

Kepler, CoRoT and MOST: Time-Series Photometry from Space

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Invited Talk

Abstract. During the last 10 years we have seen a revolution in the quality and quantity of data for time-series photometry. The two satellites MOST and WIRE were the precursors for dedicated time-series missions. CoRoT (launched in 2006) has now observed more than 100,000 targets for exoplanet studies and a few hundred stars for asteroseismology, while KEPLER (launched in 2009) is producing extended time-series data for years, aiming to discover Earth-size planets in or near the habitable zone. We discuss the accuracy of some of the parameters one may extract from the high-quality data from such photometric space missions, including the prospects for detecting oscillation-period changes due to real-time stellar evolution.

Keywords. techniques: photometric, stars: oscillations (including pulsations)

1. The Science Goals of Photometry from Space

The science goals for all the photometric space missions are high-precision asteroseismology and search for and characterization of exoplanet transits. Reaching those goals will require high-precision time-series photometry with high duty cycle for extended periods of time.

Launched on 2003 June 30, the Canadian space mission MOST became the first satellite dedicated to high-precision time-series photometry (Walker *et al.* 2003). The first indication of the quality of photometry that can be obtained from space had already been given by the NASA WIRE-mission, launched on 1999 March 4. Owing to the loss of cryogen needed for cooling the main detector, WIRE was unable to carry out its primary science mission, and operations were changed so as to use the on-board 52 mm star tracker for continuous time-series monitoring of bright stars for one to six weeks per target (Bruntt & Buzasi 2006). The results showed that even a small telescope in space may be able to reach a photometric quality which cannot be obtained from the ground because of atmospheric scintillation (Kjeldsen & Frandsen 1992).

Improved photometric accuracy (compared to WIRE) was achieved by the MOST satellite, which contains a 150 mm aperture Rumak-Maksutov telescope that feeds two frame-transfer CCDs. MOST is orbiting in a low-Earth Sun-synchronous polar orbit, allowing stars to be viewed continuously for up to 60 days (Walker *et al.* 2003). While both WIRE and MOST focused on a limited number of stars per field of view, the French (CNES) CoRoT mission, launched into a low-Earth polar orbit on 2006 December 27, made it possible to monitor several thousand stars at once. CoRoT (Auverne *et al.* 2009) was therefore the first mission capable of searching for exoplanet transits from space. CoRoT can follow a large number of stars simultaneously and continuously for up to

150 days. The CoRoT telescope has a diameter of 27 cm, and is thus more sensitive than MOST and WIRE.

A low-Earth orbit will reduce the field-of-view, and will restrict the length of time for which a given target can be followed continuously. Searching for the transit signatures of planets in orbits around stars with periods longer than a year will therefore require significantly longer time-series data than any of the above-mentioned missions can provide.

The NASA KEPLER mission is specifically designed to survey a portion of our Milky Way galaxy to discover Earth-size planets in or near the habitable zone. The KEPLER mission therefore requires higher accuracy and longer observing periods than WIRE, MOST and CoRoT can achieve.

The KEPLER instrument (Koch *et al.* 2010) contains a 95-cm Schmidt telescope with a 105 deg^2 field of view. In order to ensure a continuous time-series for each target for several years, KEPLER is placed in an Earth-trailing heliocentric orbit. From that orbit KEPLER is capable of attaining the required photometric precision for long uninterrupted periods of time.

2. The Revolution in Data Quality and Quantity

MOST and WIRE should be regarded as the precursors of dedicated time-series missions focussed on bright targets. CoRoT has now observed more than 100,000 targets for exoplanet studies and a few hundred stars for asteroseismology studies, while KEPLER is producing extended time-series data over a period of years, on targets with visual magnitude between 5 and 17.

The literature clearly shows how photometric space missions have revolutionized the quantity and quality of observational data. WIRE produced the first series of new results (Bruntt 2007; Bruntt & Southworth 2007), and publications by the MOST team reveal the high-quality photometry that can be obtained through the use of even a small telescope in space; an example is the discovery of a super-Earth transit by Winn *et al.* (2011). CoRoT has measured *p*-mode oscillations and granulation in a number of stars hotter than our Sun (Michel *et al.* 2008), and has discovered non-radial oscillations with long life-times in RGB stars (De Ridder *et al.* 2009). The first exoplanet discovered by CoRoT in 2007 was a hot Jupiter (Barge *et al.* 2008).

