

Response to "Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft" (2 August 2013) by
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THE SUN IN TIME: FROM THE YOUNG SUN TO THE CURRENT EPOCH

ABSTRACT

We propose a *Kepler* program to obtain a unique data set consisting of observations of short-term, transient activity and longer-term cycle-related, magnetic activity and associated irradiance variability in solar-type members of open clusters with ages from ~ 10 Myr – 400 Myr. We also discuss a new data collection mode for *Kepler* with broad applicability and minimal operations and cost impact. The results will significantly advance our understanding of the potential range of variability in solar-type stars on both short and evolutionary time scales, from the very young Sun to the contemporary Sun. The data can then be utilized as input for realistic models of planetary atmospheres from early to contemporary phases of evolution. In essence, we will delineate the nature and range of the joint variability of luminosity and activity experienced by planetary systems bathed in the ambient and variable radiation fields of their parent suns at all astrobiologically relevant time scales.

SCIENTIFIC PROPOSAL

1. Overview

The question before us is not whether there are terrestrial-size planets in the Habitable Zone of solar-type stars. Rather, given that there are such exoplanetary systems we must now characterize them in all the parameters relevant to biological systems, which is a fundamental goal of Astrobiology.

This premise leads to the next major step beyond the detection of exo-earth systems: the characterization of the radiative and energetic particle environment encountered by exo-earth atmospheres. Taking this step will yield the essential input for the development of realistic models of planetary atmospheres in the Habitable Zone (HZ).

The changing output of solar-type stars—from the time of planet-formation in a given system to the current epoch—provides a critical boundary condition for understanding (1) the formation and early evolution of planetary atmospheres ($t < 500$ Myr) and (2) climatic variations among more mature planets ($t > 500$ Myr). Delineating overall energy output, shorter-term transient activity, and longer-term solar-like cyclic activity in sun-like hosts of exo-earth systems yields crucial insight on how frequently earth-like atmospheres are likely to form and survive, and how often exo-earths encounter benign climatic variations.

The solar atmosphere exhibits a variety of magnetic field-related phenomena that we refer to collectively as "activity". Evidence for this same kind of activity is readily detected in spectroscopic and broadband photometric observations of sun-like stars. In particular, observations of solar-type stars have now demonstrated that activity-related, irradiance

variations are a universal property of a normal, late-type star. Moreover, the level of activity is generally correlated with age in the sense that the young precursors to solar-like stars exhibit enhanced activity. This activity then declines with age in single (i.e., non-binary or multiple) stars.

In a study of nearby, solar-type stars, Lockwood et al. (1997) find that among stars with levels of activity that are within a factor of 2 of the Sun's average value (as measured by the strength of Ca II H&K emission), over 40% of the sample exhibited irradiance variations ranging from 0.3% to 1.2%, i.e., 3 to 12 times the amplitude of irradiance variations observed in the Sun!

For solar-type members of the much younger, 700 Myr old Hyades cluster, the *mean* level of cyclic irradiance variation is about 1%, i.e., 10 times the level of present-day solar variations (Radick et al. 1998). Thus, we infer that the ~ 500 Myr-old Sun typically exhibited irradiance variability at a level that was an order of magnitude greater than what we see now, while the level of magnetic activity was at least 3.5 times greater. A mean level of magnetic activity that is about 6 times greater than the contemporary Sun characterizes younger sun-like stars in the 100 Myr Pleiades cluster. While irradiance monitoring of these stars over long time-scales has not yet been performed (an objective of this program), the predicted level of cyclic irradiance variability (based on mean chromospheric emission levels) is about 2% or 20 times that of the present-day Sun.

In addition to irradiance variations, explosive outbursts in the form of flares or Coronal Mass Ejections (CMEs) influence the radiative and energetic particle environment in which exoplanets reside, sometimes with dramatic effects. In an investigation of the potential effects of stellar activity on an earth-like atmosphere in the habitable zone of an M dwarf flare star, Segura et al. (2010) examined the response of the ozone layer to a powerful flare event characterized by strongly enhanced UV flux and an associated energetic proton flux. In their model calculations, the column density of protective ozone declines catastrophically by a factor ~ 10 in two years after the flare, and the ozone concentration does not recover to its initial column density until about 48 years after the event!

The dominant factor affecting the ozone depletion in the Segura et al. models is the impact of energetic protons on the atmosphere. It is often assumed that this effect is mitigated *if* the planet has a magnetosphere. However, magnetospheres may not be a guarantee of immunity to stellar activity. For example, another potential effect on the structure and evolution of exoplanet atmospheres, even in the presence of a planetary magnetosphere, is the possibility of atmospheric escape due to stripping by the stellar wind, analogous to the solar wind (Brain et al. 2012). Magnetic activity becomes relevant since it is associated with the field configurations that modulate stellar winds in addition to its roles in modulating luminous output and determining angular momentum evolution in solar-type stars.

