Stars and their variability observed from space
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WHAT WE CAN LEARN FROM CONSTANT STARS, AND WHAT DOES CONSTANT MEAN?

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Abstract. In this paper we postulate the need for a homogeneous sample of non-variable stars for various astrophysical applications. Although there are almost 1 000 000 high-quality space-based photometric light-curves publicly available, such a comprehensive sample still does not exist. We review the needed steps to achieve this goal, the possible pitfalls and present the first results of our corresponding project.

Keywords: Stars: variables: general, Methods: numerical, Techniques: photometric

1 Introduction

Theory predicts that if we look very closely on the brightness of any arbitrarily chosen star, we will find variability. The detection limit of the corresponding amplitude only depends on the instrumentation and accuracy of the measurements. This means that variable stars can be found at all locations across the Hertzsprung-Russell diagram (HRD). Countless papers over the last 150 years have been dedicated to the search and detection of new variable stars. Most astrophysical theories including stellar formation and evolution can be tested with variable stars because they allow a look deep into the stellar interior (e.g. Asteroseimology).

In the following, the term "non-variability" is defined as a given upper limit of variability in a certain wavelength range for a given time base and frequency domain.

Nowadays, we know of millions of variable stars in our Milky Way and other galaxies, especially due to large photometric surveys. In such a situation, it is more and more difficult to find really stable (constant), non-variable stars. However, do we need such stars? Just as an example, non-variable stars can be counted as boundary conditions of stellar models such as evolutionary tracks. It is therefore necessary to know the distribution of non-variable stars across the HRD answering questions like why there are variable together with non-variable stars in the classical instability strip.

In this paper, the need of such objects, the definition of non-variability, some time-series analysis techniques and first results of our dedicated project are reviewed.

2 Why do we need non-variable stars?

First of all, one has to keep in mind that if a star is not listed as variable within one of the various catalogues, this does not mean that it actually is non-variable. It might not be analysed in this respect or the amplitude is below the given detection limit. A photometric colour (index) of a variable object is then measured at a certain phase of the corresponding period. We know that colours and absolute magnitudes can vary significantly for different kinds of variable star groups. In Fig. 1 (adopted from Gaia Collaboration et al. 2019) those changes are shown for several groups. It is obvious that these shifts have to be taken into account when calibrating the effective temperature, mass, and age, for example.

But also studying amplitudes of variables is interesting for several fields of Astrophysics. For example, there exists an amplitude-period-metallicity relation for Cepheids and RR-Lyrae stars (Szabados & Klagyivik 2012). The question if all stars in the corresponding instability strips indeed show pulsations, is still not answered. There is also a clear correlation of the amplitude with the flare activity and spot filling-factor for M-type dwarfs (Yang et al. 2017).

Non-variable stars are very much needed for calibrations of observations as well as theories and models describing the stellar behaviour. Such calibration stars across the HRD are necessary for ground based and also satellite observations, in order to define flux standards, for example. Here, possible applications are listed:

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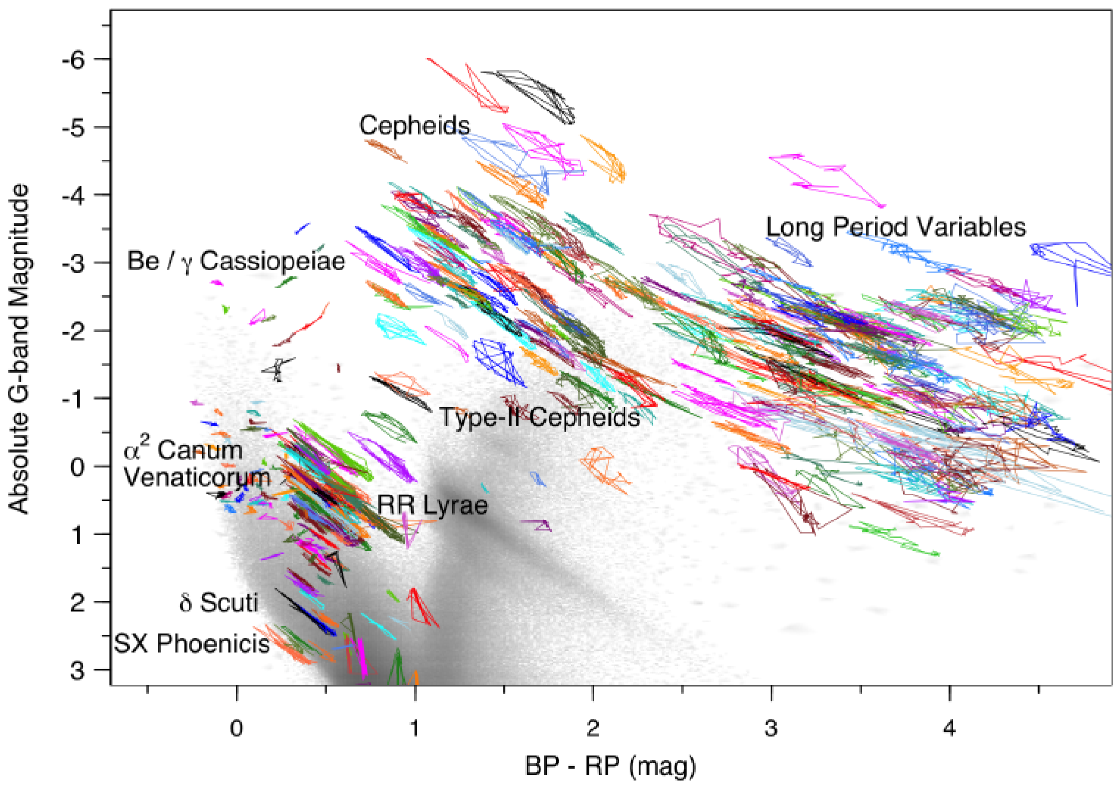

