

Monitoring young associations and open clusters with Kepler in two-wheel mode

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Abstract: We outline a proposal to use the Kepler spacecraft in two-wheel mode to monitor a handful of young associations and open clusters, for a few weeks each. Judging from the experience of similar projects using ground-based telescopes and the CoRoT spacecraft, this program would transform our understanding of early stellar evolution through the study of pulsations, rotation, activity, the detection and characterisation of eclipsing binaries, and the possible detection of transiting exoplanets. Importantly, Kepler’s wide field-of-view would enable key spatially extended, nearby regions to be monitored in their entirety for the first time, and the proposed observations would exploit unique synergies with the GAIA ESO spectroscopic survey and, in the longer term, the GAIA mission itself. We also outline possible strategies for optimising the photometric performance of Kepler in two-wheel mode by modelling pixel sensitivity variations and other systematics.

1 Introduction

Young associations and open clusters are very useful laboratories to study star formation and the early stages of stellar evolution, as they enable us to probe a specific set of properties for a group of stars sharing the same age and composition but spanning a range of masses. Time-series photometric observations of such systems, in particular, can be used to probe a host of important phenomena, including accretion (for the youngest star forming regions only), pulsations (from pre- to post-main sequence), rotation and activity. These observations can also be used to detect and characterise eclipsing binaries (EBs), and thus to constrain evolutionary models by measuring the fundamental properties (masses, radii, luminosities and temperatures) of their component stars in a model-independent manner. Finally, they can also be used to search for planetary transits, potentially offering a window into the earliest stages of the evolution of planetary systems.

Over the past decade, these science goals have motivated a number of major projects dedicated to the photometric monitoring of star forming regions and young open clusters. An exhaustive review of these projects and their achievements would be excessively long, but notable examples include the Monitor project (Aigrain et al., 2007), which monitored 9 star forming regions and open clusters aged < 200 Myr using 2–4 m telescopes worldwide. Monitor provided an unprecedented sample of rotation period measurements for young low-mass stars (see e.g. Irwin & Bouvier, 2009b; Moraux et al., 2013, and references therein) and led to the detection of the lowest mass and youngest stellar eclipsing binary known (Irwin et al., 2007b, see Fig. 4). More recently, the Palomar Transient Factory Orion project used a 1.2 m telescope and focused on the 25 Ori region, detecting a further 7 pre-main sequence (PMS) EBs (van Eyken et al., 2011) as well as what may be the first exoplanet transiting a PMS star (van Eyken et al., 2012).

An important limitation of these projects, however, has been the time-sampling achievable from the ground. By contrast, the CoRoT and MOST satellites were able to observe the NGC 2264 star forming region continuously for several weeks at a time, first in 2008 and again in 2011/2012, this time as part of a coordinated campaign using Spitzer, Chandra, VLT-FLAMES, CFHT and a number of other ground-based telescopes. The data from this program are still being analysed, but they have already provided fascinating insights into the rapid evolution of PMS pulsators (Gruber et al., 2012; Zwintz et al., 2013a,b) and the astonishing diversity of the variability of classical T Tauri stars (Alencar et al., 2010). The continuous time-sampling enabled a more robust determination of the rotation period distribution for the cluster (Affer et al., 2013), and led to the detection tens of EBs, including a dozen which are likely cluster members, one of which is the first low-mass EB to show evidence of a circumbinary

disk (Gillen et al., 2013).

Unfortunately, NGC 2264 was the only rich star forming region or open cluster located within the CoRoT ‘eyes’ (or visibility zone). The field observed by Kepler during the nominal mission contained only a handful of moderately old open clusters, although these have already yielded exciting results on rotation (Meibom et al., 2011), pulsations (Miglio et al., 2012) and the frequency of planets around cluster versus field stars (Meibom et al., 2013). The possibility of a two-wheel Kepler mission with decreased photometric precision, but increased flexibility in terms of pointing, aperture selection and observing strategy, represents a unique opportunity to monitor other key young associations and open clusters. A major advantage of Kepler over CoRoT and previous ground-based programs is its extremely wide field-of-view. This means that we can observe relatively nearby, spatially extended regions such as Taurus, the Pleiades, and the Hyades. Previous projects have avoided them because of the need to tile observations, but Kepler can observe a significant fraction of their members in a single shot. The very proximity of these regions not only makes them cornerstones of our understanding of early stellar evolution, it also greatly facilitates any follow-up observations.

2 The target clusters

Figure 1 shows the spatial and kinematic distribution of young moving groups, associations, and clusters in the solar neighbourhood, colour-coded according to age. The richest of these are prime targets for the proposed program, but we also include a few particularly important clusters at larger distances and/or older ages.