A milestone for CoRoT in particular and for exoplanet research in general was the discovery of the hot super-Earth, CoRoT-7b (Leger *et al.* 2009), with a diameter smaller than 2 Earth radii, in a 0.853 day orbit. The discovery of CoRoT-9b in an orbit with a period of 95.3 days showed how these space missions are capable of discovering exoplanets with star–planet distances that imply equilibrium temperatures near or below 300 K (Deeg *et al.* 2010). The higher precision of the KEPLER photometry, combined with the longer uninterrupted time series data obtained by that mission, enables the KEPLER team to search for exoplanets with smaller sizes and larger orbital semi-major axes than can any of the other space missions. The recent discoveries by KEPLER clearly demonstrate this capability (e.g., Batalha *et al.* 2011; Borucki *et al.* 2012).

In asteroseismology KEPLER has improved the quality of available data by at least an order of magnitude, resulting in measurements of new properties in several types of stars. The most striking example is probably the measurement of hydrogen shell and helium core fusion in RGB stars (Beck *et al.* 2011; Bedding *et al.* 2011).

If we compare the measured properties of the photometry obtained by the existing space missions, we can list the following issues that should be considered for the future space missions:

- Field crowding shows a clear effect in the data quality.
- There is a huge gain in combining the science goals for the same time-series data (asteroseismology and transit studies).
- The quality of the data analysis is improved if one can analyse the data on the ground (images).
- It is better to saturate the detector than to defocus or spread light by using a prism.
- Bright stars are preferred in order to follow-up from the ground (may require a larger field-of-view).
- For hotter stars (O and B stars) one needs observations in the plane of the Milky Way (CoRoT sees more hot stars than KEPLER does).

3. Observational Asteroseismology

3.1. KEPLER photometry on bright stars

An example of KEPLER time-series data for a star bright enough to saturate the detector is given by the KEPLER data on θ Cygni, which has a magnitude $V = 4.86$. Although that star is too bright for the instrument by a factor of 1000, the photometry for a 100-day time-series achieves a noise level of 0.13 parts per million in amplitude at frequencies near 7 mHz. Figs. 1 and 2 both show the amplitude spectrum of θ Cygni at a frequency between 1 and 2.5 mHz, but in Fig. 2 the spectrum has been smoothed by a Gaussian smoothing (FWHM of $4 \mu\text{Hz}$). In both figures we see the excess from p -mode oscillations. The broadness of the individual oscillation peaks indicates that the mode lifetime is only a few hours, which makes accurate frequency determination difficult.

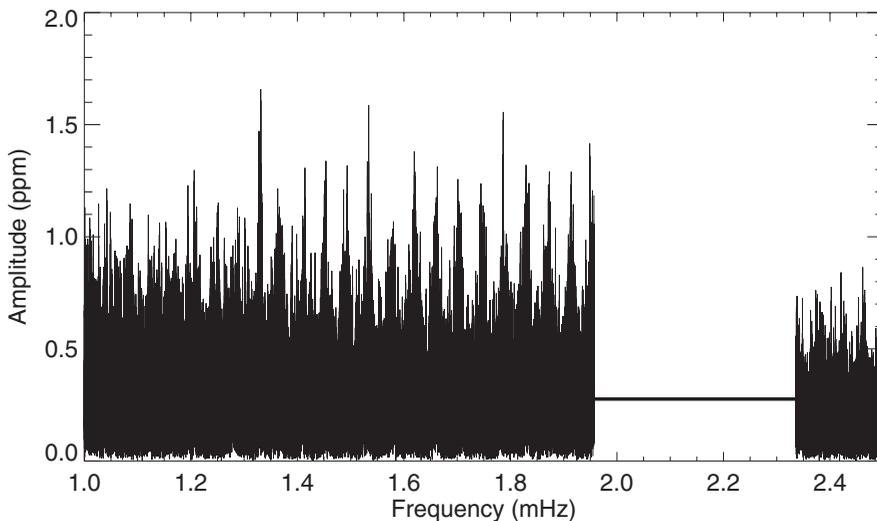


Figure 1. The amplitude spectrum of θ Cygni, observed for a period of 100 days by KEPLER. The spectrum clearly shows p -mode oscillations near 1.8 mHz despite the fact that the raw data saturated the detector by a factor of 1000.

