New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000567

The CoRoT and Kepler Revolution in Stellar Variability Studies

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Abstract. Space-based observations of variable stars have revolutionized the field of variability studies. Dedicated satellites such as the CoRoT and Kepler missions have duty cycles which are unachievable from the ground, and effectively solve many of the aliasing problems prevalent in ground-based observation campaigns. Moreover, the location above the Earth's atmosphere eliminates a major source of scatter prevalent in observations from the ground. These two major improvements in instrumentation have triggered significant increases in our knowledge of the stars, but in order to reap the full benefits they are also obliging the community to adopt more efficient techniques for handling, analysing and interpreting the vast amounts of new, high-precision data in an effective yet comprehensive manner. This workshop heard an outline of the history and development of asteroseismology, and descriptions of the two space missions (CoRoT and Kepler) which have been foremost in accelerating those recent developments. Informal discussions on numerous points peppered the proceedings, and involved the whole audience at times. The conclusions which the workshop reached have been distilled into a list of seven recommendations (Section 5) for the asteroseismology community to study and absorb. In fact, while addressing activities (such as stellar classification or analysing and modelling light curves) that could be regarded as specific to the community in question, the recommendations include advice on matters such as improving communication, incorporating trans-disciplinary knowledge and involving the non-scientific public that are broad enough to serve as guidelines for the astrophysical community at large.

Keywords. methods: data analysis, methods: numerical, methods: statistical, techniques: photometric, surveys, stars: fundamental parameters, stars: oscillations, stars: variables: other

1. Introduction

Space-based asteroseismology started with the study of α UMa (Buzasi *et al.* 2000), which was observed with the star camera on board the WIRE satellite. The first satellite dedicated to asteroseismology (MOST, Walker *et al.* 2003b) was launched shortly afterwards, and was followed in 2006 with the launch of the larger CoRoT mission (Baglin *et al.* 2006). The latter mission was designed to have two concurrent observing strategies. Besides observing thousands of stars in its programme of exoplanet surveys, CoRoT was also the first satellite to acquire high-cadence photometric time-series of thousands of stars simultaneously. It was also the first satellite to observe targets, specifically selected for their seismic potential, continuously for several months, with a 32 s sampling. Then in 2009 the large NASA mission Kepler (Koch *et al.* 2010) was launched. Kepler is the first of its kind to be launched in an Earth-trailing orbit; the purpose was to minimize the influences of Earth-scattered light, the South Atlantic Anomaly, etc. Kepler now raises the number of stars observed simultaneously to nearly 150,000. It also monitors the same field continuously for several years.

2. Two Revolutions

The CoRoT and Kepler missions have revolutionized the study of stellar variability, for two reasons. In the first place they measured light curves for a vast number of stars, thereby enforcing the application and development of stellar classification and data mining tools. Secondly, almost all of the light curves for the individual stars have a duty cycle, precision and quality that is unachievable from the ground (Fig. 1 illustrates just a few examples of CoRoT light curves). The material can thus enable in-depth studies of particular targets, with or without acquiring additional data such as multi-colour photometry, spectroscopy, magnetic field measurements and the like.

Fig. 2 shows a comparison between Kepler light curves and phase diagrams from a typical large-scale ground-based survey (Trans-Atlantic Exoplanet Survey, TrES; O'Donovan et al. 2009). The jump in data quality is evident. In the case of ground-based observations, one often needs to phase the data in order to see variability at a given frequency, making the biggest challenge to overcome the *detection* of variability. The sparse time-sampling which is most typical for ground based observations, and is due to night/day cycles, telescope allocation time, instrumental downtime, etc., severely influences the height of the side lobes in the window function, allowing for confusion in the frequency detection (i.e., aliasing), and thereby complicating the interpretation of the detections even more. In the case of space-based data, however, the *characterisation* of the variability is most often the problem, since the high precision and high duty cycle basically solve aliasing and improve detection limits significantly. A comparison between the phase diagrams from TrES and the full light curves from Kepler makes it clear that phase diagrams hide part of the information present in the light curves. In CoRoT and Kepler photometry, the shape of the light curves is in general immediately apparent, and can be tracked over the entire time-span of the observations, whereas the construction of a phase diagram in those cases would tend to *reduce* the amount of information present in the light curve. In particular, that opens up the possibility to detect frequency or amplitude changes, sometimes over short periods of time. Another example can be found in exoplanet research, where the detection of transit-timing variations is now possible.