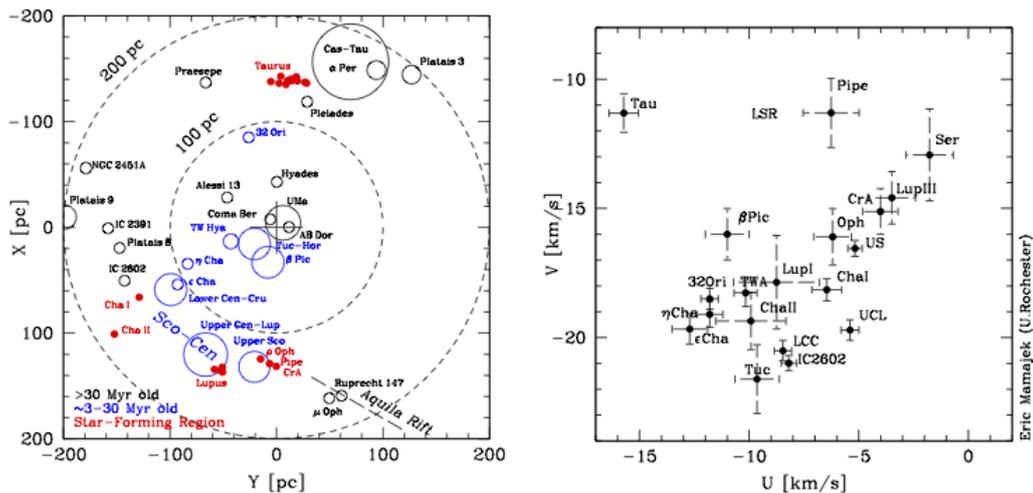


Figure 1: Spatial (left) and kinematic (right) distribution of nearby young associations (from Rice et al. 2011).

In the rest of this section, we discuss the most likely targets for this program, but we stress that this target list is neither exhaustive nor final, and would need to be adjusted depending on the total time available, constraints on the satellite pointing, preliminary indications of the photometric performance of Kepler in two-wheel mode, and detailed tallies of the latest membership information for each target.

First, Kepler has the unique ability to observe, in a single shot, the entire field of most of the nearest and richest star forming regions: such as Orion (Bally, 2008), ρ Ophiucus (Wilkins et al., 2008), Chamaeleon (Luhman, 2008) and Taurus-Auriga (Kenyon et al., 2008) complexes. In Orion alone, we could observe several thousand stars spanning an age range from 1 to ~ 12 Myr. The other three are less rich, with a few hundred members each (down to $V \sim 17$), but even more nearby (~ 150 pc), and their spatially sparse nature has so far hindered intensive photometric monitoring campaigns. The two Northern regions are extremely well-studied already, and the two Southern ones are included in the GES. Combined with the existing CoRoT observations of NGC 2264, and with the infrared variability information collected with Spitzer as part of the YSOVAR project (ysovar.ipac.caltech.edu), Kepler observations of these three regions would provide fascinating insights into the evolution of accretion, rotation, activity and structure in the first few Myr of stellar evolution.

Another very important group of targets are ‘intermediate age clusters’, ranging from ~ 30 to ~ 150 Myr, including for example: IC 4665 (Lodieu et al., 2011, 27 Myr, 350 pc), NGC 2547 (Jeffries et al., 2004, 30 Myr, 1400 pc), α Per (Lodieu et al., 2012, 80 Myr, 140 Myr), Blanco 1 (Platais et al., 2011, 90 Myr, 130 pc), and the Pleiades

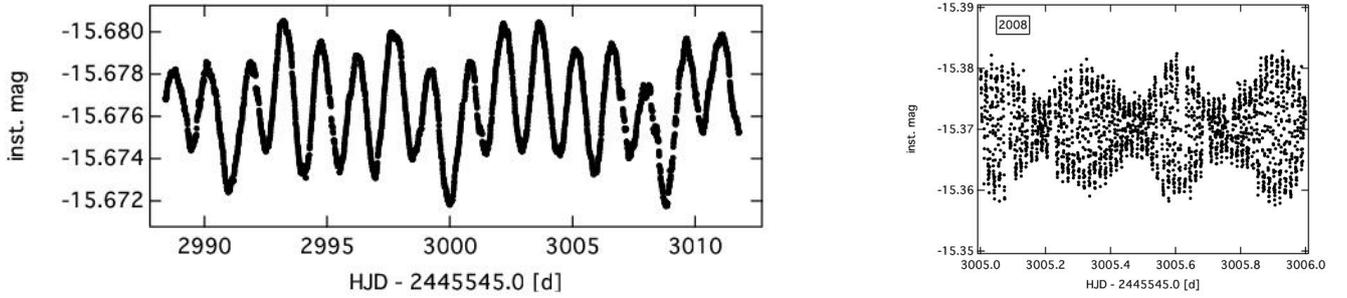


Figure 2: CoRoT light curves of PMS pulsators in NGC 2264. Left: the γ Doradus star NGC 2264 VAS 20 (Zwintz et al., 2013a). Right: 1-day section of the light curve of δ Scuti star HD 261711 (Zwintz et al., 2013b).

(Percival et al., 2005, 135 Myr, 150 pc). These clusters will enable us to probe the transition from PMS to MS and to study stellar evolution in a lower density environment. α Per and Blanco 1 in particular represent a critical age in rotational evolution, and currently have very little rotation period data. Although some are a little more distant than the youngest targets, most are still spatially extended. All those in the Southern hemisphere are in the GES, and the Northern clusters are extremely well studied already, minimising the need for dedicated follow-up observations.