3.2. Asteroseismic observables

The scientific impact which such high-precision photometric time-series data obtained from space can have on asteroseismology depends on the precision with which certain asteroseismic observables can be measured. Those observables are:

- Oscillation frequencies, frequency differences (splittings) and frequency ratios.
- Oscillation mode identification (degree, order and mode type; $g/p/f$, mixed)
- Oscillation mode properties (amplitudes, amplitude ratios, phases, phase differences, lifetimes)
- Variations (short-term and long-term) in mode parameters (frequencies, amplitudes, lifetimes)

The accuracy with which one can measure the above observables depends on the noise level per minute of observation and the length of the time series. We first consider data containing noise plus a number of coherent oscillations:

$$\text{data}(t) = \text{noise}(t) + \sum_{i=1}^n a_i \sin(2\pi f_i t - \phi_i). \quad (3.1)$$

We can estimate the uncertainties in the frequencies (f), phases (ϕ) and amplitudes (a), following Kjeldsen & Frandsen (1992) and Montgomery & ODonoghue (1999):

$$\sigma(a) = \sqrt{\frac{2}{\pi}} \langle A_{\text{noise}} \rangle = \sqrt{\frac{\langle P_{\text{noise}} \rangle}{2}} \approx 0.80 \langle A_{\text{noise}} \rangle \quad (3.2)$$

$$\sigma(\phi) = \frac{\sigma(a)}{a} \quad (3.3)$$

$$\sigma(f) = \sqrt{\frac{3}{\pi^2}} \frac{1}{T} \sigma(\phi) = \sqrt{\frac{6}{\pi^3}} \frac{\langle A_{\text{noise}} \rangle}{a T} \approx 0.44 \frac{\langle A_{\text{noise}} \rangle}{a T}, \quad (3.4)$$

where

$$\langle A_{\text{noise}} \rangle = \sqrt{\frac{\pi}{N}} \sigma_{\text{noise}} \propto T^{-1/2} \quad (3.5)$$

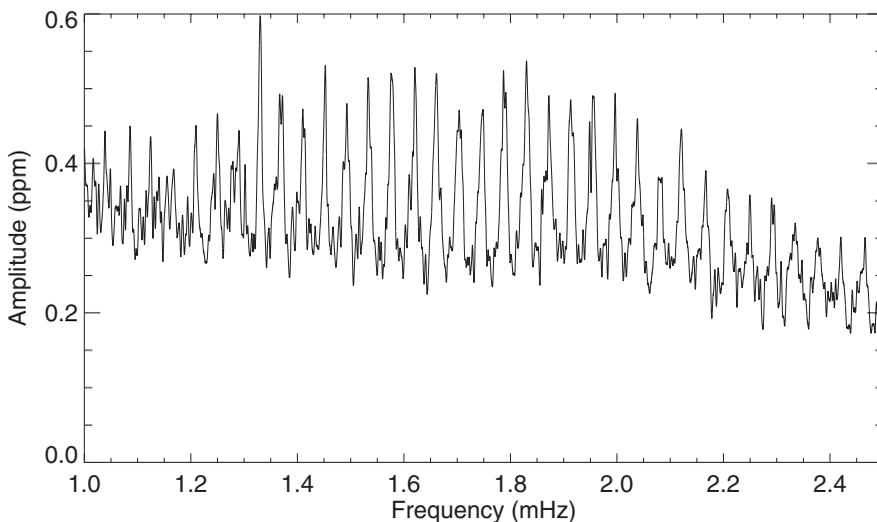


Figure 2. Same as Fig. 1, but smoothed by a Gaussian filter of FWHM of $4 \mu\text{Hz}$.

is the mean noise level in the amplitude spectrum at frequency f , T is the length of the time series, N is the number of data points in the time series and σ_{noise} is the noise per data point. If we define σ_{noise} as the noise level per minute in the time series (at frequency f) and assume that the time series is uninterrupted, we find for coherent oscillations that:

$$\sigma(a) \propto \sigma_{\text{noise}} T^{-1/2} \quad (3.6)$$

$$\sigma(\phi) \propto \sigma_{\text{noise}} a^{-1} T^{-1/2} \quad (3.7)$$

$$\sigma(f) \propto \sigma_{\text{noise}} a^{-1} T^{-3/2} \quad (3.8)$$

If instead we consider a damped and re-excited oscillation (like the one found in the Sun), we then find:

$$\sigma(f) \propto \sigma_{\text{noise}} a^{-1} T^{-1/2}. \quad (3.9)$$

For a mode lifetime of τ (which is infinite for coherent oscillations), we find the frequency accuracy to be:

$$\sigma(f) \approx 0.44 \langle A_{\text{noise}} \rangle a^{-1} \sqrt{T^{-2} + \tau^{-2}}. \quad (3.10)$$

If we consider the bright targets observed by KEPLER, we may use this last equation to estimate the accuracy in frequency obtained for solar-like oscillations. For stars brighter than magnitude $V = 8$, the noise level in the KEPLER data is 25 ppm per minute (Gilliland et al. 2010). The mean noise level in the amplitude spectrum will then be 0.13 ppm after three months, 0.04 ppm after three years and about 0.025 ppm after seven years. Table 1 shows the frequency accuracy for these values of T , for various values of amplitude and mode lifetime.