An example in which phase diagrams can still be useful is stellar classification, where simple and few attributes are to be selected. In such cases there is often no need to embark upon the subtle variations from phase to phase. The frequency of the dominant variation, for example, can already carry enough information to distinguish one class of variable stars from another.

3. Two Approaches

The two revolutions which CoRoT and Kepler have brought about (*viz.* the increase in the number of stars and the increase in precision), also gave us two approaches for treating the data: one can do case studies (for instance, those by Appourchaux *et al.* 2008 and Degroote et al. 2010), and one can do population studies, which usually involve classification algorithms or pipelines to extract useful parameters from the light curves (see, for example, Debosscher et al. 2009; Miglio *et al.* 2009). It is evident that both approaches are necessary to improve our knowledge of the stars in general and of stellar evolution in particular.

A common bias in case studies is that usually some information about the star is known (or gathered) in advance, such as its spectral type, and that the observed variability is interpreted in a matching framework. That partially solves the degeneracy that is often encountered and which is inherent to single-band light-curve analyses, i.e., that one morphological type can represent different types of underlying behaviour. Noteworthy examples of that effect include ellipsoidal deformation and mono-periodic pulsators, or spotted stars and (highly) multi-periodic oscillators. Unfortunately such an approach can lead to a false interpretation of data, and is thus not preparing us for the unexpected.

At least three methods of approach are suggested. One approach includes the treatment of the data under different assumptions about the underlying origin (perhaps together with a statistical model evaluation) or at least reporting alternative explanations. A second method, and perhaps a more objective approach, would be to refrain from physical interpretation as long as possible, but instead to describe the light curves as far as possible through purely observational parameters, and to approach observational data with an open mind. A third method is to gather more information, and it would be particularly useful to have multicolour photometric time series for the targets. Some degeneracy between effective temperature and reddening might exist, but at least in principle it can be accounted for. In that case, however, one should not rely too much on the KEPLER and CoRoT input catalogues, where various fundamental parameters for the stars are available but were derived with certain assumptions that might not be valid for all stars—as discussed by Pinsonneault *et al.* (2011). Nevertheless, the inherent faintness of virtually all CoRoT and KEPLER targets puts heavy constraints on the possibilities to acquire additional data.

Population studies of the CoRoT and KEPLER fields are often the basis for further research, so any researcher can select those targets according to a few selection