Finally, we include the Hyades (Perryman et al., 1998, 625 Myr, 47 pc) and Praesepe (Kraus & Hillenbrand, 2007, 650 Myr, 150 pc), as ‘cornerstone’ where FGK stars have all arrived on the MS, while earlier type stars are already starting to evolve. The Hyades in particular are so near to the solar system, and so extended, that Kepler really is the only instrument capable of monitoring them in their entirety.

While there are between hundreds to thousands of members in each cluster down to $V \sim 17$ (approximately corresponding to the faint limit of Kepler in nominal mode), there is a case for pushing to fainter magnitudes, in order to probe low-mass stars and brown dwarfs. If it is feasible, a faint cutoff at $V \sim 19$ would increase the number of cluster members monitored size by a factor ~ 3 and take us to the hydrogen burning mass limit for almost all target clusters (well into the substellar regime for the nearest / youngest).

3 Science drivers

3.1 Pulsations

Asteroseismology offers a unique window into the interiors of stars, as amply demonstrated by the very successful asteroseismology program carried out during the nominal Kepler mission. The reduced photometric performance expected in two-wheel mode is very likely to preclude the study of very low-amplitude, Sun-like pulsations, but it should still be possible to study slower, larger amplitude ‘classical’ pulsators. It is particularly interesting to study pulsations in young stars, which are evolving rapidly compared to their older counterparts, and can thus provide particularly stringent tests of models of stellar evolution.

Young stars with masses between 1.5 and $5 M_{\odot}$ cross the instability strip in the HR diagram during their evolution towards the zero-age main sequence, and can thus display δ Scuti-like pulsations. Theory also predicts the existence of other kinds of pulsators among B to F type PMS and early MS stars, including γ Doradus stars (Bouabid et al., 2011) and slowly pulsating B (SPB) stars. Importantly, the interior structure of young stars in this mass range differs significantly from that of their evolved counterparts located in the same region of the HR diagram, whereas their atmospheric properties (and hence colours and spectra) are quite similar, so asteroseismology uniquely constrains the evolutionary stage of such stars. Asteroseismology is also, of course, an important test of theoretical models of the interiors of PMS stars, particularly when focussing on young open clusters, where all the stars formed from the same birth cloud. For example, the joint seismic analysis of the 6 pulsators known (at that time) in the 3 Myr old star forming region NGC 2264 by Guenther et al. (2009) highlighted some important discrepancies with theoretical predictions.

Pulsating PMS stars have spectral types from B to F, periods ranging from 30 min to 1 day and amplitudes of ~ 1 mmag or less. To detect and model these pulsations thus requires tight time sampling (5 min max) over periods well in excess of a day, as well as a photometric precision of order 1 mmag, which is difficult to achieve

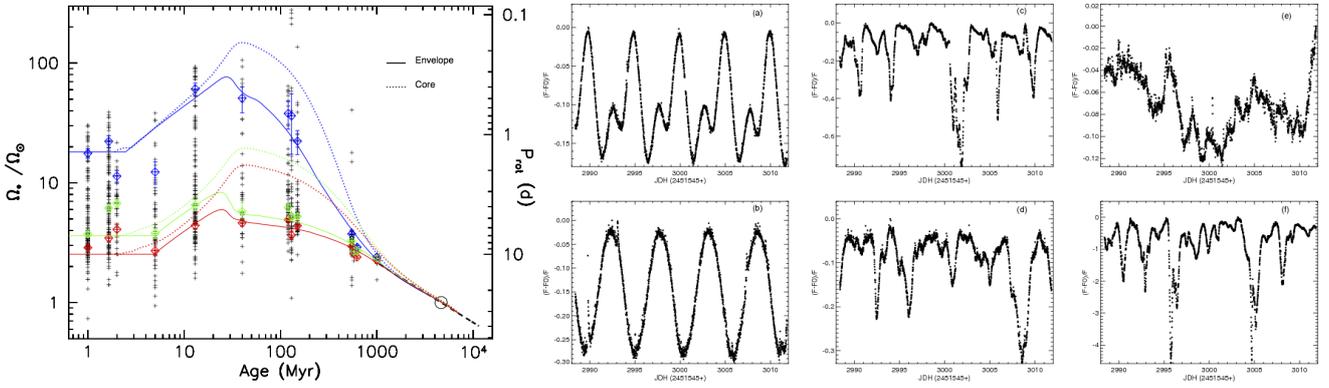


Figure 3: Left: Compilation of rotation period measurements for young open clusters with a range of angular evolution models (Gallet & Bouvier, 2013). Right: Example light curves of spectroscopically identified T Tauri stars observed by CoRoT in NGC 2264 (Alencar et al., 2010), showing spot-like, AA Tau-like and irregular variability (1st, 2nd and 3rd column, respectively).

from the ground. As a result, much of what we know about these young pulsators so far has come from a handful of objects located in NGC 2264, which has been observed repeatedly by the MOST and CoRoT satellites, and from dedicated observations of Herbig Ae field stars with the MOST space telescope. Notable achievements resulting from these observations include:

