivial and mostly not automated
- Coordinated response required
Robotic Microlensing Follow-Up

Pros:
- Fast response
- Efficient use of telescope time
- Fast coordination of networked observations
- Cheaper $\rightarrow$ more telescopes being built/converted to automated operation
- Quicker robotic data handling (used by all teams)
- Algorithmic response easier to determine observational biases
Robotic Microlensing Follow-Up

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**Cons:**
- Rely on algorithm to decide what's interesting
- Modeling binary lensing events non-linear, large parameter space problem
- Robust automation non-trivial
Determining Planet Frequency

- Large sample of stars should provide statistically significant sample of planet detections...or non-detections

→ Planet frequency beyond the snowline, down to Earth-mass objects & smaller
→ Test planet formation theories
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- **Problem: survey biases**
  → Planet detection/exclusion requires continuous coverage around the peak
  → Follow only a few events continuously
  → Prioritized by human decisions
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- **Two solutions:**
  → Follow everything:
    Ground-based survey network, KMTNet
    Space-based WFIRST, Euclid
  
  → Remove the human decision-making
Microlensing Follow-Up Sequence

Surveys issue online alerts of events in progress

Examine all known events, decide priorities

Recommend current targets per telescope

Telescopes observe targets

Image data reduced quickly

Photometry combined with existing data from all other observers

Event re-modelled, anomalies detected

Observing recommendations updated
Prioritizing Events

- Estimate gain factor from return vs. investment
- Return is the planet detection probability, function of current magnification
- Investment = $t_{\text{obs}} / dt$

Greyscale map:
White low Delta chi$^2$, black high (detection zones)

Example case:
$q = 1 \times 10^{-3}$
$A_{\text{max}} = 5$
Uniformly space datapoints
Delta chi$^2_{\text{thresh}} > 25$

Dominik et al. (2010) AN, 331, 671
Prioritizing Events

- Estimate gain factor from return vs. investment
- Return is the planet detection probability, a function of current magnification
- Investment = \( \frac{t_{\text{obs}}}{dt} \)

Sampling interval \( dt \) depends on magnification

Required exposure determined from S/N required, telescope aperture, current target brightness, observing conditions

- Targets prioritized dynamically according to gain

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**Chi-squared Map of Lensing region**

Greyscale map:
White low Delta \( \chi^2 \), black high (detection zones)

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\( A_{\text{max}} = 5 \)
Uniformly space datapoints
Delta \( \chi^2_{\text{thresh}} \) > 25

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**Online Resources**

**WebPLOP**

robonet.lcogt.net

- Online event archive and prioritizer
- Available to any observer, configurable for any telescope
- Robotically queried by RoboNet system
- Subscribes to ARTEMiS;
  can receive recommendations from humans
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**ARTEMiS**

www.artemis-uk.org

- SIGNALMEN flags suspected (check) or confirmed (anomaly) ongoing anomalies
- Recommends obs cadence / event
- Event modeling + data visualization facilities
Microlensing Follow-Up Sequence

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Examine all known events, decide priorities

*Recommend current targets per telescope*

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Event re-modeled, anomalies detected

Observing recommendations updated
ObsControl

- General-purpose software designed to run observing program with multiple targets and a dynamic target list on any number of telescopes/instruments

- Queries webPLOP for current target priorities (updated ~30min)
  Submits observing requests to telescopes
  Handles incoming data

- Human interface:
  → Allows humans to request observations also (operators subscribe to wider global follow-up teams and coordinate with them)
  → Allows Target of Opportunity overrides for urgent targets
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RoboNet-II Pipeline Status

- Last updated: 2011-06-02 21:46:06 UT

For help interpreting this page, please look here

Status of pipeline codes running under the crontab:

- pipemonitor.py Operational. Running every 10min
- dicontrl.py Operational. Running every 5min
- eventmonKorg.py Operational. Running every 5min

Pipeline Config

Instructions on how to modify the selection of event data to be processed can be found under the Pipeline Operations Help

Currently processing data for ALL events

Ongoing Reduction Processes

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</tbody>
</table>

Reduction Status for all events
### Fully robotic DIA pipeline

- Fully automated data-reduction pipeline
- Auto-target identification
- Serves updated lightcurves to world community via website/upload.
Fully robotic DIA pipeline

- Fully automated data-reduction pipeline
- Auto-target identification
- Serves updated lightcurves to world community via website/upload.
- Online facilities allow global collaborators to interact with data reductions running on LCOGT Cluster.
Robotic Observing Programs

RoboNet
- Fully automated observing system
- Human interactivity optional
- Non-dedicated (queue-scheduled+ToO) time on fully robotic telescopes

MiNDSTEp
- Fully automated observing system
- Time block allocated on quasi-robotic telescopes

SONG
- Building robotic telescopes which will join the MiNDSTEp network
Currently:
3 x 2m robotic telescopes
Liverpool Telescopes
LCOGT Faulkes North and South

→ Adaptive queue scheduler
→ Non-dedicated telescopes
→ Fully robotic observation and data reduction
→ webPLOP monitoring strategy +
  manual ToO for anomalies
**Future:**
- LCOGT and SUPA/St. Andrews building worldwide multi-aperture telescope network
- 6 sites worldwide, both hemispheres
- Two southern 1m to be deployed early 2012
- Full network by 2014:
  - 2 x 2m
  - 10 x 1m
  - 1 x 0.8m
  - 18 x 0.4m

**Currently:**
- 3 x 2m robotic telescopes
- Liverpool Telescopes
- LCOGT Faulkes North and South
- Adaptive queue scheduler
- Non-dedicated telescopes
- Fully robotic observation and data reduction
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robonet.lcogt.net
Quasi-robotic observing network:
→ Danish 1.54m at ESO La Silla (Chile)
→ MONET-S 1.2m at South African Astronomical Observatory

Future network:
+ MONET-N: 1.2, at McDonald, Texas
+ SONG network (late 2011 onwards)

Robotic observing following MiNDSTEp strategy

Block-allocated dedicated time
- Building network of robotic 1m telescopes
- 8 sites, both hemispheres

- Deployment timetable:
  → Prototype in Canary Islands online Sept 2011
  → China, Argentine in 2012
  → Chile and Hawai'i 2013
  → South Africa/Namibia and Australia 2013/2014

- Science goals
  Asteroseismology
  Microlensing

- Initially block-allocated time
  (may move to queue-scheduled)
- Will follow MiNDSTEp strategy
Future Directions

- Future worldwide networks of robotic telescopes
  - Weather/technical redundancy
  - Better coverage, more consistent datasets
  - Robotic target selection

- Anomaly modeling and assessment
  - newly automated, largely manual
  - much improved predictive models issued during events guiding observations

- Prioritization of simultaneous anomalies
  Hard to do while in progress (difficult to distinguish stellar/planetary binaries until quite late on)
  → Multiple simultaneous anomalies from upgraded surveys

- Support for space-based mission
Prioritizing Events

For event combined lightcurve, can fit:
→ PSPL model
→ PSPL + anomaly models for planets at x,y spanning grid around the Einstein ring region

Calculate $\Delta \chi^2$ at each x,y

If $\Delta \chi^2(x,y) >$ threshold, data are sensitive to planets located at (x,y) → map of detection zones

- Detection zones indicate sensitivity to planets (around major and minor image locations at time of observations)

Targets prioritized according to g values