Asteroseismology using ground-based synoptic surveys

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SATELLITE vs. GROUND-BASED ASTEROSEISMOLOGY

- SATELLITE:
  - Outstanding precision!
  - High duty cycle (no aliases)
SATELLITE vs. GROUND-BASED ASTEROSEISMOLOGY

- GROUND-BASED SYNOPTIC SURVEYS:
  - Millions of targets
  - Multicolor photometry
  - Cheaper
  - Long duration
  - Spectroscopy

OGLE
ASAS
SDSS
SuperWASP
SuperWASP

- Main goal: search for exoplanets
- Two robotic observatories, each consisting of eight 20-cm cameras
- Field of view: $7.8^\circ \times 7.8^\circ$
- Broad-band filter (400 – 700 nm)
- Typical cadence: 10 minutes
- Time span: 2004 – now
- Targets: entire sky, with the exception of the Galactic plane
- Number of stars observed: 31 million
- Precision of the photometry: <1% for stars in the magnitude range $9 < V < 12$ mag
SuperWASP

- Holdsworth et al. (2014):
  - 10 new roAp stars (20% of all known).
  - >200 δ Sct stars with frequencies greater than 50 d\(^{-1}\).
  - Several objects which show pulsations in both, the roAp and δ Scuti, ranges.
SDSS (Sloan Digital Sky Survey)

- Main goal: massive multi-filter photometric and spectroscopic survey
- 2.5-m telescope at Apache Point Observatory in New Mexico, United States + 2.5-m du Pont Telescope at Las Campanas Observatory, Chile
- Five filters: $u, g, r, i, z$
- APOGEE, APOGEE-2: high-resolution infrared spectroscopy of 300,000 stars
- Time span: 2000 – now
- Targets: entire sky
SDSS (Sloan Digital Sky Survey)

- Epstein et al. (2014)
  - APOKASC: a collaboration between the Kepler asteroseismic science consortium (KASC) and the SDSS-III APOGEE spectroscopic survey.
  - Asteroseismic analysis of 9 metal-poor red giant stars observed by Kepler (\(v_{\text{max}}, \Delta v\)) and APOGEE (\(T_{\text{eff}}, [M/H]\)).
  - Estimated masses are systematically higher than expected for stars from halo and thick disk.
ASAS (All Sky Automated Survey)

- Main goal: search for variability over the entire sky
- Two robotic observatories (Chile, Hawaii), each consisting of two 20-cm telescopes
- Field of view: 8.5° × 8.5°
- Filters: V, I
- Typical cadence: 1-3 days
- Time span: 2000 – now
- Sky coverage: entire sky
- Number of stars observed: 20 million
- The ASAS catalog of variable stars includes over 50,000 objects (80% are new discoveries) brighter than about 14 mag in the V band.
ASAS (All Sky Automated Survey)

- Pigulski & Pojmański (2009):
  - 295 new β Cephei stars (three times more than known before).
  - Up to four modes per star.
  - Statistical analysis.
  - Several hybrid β Cephei/SPB stars.
CSTAR (Chinese Small Telescope ARray)

- Main goal: testing of the atmospheric conditions in the Antarctic Plateau (Dome A).
- The telescope located about 4000 m above the sea level
- Schmidt–Cassegrain wide-field telescope
  \[ D = 145 \text{ mm} \]
- Field of view: \( 4.5^\circ \times 4.5^\circ \)
- Sloan i-band filter
- One field centered on the south celestial pole (9° from the zenith).
CSTAR (Chinese Small Telescope ARray)

- Wang et al. (2013):
  - From March to September 2010 (183 days) over 340,000 images were collected with a total integration time of 2553 hours.
  - 188 variable stars detected

![Graph showing mode amplitude vs frequency in c/d with peaks at 41.5 and 44 c/d](image)
OGLE
(Optical Gravitational Lensing Experiment)

- Original goal: search for microlensing events
- 1.3-meter Warsaw Telescope at Las Campanas Observatory, Chile
- 32-chip CCD camera with a field of view 1.4 square degrees
- Standard Johnson-Cousins $VI$ filters
- Typical cadence: from 20 minutes to several days
- Time span: 1992 – now
- Targets: Galactic bulge, Galactic disk, Magellanic Clouds
- Precision of the photometry: 5 mmag
OGLE fields

- Sky coverage: ~3000 square degrees
- ~1.3 billion stars monitored
- ~500 billion individual measurements
- ~500 thousand discovered variable stars
- ~2000 microlensing events per year
- ~50 extrasolar planets
## OGLE Collection of Variable Stars