- the detection of tens of new PMS δ Scuti stars almost doubling the total number (Zwintz, priv. comm.; see Fig. 2, right panel);
- constraining the evolutionary state of a star from its pulsation frequencies (Guenther et al., 2007);
- showing that granulation in the stars thin convective envelopes might be responsible for the high numbers of low-amplitude frequencies observed (Zwintz et al., 2011);
- the detection of the first PMS star showing hybrid δ Scuti- γ Doradus pulsations (Ripepi et al., 2011);
- the detection of the first PMS SPB candidates (Gruber et al., 2012). B-stars have short PMS lifetimes, so these objects will enable us to study the transition from PMS to MS, i.e. from gravitational contraction to the onset of hydrogen core burning;
- the detection of the first PMS γ Doradus candidates (Zwintz et al., 2013b, see Fig. 2, left panel). These have similar frequencies to SPB stars, so distinguishing between the two requires a precise estimate of the effective temperature. The CoRoT observations of NGC 2264 were the first to have the precision and time coverage to enable this.

Observing a handful of young clusters and associations with Kepler would enable us to identify and study these different kinds of pulsators at a range of ages. We expect to find between 15 and 20 pulsators in each cluster.

3.2 Accretion, rotation and activity

The angular momentum evolution of young stars results from a trade-off between competing effects: contraction onto the main sequence and the associated spin-up, star-disk interaction (disk-locking), angular momentum loss via a magnetised wind, and internal re-distribution of angular momentum as the structure of the star evolves. The past decade has seen a large increase in the number of rotation period measurements available for PMS and early MS stars, but theoretical models still struggle to reproduce all the available data (see Fig. 3, left panel). While most well-studied young clusters and associations have been the subject of rotation period searches from the ground, these have typically focussed on the denser areas, and their period sensitivity is far from uniform. Monitoring selected clusters for a few weeks each would enable us to complete the census. Typical rotation periods for young stars range from 1 to 20 days (Irwin & Bouvier, 2009b), and modulation amplitudes from 0.5 to a few %, so the main requirement placed by this part of the science case is the duration of the observations of each region (at least 20 days, ideally up to 40).

Such observations would also provide an exciting window into the relationship between the amplitude and period of starspot-related variability, and – for the younger associations – between the latter and accretion-related variability. The CoRoT observations of NGC 2264 have shown that about 20% of the classical T Tauri (CTTS)

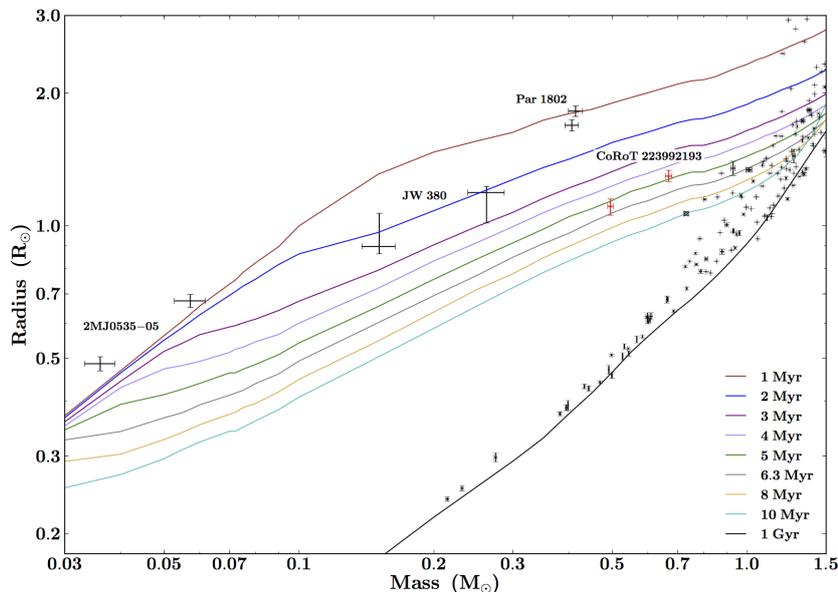


Figure 4: Mass-radius relation for low-mass stars. The lines show, from top to bottom, the theoretical isochrones of Baraffe et al. (1998). The black points show measurements for stars with masses $< 1.5 M_{\odot}$ in detached EBs (data from <http://www.astro.keele.ac.uk/~jkt/debdata/debs.html>), with one of the new systems discovered by CoRoT in NGC 2264 shown in red (Gillen et al., 2013). Note the improvement in mass and radius determination compared to other PMS systems, due mainly to the precise and continuous space-based light curve.

stars in the cluster presented light curves that can be attributed to periodic obscuration of the photosphere by the inner region of the circumstellar disk (see Fig. 3, right panel). These CTTSs, called AA Tau-like due to their resemblance to the well studied AA Tau system (Bouvier et al., 1999), offer the unique opportunity to study the properties of the inner disk region, located at only a few stellar radii from the star. This also allows the analysis of the dynamical star-disk interaction.

