Solar and Stellar Variability: Impact on Earth and Planets
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First thoughts on stellar variability from Kepler commissioning data

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Abstract. The Kepler mission will obtain high precision, continuous lightcurves for more than ~150,000 stars over the next four years. Prior to primary mission operations, ten days of commissioning data were obtained for the ~52,000 brightest targets in the Kepler field. While Kepler's main goal is the discovery of transiting low mass planets, it will also provide a rich dataset for studies of variable stars. These commissioning data give a first glimpse of the amazing diversity of stellar variability Kepler will observe. Here, we discuss the tools we are currently developing to quantify variability in the Kepler data, and show initial results on the distribution of target stars in these metrics. Ultimately these measures will be used both to characterize the data and to select active rotationally modulated stars for rotation period determination.

Keywords. stars: activity, stars: statistics

1. Introduction

The Kepler mission is a 1-meter photometer whose primary goal is to discover Earth-like planets in the habitable zones of Sun-like stars. Launched in March 2009, Kepler is now 6 months into operations, taking photometry of ~150,000 stars near Cygnus every 30 minutes. These high cadence, long duration lightcurves are not only capable of identifying small planets transiting their parent stars, they also provide opportunities for a wide variety of ancillary science. In particular, Kepler will observe stellar variability (in all its various flavors) with unprecedented coverage and precision. In this sense, Kepler will be as revolutionary for stellar astrophysics as it will be for planetary science.

Prior to the official start of Kepler science operations, the mission began with 10 days of commissioning observations. During this commissioning period, photometry was taken for the 52,496 stars in the field brighter than a Kepler magnitude† of 13.5, with the intent of characterizing the precision obtained through initial operations of the telescope and the first builds of the software pipeline. Just over half of the targets observed during this period were giants, which are typically excluded from the planetary search target list due to their large radii (making them poor candidates for observing transits of small planets). However, the giants are useful as bright targets by which to characterize the instrument, and some are kept on the observing list in subsequent quarters for use as astrometric calibration stars. The Kepler commissioning observations also allowed an extensive study of the photometric behavior of giants versus dwarfs (after the style of Gilliland 2008) – for cases where a particular target is not classified in the Kepler Input Catalogue, photometric behavior may be used to separate out desirable dwarf targets from the not-so-desirable giants. In addition to helping us understand the behavior of the instrument, the Kepler commissioning data also provides our first glimpse into the

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† Kepler magnitudes are a broad bandpass optical magnitude between ~400-800 nm.

typical variability of a large sample of stars. The large sample of homogeneous space-based observations give us an unprecedented new view on stellar variability in its many varieties, from pulsations, to eclipsing systems, to magnetic activity.

As has long been observed on our Sun as sunspots and flares, magnetic activity is a source of both periodic and transient variability. There have been prior observations of similar phenomena on stars both like our Sun and considerably alien from it (e.g. Strassmeier 2002, Eyer & Grenon 1997), but these largely ground based observations suffer from such blights on observational astronomy as "daytime" and "weather", as well as the loss of precision that comes with observing through the Earth's atmosphere. As the magnetic field generation in stars is intimately linked with stellar rotation (Pizzolato *et al.* 2003), photometric modulation by magnetic features such as starspots provide a natural way to trace the rotation of the star. By measuring rotation periods for a large sample of stars, we can better constrain the relationship of rotation, activity, and age, as well as inform models of the magnetic field production.

However, prior to launching our full study of rotation for stars in the Kepler field, we must characterize the variability of the target stars as a whole. Because the sample size is so large, with ∼50,000 lightcurves in commissioning alone and ∼150,000 every quarter of regular operations, it is not feasible to characterize variability in each of the lightcurves by eye, nor is this a quantitative way to characterize the stars. We therefore developed a number of statistics and metrics that can be calculated automatically for the entire sample. These metrics may then be used to identify interesting subsamples (such as spotted stars whose rotation can be measured) that bear further investigation. We present these metrics, along with the results of our initial foray into characterizing photometric variability in the Kepler targets, below. This work is intended to demonstrate new methods of examining a large amount of qualitatively different stellar photometry in a quantitative way–truly physical results on stellar variability with Kepler await the main mission data and the further refinement of the methods described here.

The Kepler commissioning observations took place over ∼10 days in May 2009. The target list was composed of 52,496 of the brightest targets in the field. Many of these targets had been previously classified in the Kepler Input Catalogue (KIC; Batalha *et al.* 2007), a compilation of available physical parameters for all targets in the field (for example, Kepler magnitude, T_{eff}, logg, etc.). Of the commissioning targets, the majority were giants (24,357 stars), with the rest classified either as dwarfs (20,535 stars) or unclassified (7,591 stars).

