Stellar pulsation timing

A complementary science case for the PLATO mission

Sonja Schuh

2017-03-07
1 Post-RGB planets

2 EXOTIME

3 PLATO Core Science

4 PLATO for post-RGB stars

5 Summary
Pulsation timing: "Observed minus Calculated" diagrams

full data set: calculated model C

data subsets: observations $O_i$

$O_1$  $O_2$  $O_3$

Figures from Lutz (2009), Dissertation, University of Göttingen
Light travel time effect
Post-RGB planet candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass</th>
<th>Radius</th>
<th>Period</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star1</td>
<td>10 M☉</td>
<td>1.5 R☉</td>
<td>0.5 d</td>
<td>5500 K</td>
</tr>
<tr>
<td>Star2</td>
<td>8 M☉</td>
<td>1.2 R☉</td>
<td>0.7 d</td>
<td>5800 K</td>
</tr>
<tr>
<td>Star3</td>
<td>6 M☉</td>
<td>1.0 R☉</td>
<td>0.9 d</td>
<td>6100 K</td>
</tr>
<tr>
<td>Star4</td>
<td>4 M☉</td>
<td>0.8 R☉</td>
<td>1.1 d</td>
<td>6400 K</td>
</tr>
<tr>
<td>Star5</td>
<td>2 M☉</td>
<td>0.6 R☉</td>
<td>1.3 d</td>
<td>6700 K</td>
</tr>
</tbody>
</table>

(*Note: The table continues with more entries*)
EXOTIME
Extra-solar planet search with the timing method

A giant planet orbiting the ‘extreme horizontal branch’ star V391 Pegasi
Silvotti, Schuh, Janulis et al. 2007, Nature 449, 198

EXOTIME: searching for planets around pulsating subdwarf B stars

The Potential of the Timing Method to Detect Evolved Planetary Systems
Silvotti, Szabó, Degroote, Østensen, Schuh 2011, AIPC 1331, 133

The search for substellar companions to subdwarf B stars in connection with evolutionary aspects
Lutz 2011, PhD thesis, University of Göttingen

EXOTIME: Searching for planets and measuring Pdot in sdB pulsators
Lutz, Schuh, Silvotti 2012, AN 333, 1099

The EXOTIME Monitoring Program Discovers Substellar Companion Candidates around the Rapidly Pulsating Subdwarf B Stars V1636 Ori and DW Lyn
Schuh, Silvotti, Lutz, Kim, Exotime Collaboration 2014, ASPC 481, 3
The need for confirmation

- Confirmation is difficult
  - consistency between independent pulsation frequencies?
  - prediction power of model fit?
  - reproducibility of results? with independent re-analysis and/or new data?

- Need for simulation of time-series
  - Interpretation of sparsely-sampled ground-based data

- Independent confirmation is very difficult
  - radial velocities
  - colour excess
  - direct imaging

- Pulsation timing
  - in principle, O–C method is simple
  - in practice, it is not a well-establish planet detection method
EXOTIME

Poster Mackebrandt

The Stellar Pulsation Timing Detection Method for Substellar Companions
Felix Mackebrandt, Sonja Schuh
Max Planck Institute for Solar System Research (MPS)

Abstract
We want to make use of the rapid pulsations in subdwarf B stars (sdB) to detect substellar companions from periodic variations in the expected arrival times of the pulsations. This timing method is particularly sensitive to planets at large distances and complementary to other exoplanet detection methods because they are not as efficient for stars with small radii and high gravities. Thus, the timing method opens up a new parameter range in terms of the host star. To date, substellar candidates in sdB systems are for example V391 Psc b (Silvotti et al., 2007), HW Vir b, c (Lee et al., 2019), HS 0705+67003 b (Qian et al., 2009) and Kepler-429 b, c, d (Silvotti et al., 2014).

sdB Stars
Subdwarf B stars are located at the extreme horizontal branch in the Hertzsprung-Russell diagram. They have a helium-fusion core but no hydrogen-shell burning in their thin hydrogen shells. The mass-loss leading to such thin shells can be well explained in close binary systems but is difficult for single sdB stars. Planets have been proposed to be responsible for the formation of single sdBs. Some subdwarf B stars exhibit pulsation instabilities driving acoustic modes of a few minutes period. They can be used as a clock signal to detect periodic changes in the arrival time caused by a substellar companion.

Light Travel Time Effect

\[
\Delta T = \frac{2\pi M}{c^2} \frac{1}{\sin \frac{\pi \nu}{2}}
\]

Figure: Expected amplitude of the Light Travel Time Effect as a function of planetary orbital period / for a host star of mass \( M = 1.5 \, M_\odot \), \( \nu = 1 \) and different planetary masses \( m \).