We know that solar UV radiation plays a critical role in the chemistry and dynamics of the earth's atmosphere. The UV irradiance of the young Sun may have contributed to the origin of ozone and free oxygen in the prebiotic atmosphere of the young earth (Canuto et al. 1983; France et al. 2013). Similarly, the nature of the habitable zones of planetary systems, including the chemical structure and evolution of exo-earth atmospheres, will be impacted by the level and variability of the UV irradiance as its significantly enhanced above the photospheric ultraviolet spectral irradiance by magnetic field-related activity in the host stars over both short and long (cycle-to-evolutionary) time scales.

In the case of the Earth-Sun system, UV radiation from the Sun dissociates molecules, ionizes the neutral atmosphere, and affects many chemical cycles in the terrestrial atmosphere. While the total bolometric luminosity variation of the Sun averaged over a solar cycle is only about 0.1%, the relative variation at solar UV wavelengths is over 10 to 100 times greater depending on wavelength. The solar cycle variability at UV wavelengths longward of 160 nm is 15%; 15% to 70% between 160 nm and 65 nm; and, factors of 1.5 to 7 between 65 nm and 1 nm. While not directly observable by *Kepler*, we can estimate the amplitude of UV variability from the *Kepler* variations based on correlations between visible band and UV variability derived from solar observations. More active stars will have higher relative amplitudes of UV variability.

The high-precision photometry achievable by *Kepler* can reveal the nature and range of activity-related irradiance variations in the visible band where approximately 50% of the bolometric flux in solar-type stars is emitted. The detection by *Kepler* of “superflares” on solar-type stars (Notsu et al. 2013) with total energies in the range of $10 - 10^6$ times greater than the largest flares on the Sun suggests the high likelihood of significant impacts of transient activity on the structure and chemistry of exoplanet atmospheres.

2. Science Program

We propose the establishment of a *Kepler* program to investigate the short-term and evolutionary properties of magnetic activity-related irradiance variations in solar-type stars spanning a range of ages that coincides with the joint evolution of planetary atmospheres and life in the habitable zones of extrasolar systems. The most effective and efficient approach to this kind of investigation is to obtain *Kepler* observations of *Open Clusters*. Essentially, open clusters serve as spatially confined and physically associated aggregates of stars that are homogeneous in age and chemical composition, thus removing the ambiguities inherent with samples of field stars. Moreover, this approach utilizes the key capabilities of *Kepler*, namely, the acquisition of high precision photometry for many stars simultaneously across a significant angular extent. From a programmatic perspective, this alternate science investigation is the next logical step beyond the discovery of exoplanet systems.

The spectral irradiance variations most important for exoatmosphere studies include transient outbursts such as flares or stellar analogs of Coronal Mass Ejections (CMEs), the stellar/solar rotation period on timescales of days (which modulates the strong emission from active regions), and the multi-year stellar/solar cycle time scale. In the case of the Sun, the 11-year solar cycle produces variations in the UV that are factors of 2-3 times larger than that due to rotational modulation of surface activity.

2.1. Flares and “Superflares” in Solar-Type Stars

The amplitudes of solar “white-light” flares are typically too small to be detected in the disk-integrated, “Sun-as-a-star.” However, “superflares” have been detected in solar-type stars with ground-based observations at amplitudes ~ 0.1 mag in the visible band (Schaefer et al. 2000). *Kepler* enormously expanded the number of detected flares in solar-type stars, discovering 365 superflares in ~ 120 days of observation in the *Kepler* field. As defined by Maehara et al. (2012) superflares have total energies in the range of $\sim 10^{33} - 10^{38}$ erg, or $10 - 10^6$ times the largest flares on the Sun ($\sim 10^{32}$ erg), with durations of 1 – 12 hours (Schaefer 2012). Significantly, those stars in which superflares were recorded did not exhibit any evidence for planetary transits, especially those that might be due to a hot Jupiter. Magnetic reconnection with the magnetosphere of a hot Jupiter was one model for the origin of superflares. The Maehara et al.

results suggest that any such association between superflaring stars and hot Jupiters must be rare.

The potential effects of powerful flare events on an exoplanet atmosphere include transient heating, global aurorae, disruption of the ionosphere, and ozone depletion. With respect to the latter, energetic photons and protons impinging on an earth-like exoplanet atmosphere will create nitrous oxides that will initiate a cycle of ozone destruction. This can result in an $\sim 80\%$ loss of ozone for at least one year, thus permitting irradiation of the planetary surface by stellar ultraviolet radiation (Schaefer 2000).

A program of one-month duration per cluster observation would reveal the frequency and energy distribution of flare outbursts on homogeneous samples of solar-type stars. The time-scale of one-month allows observation for at least one or more rotation periods in the solar-type members, thus sampling the entire surface of the star. The ability to look at all cluster members simultaneously means that we will see stars at random phases in their activity cycles, analogous to the 11-year sunspot cycle.

