A review on *Kepler* and PLATO 2.0 missions from the asteroseismic point of view

Tópicos em Física de Partículas, Astrofísica e Cosmologia

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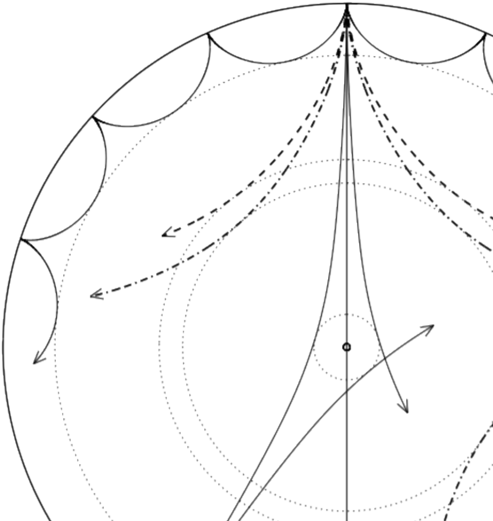
TÉCNICO LISBOA



Outline

1. Asteroseismology

2. Space missions review
    2.1 Spacecraft design
    2.2 Observing strategy
    2.3 Data handling
    2.4 Analysis of Asteroseismic data

3. *Kepler* & PLATO 2.0 results

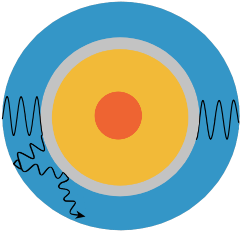
Motivation for asteroseismology

- Until the last few decades, research of stellar interiors had been restricted to theoretical models only constrained by global properties
- However, in the last 30 years, asteroseismology has revolutionized our understanding of stellar interiors
- Asteroseismology uses the frequencies, amplitudes and phases from observations of pulsating stars directly to model and probe the stellar interiors

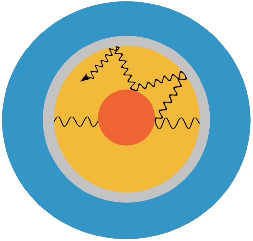
Oscillation modes

Stars oscillate around an equilibrium state of spherical symmetry.

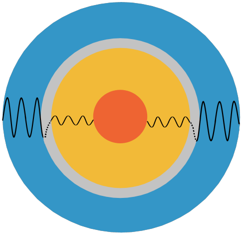
These perturbations can be studied as a solution to a wave-like equation, leading to two main types of standing waves.



p modes

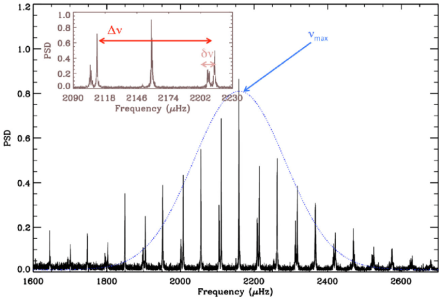


g modes



mixed modes

Power Spectrum Density



Garcia and Ballot (2019)

Frequency of maximum oscillation power

$$\nu_{max} \propto g T_{eff}^{-\frac{1}{2}} \propto M R^{-2} T_{eff}^{-\frac{1}{2}}$$

Large separation

$$\Delta\nu = \nu_{n,l} - \nu_{n-1,l}$$

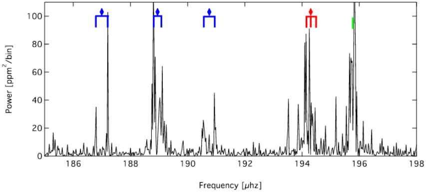
Small separation

$$\delta\nu = \nu_{n,l} - \nu_{n-1,l+2}$$

Rotational splitting

$(l = 1)$, $(l = 2)$, $(l = 0)$

$$\nu_{n,l,m} = \nu_{n,l,0} - m\delta\nu_{n,l}$$



Beck et al. (2012)

Ground vs space based missions

Outline

Space missions

Kepler

- ⋆ part of NASA's Discovery Program **(2009-2018)**
- ⋆ continually monitored the brightness of $\sim$ 150 000 MS stars in a **fixed field of view**
- ⋆ improved **mission K2**: searched a much larger area