Python Pipeline

1. determine frequency
2. periodogram algorithm
   (Astropy Lomb Scargle periodogram / conditional entropy minimization)
3. choose frequency
4. non-linear least squares fit to refine frequency
5. divide light curve into sub-intervals
6. non-linear least squares fit to determine shifts in phase
7. O-C diagram

Simulated Data

Figure: Except of the artificial observations for ground-based-like, Kepler-like and PLATO-like noise and timing. For pulsating host star \( \nu = 1 \) m ج with a period of 4 min and amplitude of 1%/10 m ج. Ground-based observations for three consecutive nights per month, cadence \( 1 \) min and noise level of 10%/10 m ج. Kepler / PLATO-like observations with a cadence of \( 10 \) min and noise level of 1%/10 m ج, respectively.

Linear Drifting Period

Figure: \( \nu \times C \) diagram for an injected linear change in stellar pulsation period \( P = 10^{-3} \) day, hence \( \nu = 10^{-4} \) d. Fitted parameters for ground-based: \( \nu \times C = (2.5 \pm 0.5) \times 10^{-1} \) d, Kepler-like: \( \nu \times C = (2.2 \pm 0.2) \times 10^{-1} \) d, PLATO-like: \( \nu \times C = (2.0 \pm 0.2) \times 10^{-1} \) d.

Planetary Signal

Figure: \( \nu \times C \) diagram for an injected planet with \( P = 0.03 \) day and \( m = 1 \, M_\oplus \), hence \( \nu \times C = 3.6 \times 10^{-1} \) d. Fitted parameters for ground-based: \( \nu \times C = (2.5 \pm 0.5) \times 10^{-1} \) d, Kepler-like: \( \nu \times C = (2.2 \pm 0.2) \times 10^{-1} \) d, PLATO-like: \( \nu \times C = (2.0 \pm 0.2) \times 10^{-1} \) d.

Outlook
Our target catalogue will consist of re-analysed EXOTIME objects (Lotz, 2011; http://www.ato.inaf.it/silvotti/exotime/) and selected Kepler stars. The Kepler field contains only few rapid pulsating sdB variables but the oscillations of slow pulsating sdB stars and ScD stars can be investigated with our pipeline.

In consideration of future photometric space missions like TESS and PLATO it is essential to enhance the diversity of potential exoplanet host stars that can be probed.

References

Acknowledgements
We would like to thank the International Space Research Centre for Solar System Science at the University of Göttingen and the German Research Foundation for financial support through the project “EXOTIME: The Stellar Pulsation Timing Detection Method for Substellar Companions” (project number 142629650) and the project “Weihofen: From Ternary Systems to the Origin of Exoplanets” (project number 149801411).

mackebrandt@mps.mpg.de
The need to go beyond ground-based data

- Ground-based data has very very low filling factors
- *Kepler* data for fast pulsators is desperately under-sampled
- Need near-continuous well-sampled data!
PLATO
PLAnetary Transits and Oscillations of stars

- ESA’s planet-hunting mission
- selected as M3 mission of the Cosmic Vision 2015-2025 program in February 2014
- mission adoption expected in June 2017
- launch expected in December 2025

Figures and quoted or paraphrased text from PLATO Definition Study Report (2016)
PLATO Definition Study Report (2016)

Revealing habitable worlds around solar-like stars

Transit survey mission detecting and providing bulk characterisation for new planets around bright stars. Design optimised to:

- Determine the bulk properties (mass, radius, mean density) of planets in a wide range of systems, including terrestrial planets in the habitable zone of solar-like stars.
- Study how planets and planet systems evolve.
- Study the typical architectures of planetary systems.
- Analyse the correlation of planet properties and their frequencies with stellar parameters (e.g. stellar metallicity, stellar type).
- Analyse the dependence of the frequency of terrestrial planets on the environment in which they formed.
- Study the internal structure of stars and how it evolves with age.
- Identify good targets for spectroscopic follow-up measurements to investigate planet atmospheres.
Multi-telescope design that makes PLATO unique

One of two proposed spacecraft designs for PLATO (OHB concept)
Multi-telescope design that makes PLATO unique

- PLATO compared to *Kepler* and Corot:
  - larger field of view
  - same performance for fainter stars
  - higher dynamic range due to multi-telescope approach
    → bright stars

- PLATO compared to TESS and CHEOPS:
  - PLATO: time base up to 3 years per target
  - TESS: short-orbit planets only (<20 days, i.e. no Earth-like orbits!)
  - CHEOPS: pointed observations at previously known planet host stars
    (i.e. not a discovery machine)
Multi-telescope design that makes PLATO unique

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  - larger field of view
  - same performance for fainter stars
  - higher dynamic range due to multi-telescope approach → bright stars