3.3 Eclipsing binaries and transits

Detached, double-lined eclipsing binaries (EBs) are extremely valuable objects because their masses, radii, effective temperatures and luminosities can be determined in a model-independent manner from the light and radial velocity curves of the system. When these reach a precision of a few percent or less, they provide one of the most powerful tests of stellar evolution models available (Andersen, 1991; Torres et al., 2010). As these models underpin most of astrophysics, it is vital that they are tested as rigorously as possible. The two components of a given EB can generally be assumed to share the same age and metallicity, which adds to the tightness of the constraints. Figure 4 shows the existing mass and radius measurements for low-mass stars belonging to detached EBs. While there are now many well-characterised systems on the main sequence, there are very few on the pre-main sequence (PMS). Furthermore, even in well-sampled regions of parameter space there are significant discrepancies between theory and observations, as models tend to under-predict the radii (or equivalently, over-predict the temperatures) of low-mass stars.

Detecting new, young, low-mass EB systems and characterising them in detail therefore remains a very important goal. The light curve shown in Figure 5 was obtained by CoRoT for a system with $V = 16.8$, and illustrates the kind of precision one can expect to achieve even in the worst case scenario with Kepler in two-wheel mode. As shown by the red points in Figure 4, this is sufficient (given suitable follow-up spectroscopic observations to measure the orbit of the system) to extract useful constraints on the masses and radii of both components. The continuous sampling achievable from space also significantly enhances the sensitivity to moderate period (8–20 days) EBs, enabling us to test the impact of varying degrees of mutual interactions between the two stars on their evolution (Chabrier, Gallardo, & Baraffe, 2007; Coughlin et al., 2011; Irwin et al., 2011). Based on experience from the Monitor project and the CoRoT observations of NGC 2264, we expect to discover around 10 new eclipsing binaries in each cluster.

Another very exciting prospect is the possible detection of transiting giant planets on short-period (< 10 days) orbits. Detecting transiting planets in open clusters has proved very difficult from the ground, not least because

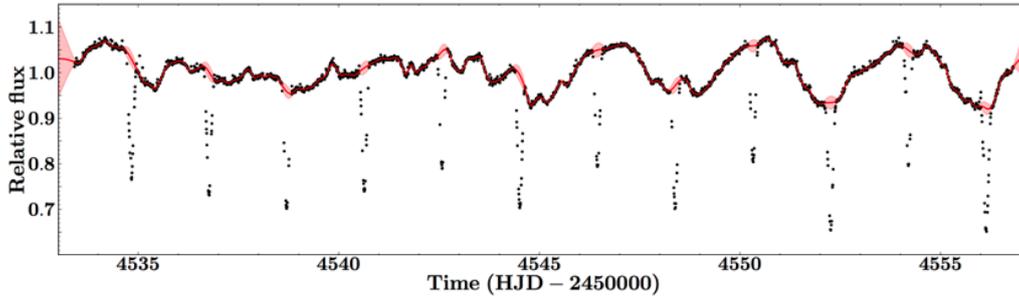


Figure 5: Light curve of CoRoT 223992193, a low-mass EB discovered by CoRoT in NGC 2264 (Gillen et al., 2013). The out-of-eclipse (OOE) variability is modelled using a Gaussian process model (red line).

the targets tend to be relatively distant, and thus faint, making spectroscopic follow-up very expensive. The PTF-Orion project has nonetheless shown that it is possible (van Eyken et al., 2012). Furthermore, the radial velocity detection by Quinn et al. (2012) of 2 planets in a sample of 53 stars monitored in Praesepe indicates that hot Jupiters are at least as common in young open clusters as in the field. Based on calculations similar to those performed for Monitor (Aigrain et al., 2007), we expect between 0 and 2 transiting planets to be detectable in each cluster; the exact number is very sensitive to the photometric precision (not yet known) and time coverage.

4 Synergy with other projects

Aside from the aforementioned CoRoT and MOST observations, the proposed program is similar to the Monitor (Aigrain et al., 2007), but would supersede it significantly in terms of field-of-view, precision and sampling. There is also some overlap with the science goals of YSOVAR project (<http://ysovar.ipac.caltech.edu/>), which monitored a number of star forming regions with warm Spitzer. The wavelength range is clearly complementary, and again Kepler observations would provide improved sampling over a much wider field of view. Re-observing some of the targets already observed by Monitor and YSOVAR will be valuable per se, for example to chart evolution in disk and star-spot activity in individual stars on multi-year timescales.