Fig. 1. The changes within the HRD for several variable star groups as adopted from Gaia Collaboration et al. (2019)

- Flux standards (Bohlin 2007)
- Radial velocity standards (Soubiran et al. 2018)
- Calibration of stellar formation and evolutionary tracks (Claret 1995)
- Testing pulsation models (Yadav & Glatzel 2017; Trabucchi et al. 2019)
- Photometric calibration of effective temperature, surface gravity, and metallicity (Netopil 2017)

Finally, the question which astrophysical parameters discriminate a variable and non-variable object in the identical [$T_{\rm eff}$,$\log L/{\rm L}_{\odot}$] or [dereddened colour, absolute magnitude] space is still not answered. One can think of the following parameters which might play a significant role:

- Rotation
- Metallicity
- Binarity
- Stellar Magnetic Field
- Circumstellar Material
- Inclination

A definite conclusion can only be drawn by comparing objects in the same astrophysical parameter space. Thus, generating a sample of non-variable stars (such a sample does not yet exist) will be useful in the wide community for many applications.

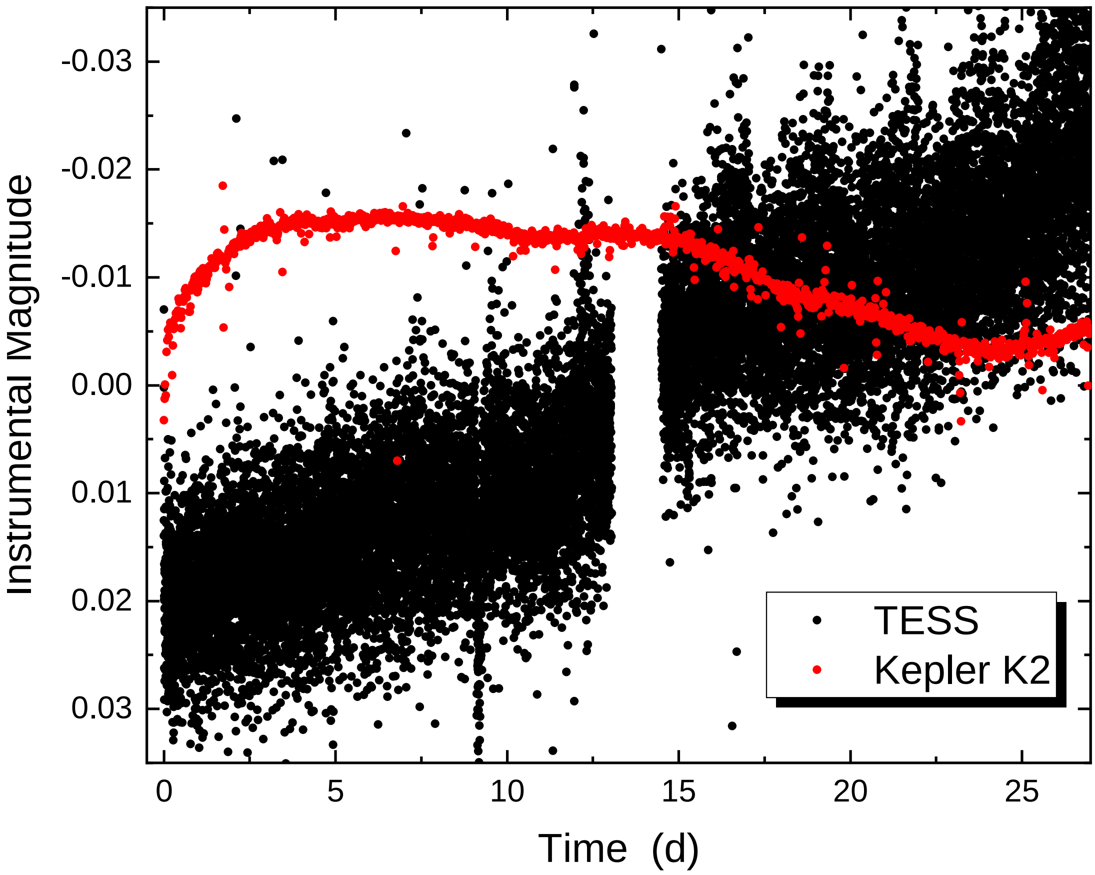

Fig. 2. The photometric data of Kepler K2 and TESS for one selected star. The light curves were shifted to the same zero points, i.e. the scales of the relative instrumental magnitudes were not changed. It is left to the reader to judge if this object is variable or not.

3 What does non-variability mean?

The classical approach is to search for a periodical (usually sinusoidal) signal in a time-series. Different criteria have been established in which frequency and amplitude range such a signal can be detected (Schwarzenberg-Czerny 1989). However, there is also a variety of other methods available, such as string-length (Schwarzenberg-Czerny 1997; Paunzen & Vanmunster 2016) and bootstrap (Paunzen et al. 2013; Mikulášek et al. 2015) methods. To define the (non-)variability, i.e. the significance of a peak in the periodogram, the False Alarm Probability (FAP) as defined in Horne & Baliunas (1986) can be used. If the usage of an automatic routine is intended, only a strict mathematical/statistical test can be applied. However, depending on the data set, the level of non-variability depends on

- Frequency range
- Time basis of the observations
- Amplitude – noise level
- Wavelength region – filter
- Applied "reduction pipeline software"
- Applied time-series analysis method

These characteristics should always be specified when publishing a corresponding analysis. In Fig. 2, the photometric time series of the Kepler K2 and TESS satellite missions for one selected star are shown. The light

Table 1. Characteristics of different data sets including the number of available light curves $N_{\rm lc}$, which is not necessarily the number of observed stars. Notice that the TESS measurements are still ongoing.

Name	Type	Cadence (d)	Time Basis (d)	Mag. range (mag)	$N_{\rm lc}$	Filter/Wavelength (nm)
CoRoT		0.00041/0.022	20 – 150	6 – 9/11 – 16	170 000	360 – 950