2. Characterizing variability in the Kepler commissioning data

The Kepler lightcurves reveal an amazing diversity of variable behavior. In Figure 1, we show Kepler lightcurves for four different examples of stellar variability, clockwise from top left: a magnetically active spotted star, a semi-periodic oscillating giant, a relatively quiet solar analogue, and a dwarf with periodic oscillations. Raw flux lightcurves are converted into differential lightcurves by normalizing the lightcurve by the median of the raw flux and subtracting 1. The lightcurves show both an overall trend and shorter timescale features as well. As the data reduction pipeline is still under revision (and has indeed already been updated since the computation of these results and publication of these proceedings), the commissioning data may contain systematic effects that are likely not physical in nature. The lightcurves shown in Figure 1 have therefore been de-trended by removing a fourth-order polynomial fit to the data, and we focus here on the bulk features of variability on timescales shorter than 10 days. While some of the long term

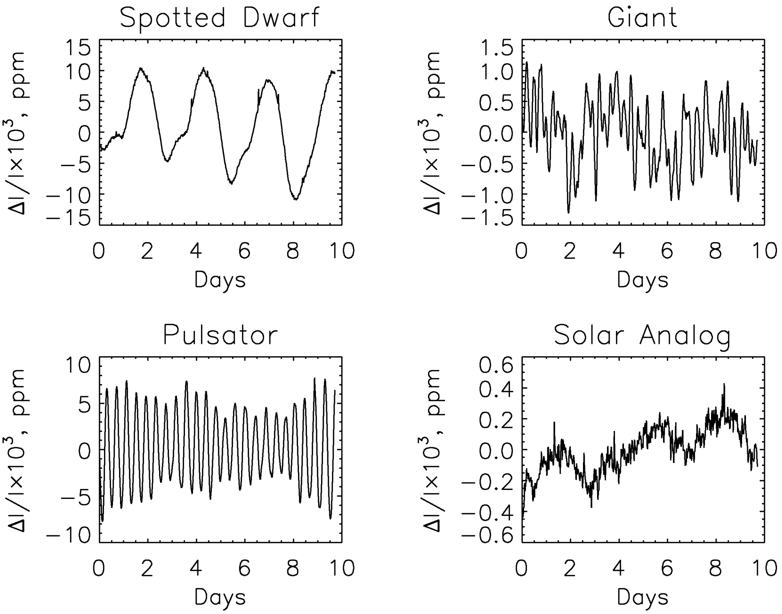

Figure 1. Example lightcurves for four different kinds of variable stars in the Kepler commissioning data, clockwise from top left: a spotted, rotationally modulated dwarf, a giant with small amplitude semi-periodic oscillations, a low activity solar analogue, and a hot pulsating dwarf.

trends our fit removes may be physical, we elected to err on the side of caution until the instrument is better understood.

From the rectified lightcurves, we calculate a set of statistics that can be used to quantify the variability. The maximum deviation above zero in the rectified curves is computed to capture the range of the largest feature in the lightcurve. To determine the point-to-point variability, we smooth the lightcurve on a 2 hour timescale and subtract this from the lightcurve itself, then calculate the standard deviation of the residuals. We use two metrics to determine the typical timescale of variability: the time separation between points where the differential lightcurve crosses zero, and the time separation between changes in the sign of the slope in the lightcurve. By searching the data using combinations of these statistics, it is possible to find populations of stars with similar variability characteristics.

3. Variability characteristics of the Kepler commissioning data

The statistics can be combined both to the characterize the sample and as filters to identify interesting populations for further study. The ability to isolate interesting categories of stars in this manner will be particularly important as the primary Kepler mission commences, when the number of targets will rise to ∼150,000 stars per quarter of observations. In Figures 2 through 4, we show the distribution of the Kepler targets in several of our metrics– all statistics are shown in parts per million (ppm), corresponding to a 0.001 fractional change in intensity. Figure 2 plots the point-to-point variability in 0.5 hour time sampling for the giants and dwarfs in the sample (top and bottom panels, respectively) as a function of Kepler magnitude. The point-to-point variability rises towards fainter magnitudes as a result of the increasing noise floor for fainter stars. As is evident in this figure, giants are more variable than dwarfs at similar magnitudes– while some of them are quiet, the majority of the giants describe a locus above the main

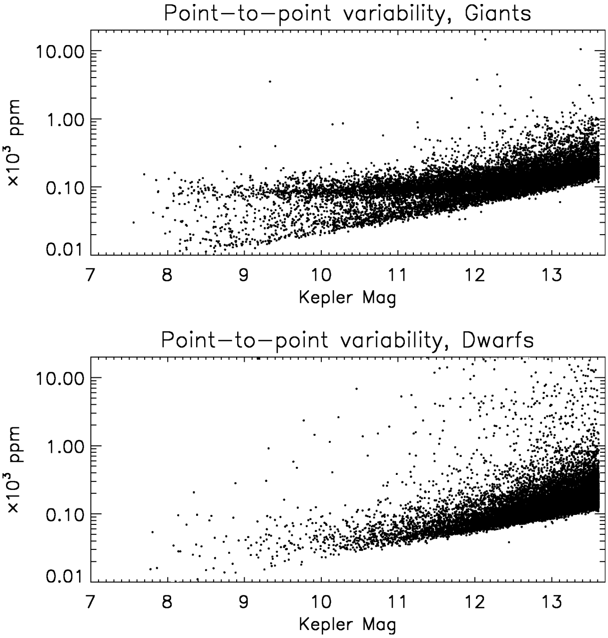

Figure 2. Point-to-point variability in parts per million (ppm) for giants (upper panel) and dwarfs (lower panel) in the Kepler commissioning data. The majority of giants are more variable on short timescales than the dwarfs, although some quite variable dwarfs (consisting of eclipsing binaries, pulsators and spotted stars) can be seen in the lower density cloud of points above the main locus of stars. The evident trend with magnitude is due to the rising noise floor for fainter stars.

density of dwarfs. The dwarfs are mostly quiet, with a lower density cloud of very variable stars lying above the main locus in the plot. These more variable stars consist of a mix of eclipsing/contact binaries, pulsators and spotted stars.