- PLATO compared to TESS and CHEOPS:

![Small planets in orbital periods <150 days](chart1)

![Small planets in the HZ of Sun-like stars](chart2)
Filling the gap
Large FOV, bright stars, long orbital periods

RV follow-up for bright solar-like stars with transiting planets in HZ
Prototype of a single telescope

H. Rauer, DLR, PLATO PI
Sensitivity varies over the field of view

Overlapping line-of-sight concept  Resulting field-of-view configuration
More than half the sky accessible
PLATO mission

Planned mission launch: Dec 2025
Planned mission duration: (2+2) years:
  2 Long-Duration Observation Phases OR 2yr LOP + 2yr LOP
  LOP+Step-and-stare Observation Phase 3yr LOP + 1yr SOP
Planned orbit: L2 every three months
90° degree rotation
Normal telescopes (for stars fainter V=8): # 24
Normal telescopes aperture: 120mm
Normal telescopes cycle time: 25s
Normal telescopes passband: wideband
Normal telescopes FOV (combined): 47.2° × 47.2°
Fast telescopes (for stars from V=4 to V=8): # 2
Fast telescopes aperture: 120mm
Fast telescopes cycle time: 2.5s
Fast telescopes passband: one colour per telescope
Filling the gap
Large FOV, bright stars, long orbital periods

Large FOV & access to long orbital periods

⇒
Also great to look for planets around evolved stars, including via pulsation timing!
PLATO Science Management

PSM Coordination
D. Pollacco

Exoplanet Science
D. Pollacco

Stellar Science
M. J. Goupil

Target / Field Characterization and Selection
G. Pietro

Follow-up Coordination
S. Udry

Complementary Science
C. Aerts

Complementary Science
C. Aerts

Production of Variability Catalogue

Binary and Multiple Stars

Pulsating Stars Earlier Than F5

Multi-Wavelength Analysis of Young Stellar Objects

Solar System and Other Moving Objects

Microlensing

Galactic Structure

Extragalactic Structure

Spectroscopic and Interferometric Follow-Up

Transient Phenomena
Evolved stars with PLATO

Exoplanet science

PLATO Definition Study Report (2016)

2.1.9 Planets around post-RGB stars

- new sdB planets from illumination effects
- first sdB planets from transits
- first WD planets from transits

+ sdB/WD asteroseismology allows very good characterisation of these stars and their planets
Evolved stars with PLATO

Complementary science

**PLATO Definition Study Report (2016)**

2.3.1.2 Hot OB sub-dwarf stars

[... ] Thanks to the combination of its rapid observing cadence and bright targets, PLATO will be the only space-based facility able to develop the science of deep seismic probing of sdB stars. It will provide high-quality data on g-mode pulsations in these stars that cannot be obtained from the ground. Thereby, PLATO will increase the number of sdB stars that can be modelled by asteroseismology. It will also discover new planets around these objects, enabling us to disentangle the question of the origin of such stars and explore star-planet interactions in the advanced stages of stellar evolution.
PLATO Data Center

PDC Executive Board
(WP3X-Leaders)
Invited: PSMC, PCOTM, PCL, SOCDM

PDC Project Office Manager
(Burston, MPSSR)

PDCM (Gizon, MPSSR)
Chair of Executive Board

PDC-DB
WP 31: System Architecture and Management
(Burston, MPSSR)

WP 32: Data Processing Algorithms
(Samadi, LESIA)

WP 33: Data Processing Development Support
(Gizon, MPSSR)

PDPC-A
WP 34: Input Catalogue
(Giommi, ASDC)

PDPC-C
WP 35: Preparatory and FU Database Management
(Deleuil, LAM)

PDPC-L
WP 36: Exoplanet Analysis System
(Walton, IoA-Cam)

PDPC-I
WP 37: Stellar Analysis System
(Appourchaux, IAS)

PDPC-M
WP 38: Data Analysis Support Tools
(Ammler-von Eiff, MPSSR)

WP 371
WP 372
WP 373
WP 374
WP 375

top level WP leaders
(TLWPL)

sub-WPs:
example for WP 37
PDC at Max Planck Institute for Solar System Research

PDC is under the responsibility of the PLATO Mission Consortium. PDC supports the production of the L1 data. PDC-DB at MPS will hold the PLATO scientific data products.
Summary

- Understand currently available pulsation timing better with simulations
- Establish pulsation timing as an exoplanet detection method with PLATO

Do you have students who want to get involved with PLATO science?
→ http://www.solar-system-school.de
Outlook

PLATO Science Conference
5-7 September 2017 Warwick, UK

http://www2.warwick.ac.uk/fac/sci/physics/research/astro/research/meetings/plato_mission_conference2017/

http://tinyurl.com/plato2017