Kepler		0.00069/0.2083	1500	8 – 19	200 000	420 – 900
K2	Long Cadence	0.2083	80	8 – 19	490 000	420 – 900
	Short Cadence	0.00069	80	8 – 19	2 000	420 – 900
TESS		0.00139/0.02083	27 – 351	4 – 17	250 000	600 – 1 000

curves were shifted to the same zero points, i.e. the scales of the relative instrumental magnitudes were not changed. It is left to the reader to judge if this object is variable or not. However, this star is not listed in the latest version of the The International Variable Star Index (VSX, Watson et al. 2006). But it is obvious that an automatic analysis for such an object is very difficult to interpret in an astrophysical context.

4 How to determine non-variability

The number of available space-based photometric time-series, i.e. photometric light curves, which are publicly available for a significant number of stars is already huge (Table 1). For most of these data sources, an extensive analysis of the instrumental effects and thus introduced false periods is already available. The knowledge of these effects is very important for any time-series analysis (see Fig. 2).

The individual data sets have a different quality due to the processing pipelines. For example, the CoRoT data show small jumps and spurious trends (Paunzen et al. 2015). Before a time series analyses can be applied, an automatic cleaning and pre-processing of the data sets has to be performed. This procedure includes subtracting off the known instrumentally and orbitally introduced frequencies. Also a detrending has to be done.

Depending on the cadence and overall time basis of the data sets (see Table 1), the measurements have to be binned for analysing the desired frequency range. For example, if looking for periods of a few days, bins of one hour and one day should guarantee the search for possible variability in the most convenient way, smoothing out possible short-term variations.

From our experience, we wish to point out a few critical issues which are important in order to generate an automatic way of detecting (non-)variability

- Learning all about the "instrumental frequencies"
- Studying known variable stars in the used data set
- Being aware of the time basis
- Being aware of the frequencies removed by your method/algorithm
- Dividing the investigated frequency range, for example in a low- and high-frequency region
- Frequencies in an "uninteresting" domain may also affect the "interesting" domain
- Being aware of irregular (non-sinusoidal) variability
- Using more than one time series analysis method, i.e. Fourier and String based techniques
- Comparing measurements of objects from common data sets helps learning about the pitfalls

5 What is the current status of non-variable stars?

The status of non-variable stars from different data sources is very unsatisfying. Normally, their characteristics and statistical occurrence compared to the variable stars in the same [$T_{\rm eff}$,$\log L/{\rm L}_{\odot}$] or [dereddened colour, absolute magnitude] space are widely neglected and even not known.