PLATO 2.0

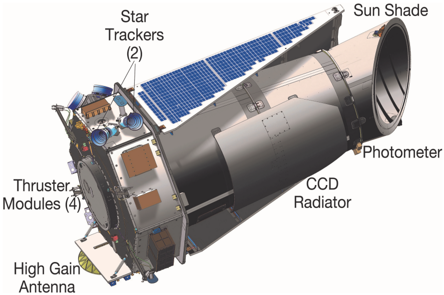
- ⋆ part of ESA's Cosmic Vision Programme **(2026-2030)**
- ⋆ will monitor a wide range of bright stars in an extremely **wide field of view**
- ⋆ vast ground based programme: spectroscopy, interferometry, and others

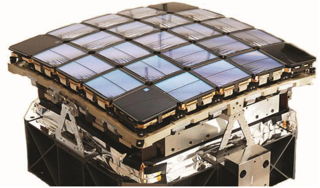
Main goal: discover many of the billions of stars that might harbour potentially habitable exoplanets

Spacecraft design

Kepler

- ⋆ Photometer: telescope, focal plane and local detector electronics
- ⋆ Schmidt telescope provides an 105 deg^2 FoV
- ⋆ Focal plane: 42 CCDs with 2200×1024 pixels each - total 95 Mpixels
    - 270 readouts to form a long cadence (LC) 30 min data
    - 9 readouts to provide short cadence (SC) 1 min data





Kepler photometer

Spacecraft design

PLATO 2.0

- Telescope: optical unit, focal plane, and electronics unit
- 32 ’normal’ telescopes providing a very wide circular FoV (2232 deg^2), and 2 ’fast’ cameras used as fine guidance sensor
- Focal plane: each telescope has 4 CCDs, each with 4510 × 4510 pixels - total 2.12 Gpixels
  - 4 groups of ’normal’ cameras each with 8 cameras with a pointing offset of 9.2°

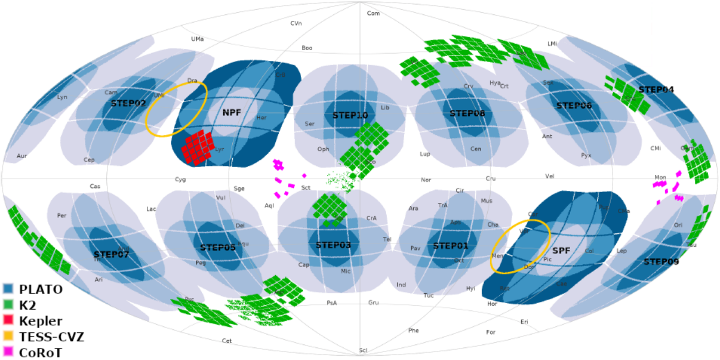
Schematic for the overlapping FoV.

Spacecraft design
Kepler & PLATO 2.0

	Kepler	**PLATO 2.0**
FoV	105 deg ^{2}	2232 deg ^{2}
Spectral range	423-897 nm	normal: 500-1000 nm
Magnitude	7-17 mg	normal: 8-16 mag
		fast: 4-8 mag
Readout cadence	LC: 30 min	normal:25 s
	SC: 1 min	fast: 2.5 s
Total no. of target stars	150 000	> 1 000 000
No. of bright stars	∼6 000	∼85 000
No. of dwarf star asteroseismology targets	> 512	∼85 000