Importantly, the proposed observations will benefit from a very natural synergy with the Gaia-ESO Public Spectroscopic Survey (GES, PIs G. Gilmore and S. Randich, Gilmore et al. 2012), a large homogeneous survey of the distributions of kinematics and chemical element abundances in the Galaxy, designed to complement the astrometric, photometric and low-resolution spectroscopic data that GAIA itself will provide. The GES will obtain spectra of $\sim 100\,000$ stars with VLT/FLAMES, focussing on well-defined samples of Milky Way field and cluster stars. The cluster component of GES will cover 80–90 clusters spanning a wide range of age, richness, mass, composition, morphology, etc, ranging from the closest associations to massive clusters at few kpc from the Sun, with ages from 1 Myr to 10 Gyr. For each cluster, an unbiased sample of stars are selected in order to derive, together with the Gaia data, accurate distances, 3-D spatial distributions and motions. It will also provide precise radial velocities for each star observed, and hence unbiased (w.r.t. activity) estimates of membership probability, as well as the mass, age, abundance, binarity, lithium abundance, and $v \sin i$ of most members. For the youngest clusters, GES will discriminate between classical and weak-lined T Tauri stars (CTTS/WTTS), and thus between active and inert disks. All of this information will be crucial to interpret the light curves provided by Kepler. The GES observations started in January 2012 and ~ 15 clusters have already been observed, including several of the nearest young clusters included in this proposal. If the Kepler observations proposed here go ahead, a detailed plan and formal agreement with the GES management team will be put in place to make the most of the synergy, but we note that all GES data are public in any case.

The GAIA mission itself is due for launch in late 2013 and will, over the course of a 5 year mission, provide micro-arcsec astrometry, multi-epoch (70 epochs average, 200 max.) millimag photometry, low-res (20–50) spectra and, for the brighter objects ($V < 15$), moderate resolution spectra and km/s radial velocities. It will deliver proper motions with $\sim 20\,\mu\text{as}$ accuracy down to $V \sim 15$, and $\sim 200\,\mu\text{as}$ accuracy down to $V \sim 20$, as well as sub-milliarcsecond parallaxes down to $V \sim 20^1$. This will enable the derivation of model-independent (kinematic trace-back) ages for young clusters and associations, and distances with relative precision better than 10% down

¹GAIA performance data from <http://www.rssd.esa.int/index.php?page=Science.Performance&project=GAIA>.

to the brown dwarf regime for the nearest clusters in this proposal. GAIA will also yield orbital solutions for multiple systems, including binary stars and gas giant planets at a few AU from their host star. The first GAIA positions will become available 2 years after launch and the first parallaxes 6 months after that, while the full dataset will be delivered at the end of the mission.

At the preparation stage, preliminary results from GES (and GAIA, depending on the timing) will make the definition of photometric windows for individual cluster members to be observed by Kepler extremely efficient. The detailed characterisation of the clusters and their members provided by GAIA and GES data will also, of course, facilitate the interpretation of the Kepler time-series. GAIA will also help in other way, for example its photometry will extend the period sensitivity of the Kepler observations; the GES and GAIA RVs will provide orbital solutions for the EBs identified by Kepler, and the GAIA astrometric data will complement the EB sample at wide separations.

Finally, we note that many of the stars which we propose to monitor would be prime targets for follow-up observations with the James Webb Space Telescope (JWST), due to their youth and proximity.

5 Proposed observations

5.1 Expected photometric performance

The reduced pointing performance of Kepler in two-wheel mode is expected to affect the photometric performance significantly. Based on simulations performed to date, the call for white papers forecasts a photometric precision of about 0.5–1 mmag per 1 minute integration for a $V = 12$ star (cf. 30 ppm during the nominal mission), but warns that pixel sensitivity variations may limit the overall relative photometry to 0.3–1%. We take these two extremes as our best and worst case scenarios, respectively. The best-case scenario might be attained by implementing novel methods for calibrating the pixel sensitivity variations, extracting photometry from trailed images, and/or disentangling the systematic effects from the intrinsic variability of each star in the light curve itself (see Section 6). Since the decrease in precision in two- compared to three-wheel mode is due to systematics, we do not expect the faint-end performance to be affected significantly, so that $\sim 1\%$ photometry could be achieved down to Kepler magnitudes of ~ 19 (extrapolated from Jenkins et al. 2010).

5.2 Observing strategy

The projected lifetime of Kepler in two-wheel mode is 1 to 2 years. In a one-year program, we would be able to monitor 8–12 clusters for 4 to 6 weeks each. The main driver for the duration of the observations is sensitivity to longer rotation periods and longer period EBs, but the duration will also affect – for example – the precision of the asteroseismic analysis. Given two years, we could extend the target set, or the duration of each run (increasing sensitivity to long-period rotators and EBs) or return to some of the clusters observed in year 1 to probe long-term evolution of the variability properties. Even if the time available is much more restricted, so that only a few clusters can be observed, this will already represent a many-fold increase in the number and range of stars monitored in this way.

Target lists for each cluster will be constructed by collating all the membership information available in the literature and from the GES and GAIA. The number of known members in each of the clusters listed in the previous section ranges from a few hundred to several thousand. Photometric apertures will be defined so as to follow the trail of each star, and will be allocated in priority to known members of the cluster. The remaining telemetry can be used to observe other targets in the same fields. In the denser, central regions of some clusters, it may be advantageous to download contiguous sections of the detector by collating multiple apertures.

The standard 30 min cadence is acceptable for some of the science goals discussed above (rotation, activity, EBs and transits), but some require a cadence of ~ 5 min or better (pulsations, rapid variability in T Tauri stars). Whether a subset of the targets are selected to be observed at the standard short cadence (1 min), or a different combination of exposure times, it is clear that the time sampling requirements of this program are not expected to be problematic. While observing any given region once would already represent a significant advance, if the possibility arises, it would also be interesting to revisit one or more of the targets after one or more years, as done with CoRoT for NGC 2264, to track secular changes in the different types of variability being studied.