<table>
<thead>
<tr>
<th>Type of variable stars</th>
<th>Environments</th>
<th>Number of stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical Cepheids</td>
<td>LMC, SMC, GB</td>
<td>8 037</td>
</tr>
<tr>
<td>Type II Cepheids</td>
<td>LMC, SMC, GB</td>
<td>581</td>
</tr>
<tr>
<td>Anomalous Cepheids</td>
<td>LMC, SMC</td>
<td>250</td>
</tr>
<tr>
<td>RR Lyrae stars</td>
<td>LMC, SMC, GB</td>
<td>65 638</td>
</tr>
<tr>
<td>δ Scuti stars</td>
<td>LMC, GD</td>
<td>2 844</td>
</tr>
<tr>
<td>Long-Period Variables (Miras, SRVs, OSARGs)</td>
<td>LMC, SMC, GB</td>
<td>344 214</td>
</tr>
<tr>
<td>Eclipsing binaries</td>
<td>LMC, SMC, GD</td>
<td>43 845</td>
</tr>
<tr>
<td>R Coronae Borealis stars</td>
<td>LMC</td>
<td>23</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>465 432</strong></td>
</tr>
</tbody>
</table>
Pulsating stars in the LMC

![Graph showing pulsating stars in the LMC, with various types of cepheids and long secondary periods marked.]
Classical Cepheids in the Magellanic Clouds

LMC | SMC
RR Lyrae stars in the Magellanic Clouds
Triple-mode Cepheids

5 in the LMC, 3 in the SMC, 2 in the Bulge

4 F/1O/2O, 6 1O/2O/3O
Double-mode 10/30 Cepheids

2 stars in the LMC

\[ \frac{P_S}{P_L} = 0.677 \]
Classical Cepheids in the MCs

Non-radial modes in the first-overtone Cepheids

\[ P_X/P_{10} = 0.60 - 0.64 \]

LMC: 30 objects

SMC: 139 objects
Non-radial modes in the first-overtone RR Lyrae stars

\(~300\) stars (13 observed by *Kepler*)

\[ \frac{P_X}{P_{10}} = 0.60 - 0.64 \]

Netzel et al. (2015)

[Graph showing distribution of RRd stars]
Non-radial modes in the first-overtone RR Lyrae stars

12 stars (1 observed by *Kepler*)

\[ P_{10}/P_X = 0.686 \]

Netzel et al. (2015)
Mode switching in RR Lyrae stars

OGLE-BLG-RRLYR-12245

OGLE-III

OGLE-IV

RRd

RRab
Mode switching in RR Lyrae stars

OGLE-BLG-RRLYR-12245
Blazhko effect in RR Lyrae stars

![Blazhko effect in RR Lyrae stars](http://ogle.astrouw.edu.pl/atlas/)
Blazhko effect in RRd stars

Smolec et al. (2014)

Jurcsik et al. (2014)
Blazhko effect in RR Lyrae stars

Soszyński et al. (2014)
Period doubling in BL Herculis stars

\[ \Delta I \text{ [mag]} \]

\( OGLE-\text{BLG-T2CEP-279} \)

Smolec et al. (2012)
Period doubling in BL Herculis stars

Smolec et al. (2012)

3:2 resonance between the fundamental and first overtone modes

Amplitude of the pulsation
Long-Period Variables

- Miras

- Semiregular Variables (SRVs)

- OGLE Small Amplitude Red Giants (OSARGs)
Period-Luminosity Diagram for Long-Period Variables in the LMC

- OSARGs
- SRVs & Miras
- Long Secondary Periods
- Ellipsoidal & Eclipsing Variables
Pulsation modes in the PL plane

Soszyński et al. (2013)
OSARGs – solar-like oscillators?

Dziembowski & Soszyński (2010)
LSST

Large Synoptic Survey Telescope

- Main goal: 10-year survey for variability in the sky
- The 8.4-meter telescope on the Cerro Pachón, Chile
- Field of view: **9.6 square degrees**
- Typical cadence: **3 days**
- Data flow: **30 TB per night**
- Targets: entire sky
- Number of observed variable stars (expected): **135 million**
  - **57 million** eclipsing/ellipsoidal variables,
  - **59 million** pulsating variables,
  - **2.7 million** flaring stars,
  - **0.78 million** extrasolar planetary transits
CONCLUSIONS

- Ground-based large-scale sky surveys are still in the asteroseismological game.

- Huge samples of pulsating stars are crucial for
  - detecting new phenomena
  - studying statistical features of stars

- Ground-based and satellite data are complementary.
ACKNOWLEDGMENTS

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