One exception is, for example, the paper by Adelman (2001) who investigated time series from the Hipparcos mission. He found many objects reported as variable but turned out to be constant and vice versa.

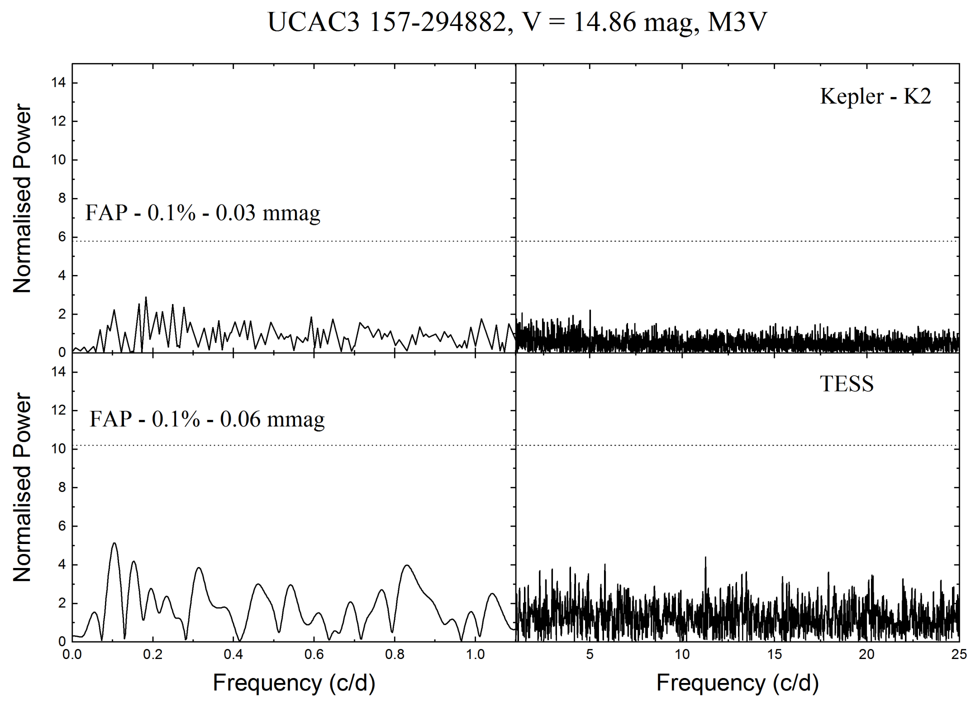

Fig. 3. An example of the result from our automatic algorithm analysing the Kepler K2 and TESS light curves for M3 V star UCAC3 157-294882. It shows two different frequency domains which were analysed.

Recently, a first basic study in this respect entitled "Gaia Data Release 2 – Variable stars in the colour–absolute magnitude diagram" (Gaia Collaboration et al. 2019) was published which we want to discuss in more detail in the following way. On the basis of the available Gaia observations, they searched for (non-)variable stars for which more than 20 observations in the three different bands are available and which have a relative parallax uncertainty of less than 5%. This transforms to a precision level of approximately 5 to 10 mmag. Furthermore, the reddening for all stars was neglected, which excludes the Galactic disk within $\pm 5^{\circ}$. Therefore, they have introduced a bias in their analysis because it is well known that especially young and massive stars are concentrated in the Galactic disk (Carraro 2014). These stars are missing in the published colour-absolute magnitude diagram. In summary, the paper by the Gaia consortium is an excellent guide-line and comparison for any new comprehensive study, but the given accuracy can be significantly improved using other data sets.

We have started a project for automatically analysing photometric light curves in order to define upper limits for non-variability. The algorithm is built such that any data set can be analysed with input parameters, such as known instrumental frequencies and trends, for example.

In Fig. 3, the example of the M3 V star UCAC3 157-294882 is shown. We used the Kepler K2 and TESS light curves for this object and the FAP as defined in Sect. 3 for two different frequency domains. The established non-variability for this 15th magnitude stars is in the sub-mmag region. Such an amplitude limit is need for testing the available pulsation models, for example.

The next step is now to analyse all available light curves from the data sets listed in Table 1 in a homogeneous way. The programs and results will be publicly available to the whole community.

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