As discussed previously, a lot of information is already available about the properties of the target regions and their members. Nonetheless, if this program goes ahead, we will also seek to organise simultaneous monitoring campaign with other ground- and space-based facilities (spanning complementary wavelength ranges), as we have done in the past for NGC 2264.

6 Possible strategies for optimising photometric performance

The reduced pointing performance affects the photometric performance in two ways: through pixel sensitivity variations (the star samples many more pixels during an observation, each of which may have a slightly different sensitivity) and because the images will be come trailed for any integrations longer than about 5 min.

6.1 Modelling inter- and intra-pixel sensitivity variations

The best way to reduce the impact of inter- and intra-pixel variations may be to devise a novel way of calibrating them prior to the observations. In the absence of such a development, however, it might be possible to calibrate them, on a star-by-star basis, from the pixel time-series themselves. Below we outline a simple model for doing this. This model relies on a number of simplifying assumptions, some of which may well be excessively naive, but we merely suggest it here as an idea. We have not had the opportunity to implement and test it yet, but we would be interested in working with the science office to do so, if the opportunity arises.

Consider one star whose flux and position on the detector at time t are given by $S(t)$, $x_0(t)$ and $y_0(t)$, respectively. The ultimate quantity of interest is S , which is not known *a priori*. On the other hand, it is reasonable to assume that x_0 and y_0 are known (from individual centroid measurements and/or global modelling of the satellite pointing). The spatial distribution of the flux on the detector is defined by the point-spread function, $P(\delta x, \delta y)$, where δx and δy are the departures from the star's nominal position in the x and y directions, respectively. For now we assume that the point-spread function for a given star is constant in time – we address the time-dependence of the PSF introduced by the pointing drift later. Again, it is reasonable to assume that the PSF is well-known, or at least that it can be reduced to a known function with a small number of free parameters. The flux recorded during the k^{th} integration by the $(i, j)^{\text{th}}$ pixel is then

$$F_{ijk} = S(t_k) R_{ij} \int_{x=i-0.5}^{x=i+0.5} \int_{y=j-0.5}^{y=j+0.5} D(x-i, y-j) P(x-x_0(t_k), y-y_0(t_k)) dx dy, \quad (1)$$

where R_{ij} is the (unknown) peak sensitivity of the $(i, j)^{\text{th}}$ pixel, which we assume to be constant in time, and $D(\delta x, \delta y)$ represents the relative intra-pixel sensitivity variations, where $D = 1$ for $\delta x = \delta y = 0$. Once more, we have assumed that D is independent of time, that it is the same for all pixels, and that it can be described by a simple parametric function (in the simplest extreme, $D = 1$ everywhere).

If there are N observations spanning M pixels, i.e. $N \times M$ data points in the entire time-series, the above model has $N + M + K$ free parameters, where K is the number of parameters associated with the functions P and D , and is assumed to be small. In practice, the effective number of data points will be smaller, as only $M' < M$ pixels will contribute significantly to the PSF at any given time. On the other hand, as the pointing of the satellite will be reset periodically, the same pixels will be sampled multiple times. Therefore, overall the problem should still be well constrained. Where appropriate, additional leverage may also be gained by placing certain restrictions on the form of S (e.g. by constraining it to vary smoothly, quasi-periodically, etc. . .), if the star in question is a known type of variable, for example.

The practical implementation of this model will be challenging, due to the large number of parameters. However, we do expect it to be feasible, for example using advanced Markov Chain Monte Carlo sampling methods (see e.g. Foreman-Mackey et al., 2013) specifically designed to explore large and complex parameter spaces. Whatever the inference method used, this will be a computationally intensive process, and it may be that this approach could be applied only to specific objects where attaining maximum precision is particularly important.

Moving stars and trailed images In practice, the pointing drift will cause the PSF to be elongated for any integration lasting more than a few minutes. It will also mean that the position of a star can change significantly,