Observing strategy

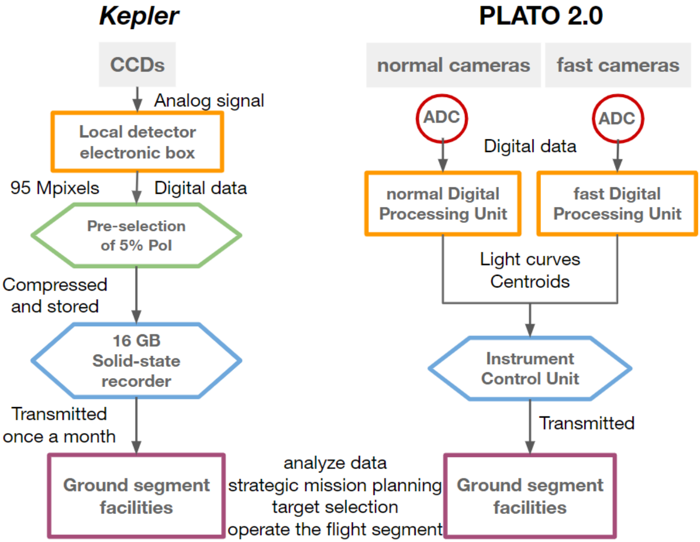
Kepler & PLATO 2.0



Marchiori et al. (2019)

1. stars must be monitored continuously
2. prevent Sunlight from saturating the CCDs
3. minimize no. of bright stars
4. largest possible number of star

Data handling



Analysis of asteroseismic data

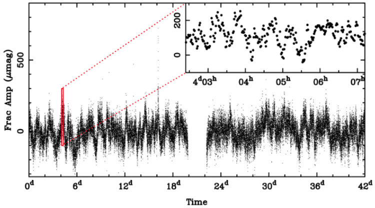
Kepler & PLATO 2.0

- ⋆ The techniques used for analysis of pulsating stars require continuous long data coverage (weeks/months/years)
- ⋆ **Phenomena** that might cause brightness variabilities: surface granulation, star spots and faculae, rotational variability and even accretion, eruption or cataclysmic behaviour
- ⋆ Distinct types of **noise** that determine the detection threshold: systematic instrumental errors, environmental noise, photon-counting shotnoise, and flux fluctuations due to intrinsic stellar variability

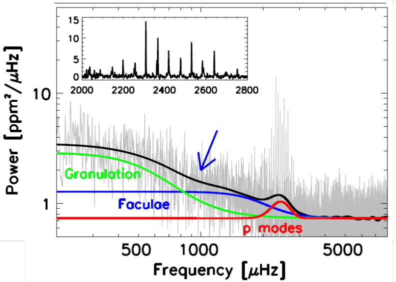
Analysis of asteroseismic data

Power Spectrum Density

- The stellar oscillations generate small amplitude variations of the light curves, that result from complicated nonlinear processes
- Therefore, an initial step requires a time series of light curve modulation values
- Since, the primary targets of the analysis are the frequencies and amplitudes of the detected modes
- The complete DFT of interest is the set of amplitude values calculated for all the chosen frequencies



Kepler light curve (NASA)



Gilliland et al. (2010)

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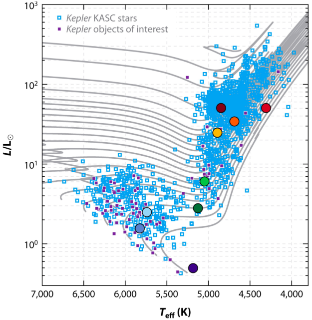
Kepler & K2 results

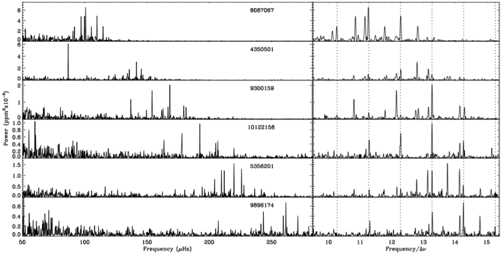
- These missions have provided over 5100 exoplanet candidates
- *Kepler* Input Catalog (KIC)

- Measured approximately 150 000 MS stars



Chaplin and Miglio (2013)

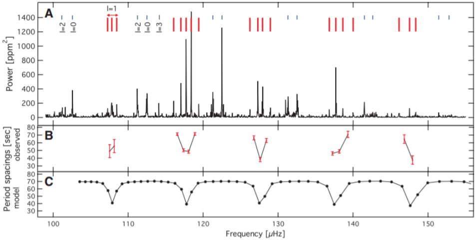
- Measurement of solar-like Oscillations in Low-luminosity Red Giants



Bedding et al. (2010)