Table 1. Frequency accuracy for a $V = 8$ target observed by KEPLER

T	Coherent		Damped		
	$a = 0.01$ ppm	$a = 100$ ppm	$\tau = 10$ d $a = 50$ ppm	$\tau = 3$ d $a = 5$ ppm	$\tau = 6$ hr $a = 5$ ppm
90 d	0.7 pHz	70 pHz	0.0013 μ Hz	0.040 μ Hz	0.50 μ Hz
3 yr	0.02 pHz	2 pHz	0.0004 μ Hz	0.013 μ Hz	0.16 μ Hz
7 yr	0.005 pHz	0.5 pHz	0.0002 μ Hz	0.008 μ Hz	0.10 μ Hz

3.3. Evolution-related variations in the oscillation period

One of the main goals for long uninterrupted observations of stars with a large amplitude is to detect stellar evolution of main-sequence stars. That can be done by detecting slow variations in the oscillation period (Breger & Pamyatnykh 1998). The expected change in the quantity

$$\frac{1}{P} \frac{dP}{dt} \quad (3.11)$$

is larger than 10^{-8} yr^{-1} for δ Scuti Stars (Breger & Pamyatnykh 1998). According to the values in Table 1, the accuracy of the period determination for coherent oscillations increases rapidly with the length of observing time. For observing periods of 5–7 years, we should therefore be able to make a definite detection of stellar evolution in δ Scuti stars.

The accuracy with which one can determine a change in the oscillation period can be estimated from the equations above (for coherent oscillations):

$$\sigma \left(\frac{1}{P} \frac{dP}{dt} \right) \approx \frac{\sigma(f)}{f} \frac{1}{T} \propto \sigma_{\text{noise}} a^{-1} f^{-1} T^{-5/2}, \quad (3.12)$$

where σ_{noise} is the noise per minute of observations. As can be seen, we will increase by a factor of 100 the accuracy with which we can determine the effect of stellar evolution if observations are maintained continuously for 6 years compared to a 1-year campaign. The increase in accuracy from 3 to 7 years is a factor of 10. Such gain from long uninterrupted space observations clearly provides a strong incentive for extending the KEPLER mission beyond its nominal 3.5-year lifetime.

4. Acknowledgement

I acknowledge the huge work of the team behind KEPLER. Funding for the KEPLER Mission is provided by NASAs Science Mission Directorate.

References

- Auvergne, M., *et al.* 2009, *AA*, 506, 411
 Barge, P., *et al.* 2008, *AA*, 482, L17
 Batalha, N. M., *et al.* 2011, *ApJ*, 729, 27
 Beck, P. G., *et al.* 2011, *Science*, 332, 205
 Bedding, T. R., *et al.* 2011, *Nature*, 471, 608
 Borucki, W. J., *et al.* 2012, *accepted for publication in ApJ*
 Breger, M. & Pamyatnykh, A. A. 1998, *AA*, 332, 958
 Bruntt, H. 2007, *Communications in Asteroseismology*, 150, 326
 Bruntt, H. & Buzasi, D. L. 2006, *Mem. della Soc. Astron. Italiana*, 77, 278
 Bruntt, H. & Southworth, J. 2007, in: W. I. Hartkopf, E. F. Guinan, & P. Harmanec (eds.), *Binary Stars as Critical Tools and Tests in Contemporary Astrophysics*, Proc. IAUS. 240 (Cambridge, UK: Cambridge University Press), p. 624
 Deeg, H. J., *et al.* 2010, *Nature*, 464, 384
 De Ridder, J., *et al.* 2009, *Nature*, 459, 398
 Gilliland R. L., *et al.* 2010, *ApJ Letters*, 713, L160
 Kjeldsen, H. & Frandsen, S. 1992, *PASP*, 104, 413
 Koch, D. G., Borucki, W. J., & Basri, G. *et al.* 2010, *ApJ Letters*, 713, L79
 Leger, A., *et al.* 2009, *AA*, 506, 287
 Michel, E., *et al.* 2008, *Nature*, 322, 558
 Montgomery, M. H. & O'Donoghue, D. 1999, *DSSN*, 13, 28
 Walker, G., *et al.* 2003, *PASP*, 115, 1023
 Winn, J. N., *et al.* 2011, *ApJ Letters*, 737, L18