Large-Telescope Instrumentation
For Time-Domain Astronomy
(Andy Gould – Ohio State)

• Transients:
  GRBs
  Novae
  Supernovae
  Occultations
  Microlensing Events
  New Phenomena

• Astrometry:
  Parallaxes
  Proper Motions

• Planets:
  Doppler
  Transits
  Astrometry
  Microlensing

• Variables:
  CVs

• Solar System:
  KBOs, NEOs
TRIAGE

• Already Being Done
• Ripe for Large-Telescope Instruments
• Smaller = Better
• 6.5m (equiv), 10 deg^2
• 15 sec exposures
• Every 3 nights
• 16 < V < 24
• 10 mas astrometry (systematics)
LSST: What's Left?

**SURVEYS**
- V<16 (a lot!)
- Timescale < 3 days (GRBs, ulensing, occultations, unknowns)
- Spectroscopy (RV planet searches)
- Ultra-deep

**TARGETED**
- Just About Everything
Coming Sooner (and Brighter):

- 1.8m, 7 deg^2 (ultimately 4 mirrors)
- 30 sec exposures
- 3 obs/lunar cycle
- 14 < V < 23

- 2 DELTA's
- 14<V<16 removed
- Single-Telescope survey begins “soon”
Genesis of KELT
(Kilodegree Extremely Little Telescope)

- 2 inch lens
- f/1.8
- 4Kx4K chip
- (23 deg)^2 FOV
Transiting Planets
A “Surface-Brightness” Problem

- KELT equation
  \[ \gamma = \frac{KEL^2T}{4\pi F^2} \]
- K: throughput const.
- E: time efficiency
- L: detector length
- T: experiment duration
- F: Focal ratio
- gamma: photons rec'd
Why No Scaling With Primary Diameter, D?

- Fix focal ratio (F) and detector size (L)
- Double D -> 4x Area -> (1/4)x Exposure time
- But ... (1/4)x Field -> 4x More exposures
- Smaller D -> Smaller time fraction in readout
- --> Choose smaller and smaller D, until ...
- ... Sky dominates \[V \sim 12 + 5\log(D/5\text{cm})\]
- [Assumes: \(\text{pixel/F}=5\text{ um}, \ V(\text{sky})=21.3\)]
Fly's Eye Telescope

- 120 4-inch telescopes
- 5K commercial chips
- 9 um, 7'' pixels
- 10,000 deg\(^2\)
- 30 sec exposures
- 3% at V=14
- Saturates at V~8.5
- Parts: $1.5M
Lazy-Susan Mount
Fly's Eye Applications

- **Transits**

- **Jupiters:**
  \( V=13: \ P<1\text{yr} \)

- **Neptunes:**
  \( V=11: \ P < 4 \text{ days} \)

- **Earths:**
  \( V=10 \ M\text{-star} \)
  Habitable Zone

- **GRBs**
  Optical Afterglows
  Alerts to SWIFT!!!

- **Nova, SN, rises**

- **New Phenomena**

- **Killer Rocks**
Terrestrial Impact Frequency

- Hiroshima
- Tunguska
- Global catastrophe
- K/T

TNT equivalent yield (MT)

Morrison August 2006
Perhaps Complemented by a ...

- Satellite at L1
Time-Domain Parameter Space for Large-Telescope Instruments

I: Photometry Surveys

- Smaller Area/Deeper/Crowded/Higher Sampling
- LSST: \((33\text{m}^2) \times (10 \text{ deg}^2) \times (15\text{s}/30\text{hrs}) = 0.05 \text{ m}^2 \text{ deg}^2\)
- Examples
  1) Microlensing (Bulge)
  2) Microlensing (M31, other?)
  3) Supernovae (e.g. DES)
  4) Other?
How Microlensing Works
How Microlensing Finds Planets
Generation 0

- Eddington 1920, Space, Time, and Gravitation
- Chwolson 1924, Astron. Nachr. 221, 329
- Einstein 1936a, Science, 84, 506
  
  "Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request .... there is no great chance of observing this phenomenon."

- Einstein 1936b (private letter to Science editor)
  
  "Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."
Generation -1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]
Massive Surveys Induce Optimism...

Gravitational microlensing by double stars and planetary systems

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Geometrical view of microlensing by a binary, as seen from the sky. The primary of \( M_p \) is located at the center of the figure, and the secondary of \( M_2 \) is located on the right, on the Einstein ring of the primary.