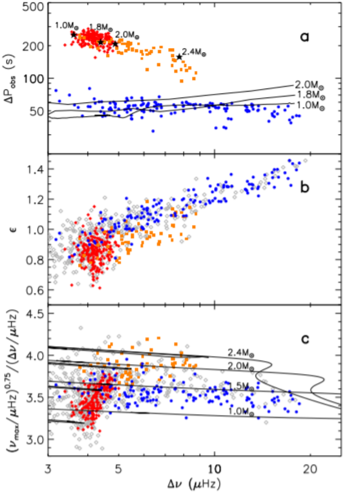
Kepler & K2 results

- ⋆ Detection of gravity-mode period spacings in a red giants



Beck et al. (2011)

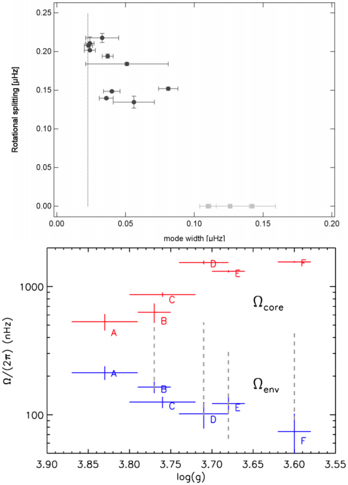
- ⋆ Discovery of gravity dominated mixed modes



Bedding et al. (2011)

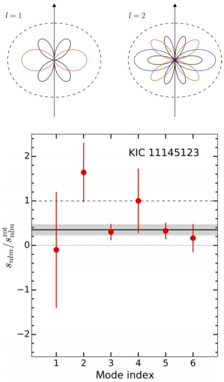
Kepler & K2 results

- ⋆ Fast core rotation in red giants revealed by gravity-dominated mixed modes



Beck et al. (2011), Deheuvels et al. (2014)

- ⋆ Measurement of the oblateness of a slowly rotating star with unprecedented precision



Gizon et al. (2021)

Some PLATO 2.0 predicted results

- ⋆ The main stellar objectives of the mission is to study seismic activity in stars to precisely measure stellar masses and their evolution
- ⋆ Measurements of oscillation modes with values up to at least l=3 are expected for PLATO 2.0 targets
- ⋆ Provide photometric data to measure frequencies of oscillation modes in MS stars with precisions $\sim 0.1\,\mu$Hz to allow separating solarlike oscillations (CoRoT $\sim 0.3\,\mu$H,z *Kepler* 0.1-0.3 μHz)
- ⋆ The PLATO 2.0 input catalogue (PIC) of thousands of characterized planets and $\sim$ 1 000 000 stellar light curves will provide the basis for a huge long-lasting legacy programme for the science community
- ⋆ Has the potential for probing the major missing ingredients in stellar evolution theory, such as AM transport and dynamo formation

Closing remarks

- ⋆ Space instruments have revolutionised our data analysis ability and understanding of all kinds of pulsating star
- ⋆ The *Kepler* legacy is an incredible amount of very high quality data and the analysis and interpretation of these data will continue to reveal important results
- ⋆ The search for the unknown mysteries of stellar interiors continues with asteroseismology as a guide and the support from this new generation of space/ground based telescopes
- ⋆ The future seems optimistically promising with the innovative technology implemented in PLATO 2.0

Thanks for your attention

Main bibliography

[1] Gilliland, Ronald L. et al. (2010). “Kepler Asteroseismology Program: Introduction and First Results”. In: Publications of the Astronomical Society of the Pacific, pp. 131-143

[2] Rauer, H. et al. (Oct. 2014a). “The PLATO 2.0 mission”. In: Experimental Astronomy 38, p. 249-330

Treatment of light curves

- ⋆ Processing the time series in the optimum way in order to obtain a power spectrum is the primary goal
- ⋆ So conversion of the variable star data to fractional excursions about a running mean is required
- ⋆ The first step, is to divide the sky-corrected variable data by the sky-corrected comparison data and multiply by an appropriate constant to yield a time-series curve with the correct mean value
- ⋆ The second step is to convert light curve intensities to fractional deviation values about the running mean
- ⋆ Having suitably prepared the light curve time series, the next step is to perform a Fourier transform