In Figure 3, we show the maximum deviation of the lightcurves from zero as a function of log (g). This metric quantifies the half amplitude of the largest features in the lightcurves– stars that are very variable have a high maximum peak height, while stars that are quiet have a low maximum peak height. Two main overdensities are seen here, the giants residing around a log (g) of $\sim$ 2.5 and a typical maximum peak height of just under 1 part in a thousand, while the dwarfs are located around a log (g) of $\sim$4.3 and a typical amplitude of 0.2 parts in a thousand. These two main populations are bridged by a lower density region of subgiants in between them. The population of active, pulsating or eclipsing dwarfs can be seen around the same log (g) $\sim$ 4.3 as the rest of the dwarf sample, but at much higher maximum deviations.

Lastly, Figure 4 shows the typical timescale of variability as measured by the "slope separation", or the median timescale of changes in slope in the lightcurves. The utility of this metric is that it quantifies the timescale of the features in each lightcurve, regardless of whether they are periodic. Large slope separations correspond to larger bulk features in the lightcurves, whereas very small slope separations are typically the result of quiet lightcurves with few large features (if any). In the figure, giants and dwarfs both appear to be active on all timescales, but only the dwarfs have members with very small slope separations, quiet lightcurves with few features.

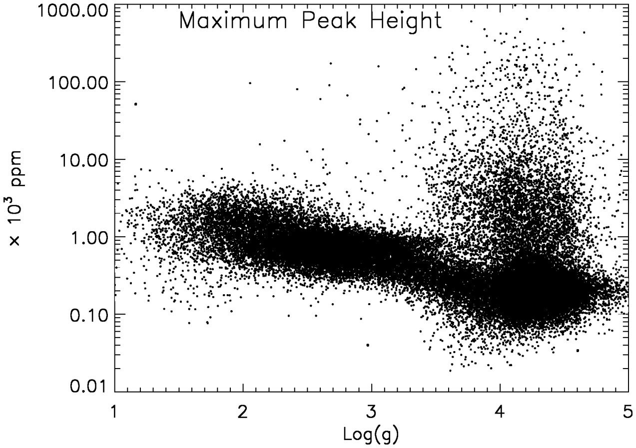

Figure 3. Maximum deviation from zero for all lightcurves in parts per million (ppm) as a function of log (g). There are two main overdensities of dwarfs and giants, bridged by a transitional population of subgiants. Active stars can be seen in the cloud of points at high gravity and high maximum deviation.

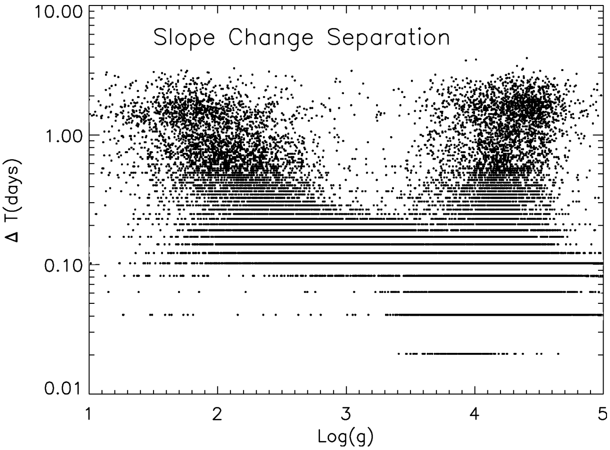

Figure 4. "Slope separation", or the median time between slope changes in the lightcurves, as a function of gravity. Slope separation shows the typical timescale of features in the lightcurve, whether they are periodic or not. Stars with large slope separation have features on longer timescales than those with small slope separation. Very small slope separation is characteristic of quiet stars without bulk features, where slope changes in the lightcurve are due to the point to point variability rather than large features.

4. Conclusions and Future Work

The Kepler mission holds great promise for investigations stellar variability in the years to come. Even in these relatively raw commissioning data, there are a multitude of interesting phenomena to whet the appetite for primary mission observations. The statistics and metrics we have developed and discussed here will be used to characterize variability for the full Kepler data set, and in particular to identify active spotted stars for rotation period determination. Ultimately, we intend to derive rotation periods, spot coverage, spot lifetimes and differential rotation parameters for as many of the Kepler targets as possible. In the coming months we expect to improve upon these metrics so that we may fully take advantage of the rich information content of the Kepler lightcurves.

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