The radius of the ring is 1.0 mas for a source located at a distance of 6 kpc from the lens at 4 kpc. The two complicated shapes around the primary are the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.
5. OBSERVATIONAL REQUIREMENTS

Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

While observations from one site would be useful, there are advantages to be gained by observing from several sites. First, two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,
1995 PLANET Pilot Season

Second Microlensing Planet
The New Zealand Connection
Grant, Ian, Jennie, Phil
Amateurs + Professionals

"It just shows that you can be a mother you can work full-time, and you can still go out there and find planets."

Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)
OGLE-2004-BLG-343
A Magnification A=3000 Event
Sensitivity to Planets
OGLE-2005-BLG-169

Cold Neptune in Hi-Mag Event
NextGen Microlensing Planet Search
Simulations by Scott Gaudi

- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit
### Summary of Baseline Results

<table>
<thead>
<tr>
<th>log(a/AU)</th>
<th>-0.35</th>
<th>-0.10</th>
<th>0.15</th>
<th>0.40</th>
<th>0.65</th>
<th>0.90</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$ (yr$^{-1}$)</td>
<td>0.4±0.4</td>
<td>3.8±1.2</td>
<td>12.5±3.1</td>
<td>10.9±1.7</td>
<td>8.8±1.9</td>
<td>4.3±1.2</td>
<td>1.0±0.7</td>
</tr>
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Every MS star has one Earth-mass planet

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<tbody>
<tr>
<td>$\Gamma$ (yr$^{-1}$)</td>
<td>0</td>
<td>0.6±0.3</td>
<td>0.6±0.4</td>
<td>3.1±0.9</td>
<td>3.9±1.2</td>
<td>1.8±0.9</td>
<td>0.2±0.2</td>
</tr>
</tbody>
</table>

Every MS star has one Earth-mass ratio planet

<table>
<thead>
<tr>
<th>log($M/M_\odot$)</th>
<th>-1.0</th>
<th>-0.5</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$ (yr$^{-1}$)</td>
<td>1.5±0.3</td>
<td>3.7±0.5</td>
<td>12±1</td>
<td>30±3</td>
<td>78±8</td>
<td>150±10</td>
<td>350±20</td>
<td>590±30</td>
<td>1012±40</td>
</tr>
</tbody>
</table>

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU
Time-Domain Parameter Space for Large-Telescope Instruments

II: Targeted Photometry

- **Target of Opportunity**
  High-mag microlensing events
  GRBs
  Unclassified Transients

- **Periodic Variables**
  Transits

- **High-Speed and Ultra-High Speed**
  Cataclysmic Variables
  Occultations
ULTRACAM (VLT)

- 2.5' FOV
- 0.15" pixels
- up to 500 Hz
- Simultaneous 3-color
WIYN Orthogonal-Transfer Chips

- Separate (rapid)readout for bright stars
- Primary purpose: tip-tilt corrections
- Could be used for high-speed photometry
Time-Domain Parameter Space for Large-Telescope Instruments

III: Targeted Spectroscopy

- **Target of Opportunity**
  - High-mag microlensing events
  - GRBs
  - SNe
  - Unclassified Transients

- **Periodic Variables**
  - Transits
  - RV
OGLE-2006-BLG-265
15-min exposure on “V=20” star
Time-Domain Parameter Space for Large-Telescope Instruments

IV: Spectroscopy Survey

• RV Planet Searches

• Multi-Object
  (Surface Brightness Prob)

• Single-Object
  Earth-mass habitable-zone planets
Standard Lore on RV Precision

- 1 m/s per observation achievable
- Can continue to beat down noise by root-N
- Fundamental limit: stellar-atmosphere noise
- Dramatically confirmed in Sun
SOHO RV Data

[Graph showing solar velocity (m/s) over time (Years) from 1996 to 1999, with a 292 day shift indicated.]
Earth-Mass Habitable-Zone RV Search

- Slightly earlier (Mv=6) stars more stable
- \( \sigma = 1 \text{m/s} \): \( D=6 \text{m}, \ 5 \text{ min exp, at 10pc } (V=6) \)
- Reflex speed = 17 cm/s
- Each measurement: \( \sim \text{Reflex}/\sqrt{3} = 10 \text{ cm/s} \)
- 2500 measurements for 5 sigma detection
- \( (80 \text{ meas/night}) \times (250 \text{ night/yr}) \times 5 \text{ yrs} = 10^5 \text{ meas} \)
- Could probe 40 stars
Summary

- **Targeted Photometry**: Rapid, reliable access to “standard instruments” + High-speed photometers (“specialized”)
- **Targeted Spectroscopy**: Rapid reliable access to “standard instruments”
- **Photometric Surveys**: Microlensing, SN [need semi-dedicated access]
- **Spectroscopic Surveys**: Dedicated RV search for Habitable Earths