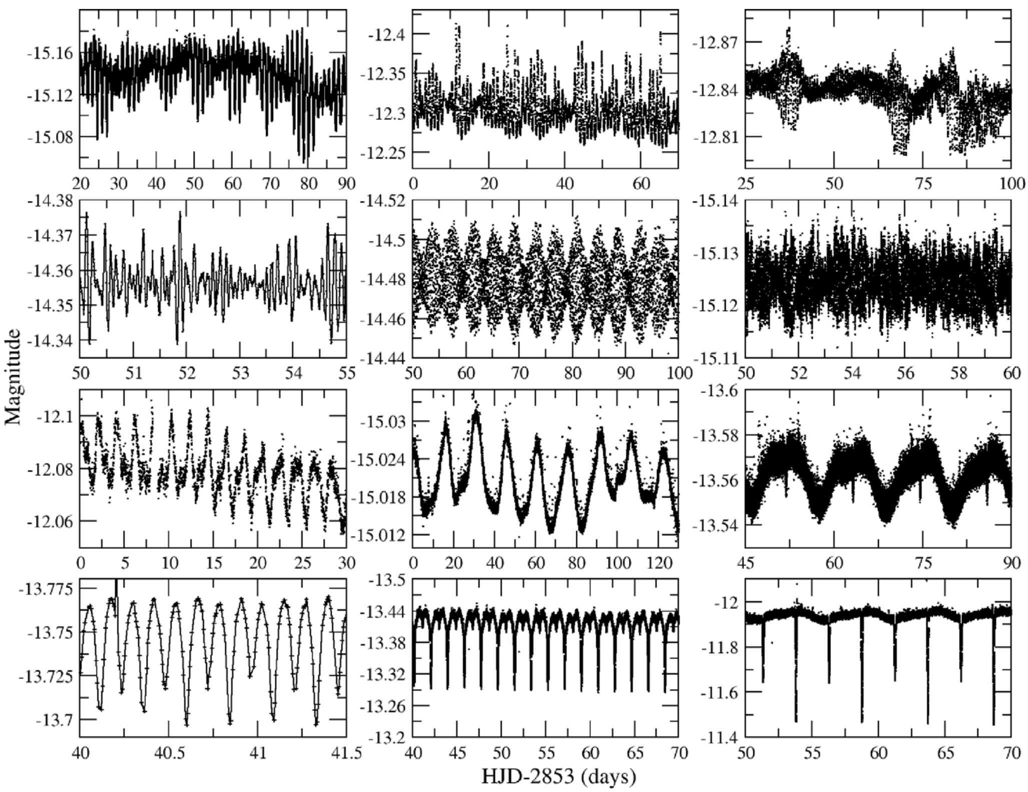

Figure 1. A sample of light curves measured by the CoRoT space mission, illustrating the enormous variety of stellar variability that can be observed with space-based instruments.

https://doi.org/10.1017/S1743921312000567 Published online by Cambridge University Press

criteria. Most classifiers label their targets and put them in predefined classes (supervised classification), while failing to recognise the underlying continuous spectrum of characteristics or possible hybrid properties. An alternative approach might be to use a list of tags (for example, the star is red/blue, is a high/low amplitude pulsator, is a slow/rapid pulsator... instead of labelling it as—say—an RR Lyræ star) or even representing the tags by a continuous number to indicate *how* red or *how* blue, and so on. On the other hand, such an approach could imply wrongly that classification can be carried out in an unbiased frame, but in fact there is a general tendency to agree that a truly unbiased and blind classification is impossible and that one should perhaps refrain from such a pursuit. A possible approach to a fairly unbiased (but not all-blind) classification could be the use of the non-scientific community to classify light curves, in analogy with the Galactic Zoo programme. Indeed, proposals and projects are actually under way to set up such endeavours.

Many of the methods that are currently applied to analysing and interpreting variable stars in the CoRoT and Kepler fields suffer from the bias arising from our prior knowledge. However, it is most difficult to account for the unexpected, so starting from what we already know is certainly the easiest way to start. We should be prepared to learn