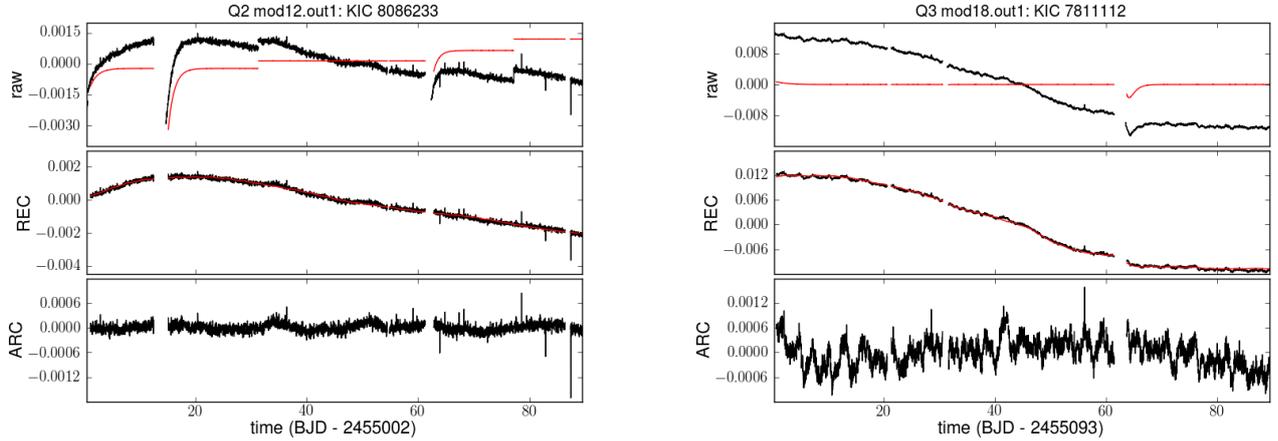


Figure 6: Two-step systematic correction for two representative examples from quarters 2 (left) and 3 (right). Top: raw data (black) and correction applied for discontinuities (‘REC’, red). Middle: REC-corrected data (black) and correction applied for common-mode systematic trends (ARC, red). Bottom: ARC-corrected data.

which may alter the PSF. To address this we replace equation 1 with the slightly more complex expression:

$$F_{ijk} = \int_{t=t_k}^{t=t_k+\delta t} S(t_k) R_{ij} \int_{x=i-0.5}^{x=i+0.5} \int_{y=j-0.5}^{y=j+0.5} D(x-i, y-j) P(x-x_0(t), y-y_0(t), x_0(t), y_0(t)) dx dy dt, \quad (2)$$

where P is now a function of the instantaneous position of the star as well as the departure from this position.

6.2 *A posteriori* correction of systematic effects

In this section we discuss potential strategies for mitigating the effects of any instrumental systematics, which are not calibrated out at the light curve extraction stage. During the nominal mission, the light curves extracted and calibrated by the standard pipeline displayed systematic effects, which were corrected in part by the pre-search data conditioning (PDC) step, albeit often at the expense of the intrinsic variability (other than transits).

To address this problem, we have adopted a two-step approach, which is still under development but is giving good results. We model common-mode systematic trends by modelling each light curve in turn as a linear combination of all the other light curves, and then applying a statistical entropy criterion to ensure that any trends identified in this manner are genuinely systematic (Roberts et al., 2013). This algorithm, which we call ‘ARC’ (Astrophysically Robust Correction of systematic trends), uses a Bayesian approach with shrinkage priors to avoid overfitting, which we implement within a variational inference framework to ensure computational efficiency. On the other hand, some instrumental effects, in particular the discontinuities and thermal decays associated with monthly data download events, are present in all the light curves, but cannot be represented adequately by a linear basis model such as the one used by the ARC. We model these on a star by star basis, postulating a functional form for the systematic effect, and modelling it at the same time as the stellar variability itself, which we treat as a Gaussian process (GP, a very flexible, yet robust class of models, where functions are parametrised indirectly through their covariance properties). We refer to this as fault rectification (REC), and apply it before the ARC (see Figure 6 for examples).

In two-wheel mode, we anticipate that common-mode systematics will be less widespread, as inter-pixel sensitivity variations (rather than global effects such as focus changes associated with the thermal relaxation of the satellite) are expected to dominate the systematics budget. Therefore, it may not be possible to describe any systematic effects which make it through the light curve as a linear combination of a small number of basis trends common to many light curves, which is the basis of the ARC algorithm. Indeed, the form of the systematics might well be unique to each light curve. On the other hand, it is also unlikely that we will be able to describe them using a specific functional form, as we have done for the thermal decay events during the nominal mission. However, the systematics are likely to be correlated in some way with the position of the star on the detector. We therefore suggest that it might be possible to model them using a GP, whose inputs are the x and y positions of the star on the detector. This is very similar to the technique developed by our group to treat systematics in

Hubble Space Telescope exoplanet transmission spectra observations (Gibson et al., 2012), which we have also successfully used to model the pixel response function of Spitzer (Evans et al., in prep.).

7 Conclusions

We have shown that Kepler in two wheel mode could be a very powerful tool to monitor nearby, spatially extended young clusters and associations, thanks to its unique field of view, continuous coverage, and a photometric performance which, while reduced, is still likely to be very good. For example, observing 8–12 clusters for 4–6 weeks each, would lead to an order of magnitude increase in the number of known PMS and early MS pulsators, and enable us to chart the evolution of intermediate and low-mass stars onto the main sequence in unprecedented detail. It would complete enable us to probe the full diversity of accretion and activity-induced variability right (right into the brown dwarf regime for the some clusters), and complete the census of rotation periods in some of the nearest and best studied young associations. Finally, it will also lead to an order of magnitude increase in the number of well-characterised, young eclipsing binaries, and may lead to the detection of a few young transiting planets. We have shown that there are valuable synergies between the proposed observations and the GAIA-ESO survey, as well as the GAIA space mission itself. Finally, we have also outlined possible strategies for optimising the photometric performance of Kepler in two-wheel mode, which could be used for a wide range of observing programs.

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