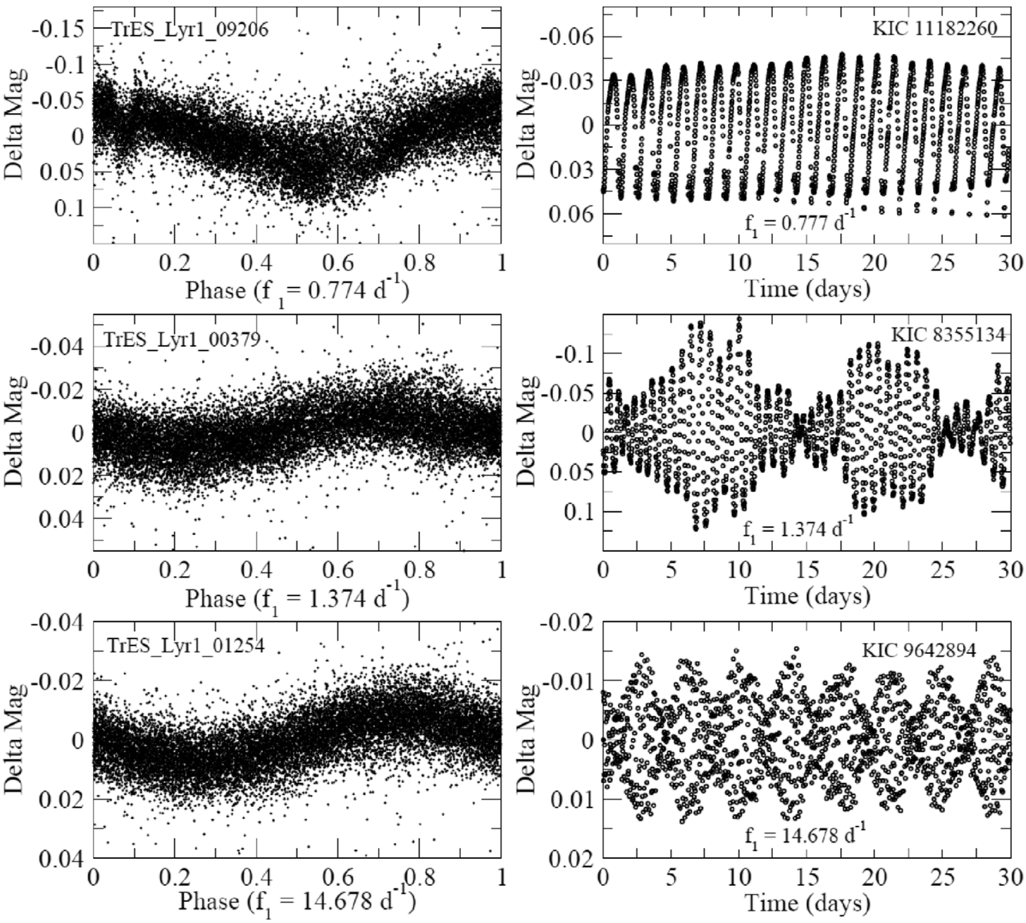

Figure 2. Comparison of light curves for the same targets from the ground-based TrES survey and the Kepler space mission. The TrES light curves had to be phased according to the dominant detected frequency to show the variability.

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more about the stars in the coming years, and incorporate that acquired knowledge in the further treatment of the CoRoT and KEPLER targets, ideally with a close involvement of theoreticians. We believe the knowledge and expertise, in contrast to the data quality, will not immediately make huge leaps (such as the sudden discovery of several new classes of variable stars). We also believe that this is even not desirable, because it would greatly increase the risk of false and hasty discoveries. The arrival of data with an unprecedented quality implies the use of new techniques, with which we are by definition not familiar. Instead of seeking the giant leaps, we should take small steps, and make sure we understand them before advancing further in the realm of the unknown and unexpected.

4. Long term Variability

Some stars have been observed photometrically for a century or more. That raises the question of whether it is possible to see real-time stellar evolution in some of them. It is the feeling of many, however, that even that time frame is still too short to witness the effects of evolution unambiguously, except in the case of the most rapidly evolving objects. The point is well illustrated by studies of Cepheid pulsators. From the O-C diagrams of these stars, it seems that the intrinsic phase-to-phase scatter of the periods is larger than the expected period change arising from evolutionary changes. On the other hand, some trends are noticeable in some Cepheid light curves—but the *sense* of the period change is often opposite to what is expected from evolutionary models. It is noted that that can be interpreted as evolutionary weather or noise, and reflects the fact that most of our models only reproduce long-term evolution, which for most stars implies longer than at least a century.

5. Recommendations

The Workshop discussed the above issues in some depth, and reached a variety of conclusions which we now list below as a number of recommendations:

(*a*) There are two areas where closer collaboration in the community could be beneficial. One is stellar classification, where the sharing of prior knowledge and newly acquired knowledge are critical to progress. The other is effective communication about the use of observational diagnostic tools and statistics in the treatment of light curves; the objective is to apply appropriate techniques for describing and analysing the exquisite light curves coming from CoRoT and KEPLER.

(*b*) Collaboration between groups can also be in the form of competition: the same data sets could be given to different groups for blind tests, in order to compare and evaluate different approaches.

(*c*) The inclusion of the non-scientific community is recommended, in particular for classification purposes. The non-scientific community could classify light curves visually (in a guided process), in an analogy to the Galaxy Zoo programme.

(*d*) The community is encouraged to communicate data and methods efficiently and uniformly. Various frameworks for that are already in place (e.g., the Virtual Observatory).

(*e*) We have entered a phase in variable-star research where input of new methods is particularly to be welcomed. We could benefit especially from looking at other scientific fields, such as geology, meteorology or computer sciences, which share an interest in time-series analysis and are (on some levels) more advanced than some of the practices that are common in the astronomical community.

(*f*) Observers are encouraged to separate theory from observation, and to try to parameterize light curves observationally. The optimal procedure is to use models that are independent from theory, but to use parameters which can be interpreted by theory (cf. the Gussian processes for modelling spots, instead of a spot model).

(*g*) The community is encouraged to be cautious, and to try to advance the field in small steps so as to acquire new knowledge in a reliable way. In particular one should be careful to draw firm conclusions from blind analyses, and to be fully aware of prior knowledge. Thus, instead of going for giant leaps we should take small steps, and should make sure we understand them before advancing further in the realm of the unknown and unexpected.

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