By conducting this program for a sequence of clusters, we will gain insight on the evolution of flare activity in both frequency and energetics at all stages of importance for the evolution of exoplanet atmospheres. Of course, solar-type stars are expected to flare more frequently at the ages of the younger clusters though the maximum power and energy of observed flares may be the same at all ages, up to solar age (Notsu et al. 2013).

2.2. Angular Momentum Evolution in Solar-Type Stars

The data obtained for the flare program can be utilized to obtain rotation periods from the rotational modulation of the light-curve by starspots. In fact, superflaring and rotation period appear to be intimately related in the sense that more rapidly rotating solar-type stars have a higher frequency of powerful flare events. In addition, the amplitude of the modulation, corresponding to the area coverage of spots, is correlated with flare energy. On the other hand, more slowly rotating sunlike stars can exhibit flares that are as energetic as those seen in more rapid rotators though at a lower frequency of occurrence (Notsu et al. 2013).

The measurement of rotation periods combined with future sensitive Doppler searches for exoplanets in cluster members will address the open question of the relationship, if any, between stellar angular momentum evolution and exoplanet system formation and evolution. The rotation measures also can address key questions in the origin of magnetic activity in late-type stars.

We know that a regenerative dynamo gives rise to emergent magnetic fields and the associated array of “activity” that we see in the Sun and solar-type stars. The dynamo involves the interaction between rotation and convection in a plasma. The activity we see is empirically correlated with rotation so that, in general, stars that rotate more rapidly have higher levels of chromospheric and coronal emission.

But we also know that a critical ingredient in dynamo models is differential rotation. For example, scaling relations suggest that activity cycle periods are more sensitive to differential rotation than to rotation rate alone (Giampapa 2012). To measure differential rotation would require multiple visits to clusters to detect drifts in rotation periods. Since we will be observing samples of stars at random phases in their cycles, it is likely that we will be able to see small

changes in rotation period in many objects during the life of this program. The results also will yield the distribution of rotation periods with spectral type (mass) and its evolution between clusters, thus providing a picture of angular momentum evolution in late-type stars with unprecedented accuracy.

2.3. Irradiance Variability in Solar-type Stars

As discussed in §1, irradiance changes on short (rotational) and long (cycle modulation) time scales are a universal property of solar-type stars. Clusters provide a view of irradiance variability as a function of age and at random cycle phases. Therefore, a program of 1 – 2 years can yield insights for stars with multi-year cycles. Observations of a sequence of clusters will yield the evolution of broad-band brightness changes in solar-type stars.

Solar UV radiation plays a dominant role in the chemistry and dynamics of the earth's atmosphere. Similarly, the nature of the habitable zones of young planetary systems, including the chemical evolution of young planetary atmospheres, will be impacted by the level and variability of the UV irradiance arising from magnetic field-related activity in the parent stars over both short and long (cycle-to-evolutionary) time scales.

Of course, the UV emittance is not directly observable with *Kepler*. Therefore, our approach will be to rely on the observation of brightness changes in the visible as an accessible surrogate for UV irradiance changes in solar-type stars that are members of open clusters of known ages. In particular, we will use solar multi-band visible and UV observations that have been collected since 2003 by the SORCE (Solar Radiation and Climate Experiment) spacecraft. The SOLSTICE (Solar Stellar Total Irradiance Comparison Experiment) instrument onboard the SORCE satellite obtains daily ultraviolet (115-320 nm divided into two bands) irradiance measurements while the SIM (Solar Irradiance Monitor) instrument acquires visible band data that overlaps with the *Kepler* bandpass. Unruh et al. (2011) have shown that there is a strong correlation between the UV and visible band irradiance changes. We can apply this correlation to our solar-type star data from *Kepler* to obtain an estimate of the amplitude of corresponding UV irradiance changes.

Kepler observations of irradiance changes on short and long time scales in multi-year observations of individual clusters would be referenced to the ensemble average (which should be stable for uncorrelated variability among cluster members) and a single, high-quality reference frame.

3. Target Clusters and Observing Program

The mean level of normalized chromospheric Ca II line emission in sun-like stars in clusters of known age is illustrated in Fig. 1 (adapted from Walter & Barry 1991) and summarized in Table 1 below. Table 1 also gives the approximate position of the cluster center, the apparent diameter in arcminutes and the apparent V magnitude of the Sun at the cluster distance based on the distance moduli given by Becker and Fenkart (1971), which are good enough for initial planning purposes. The selected clusters not only represent a meaningful range in age but they also have complete membership lists along with a rich database of ground- and space-based observations.

The focus of this program will be on the first five clusters. However, we also include the young clusters, α Per and NGC 2264, as options for the study of variability in solar-type stars at the

young ages that presumably correspond to the early history in the evolution of planetary atmospheres soon after the epoch of planet building.

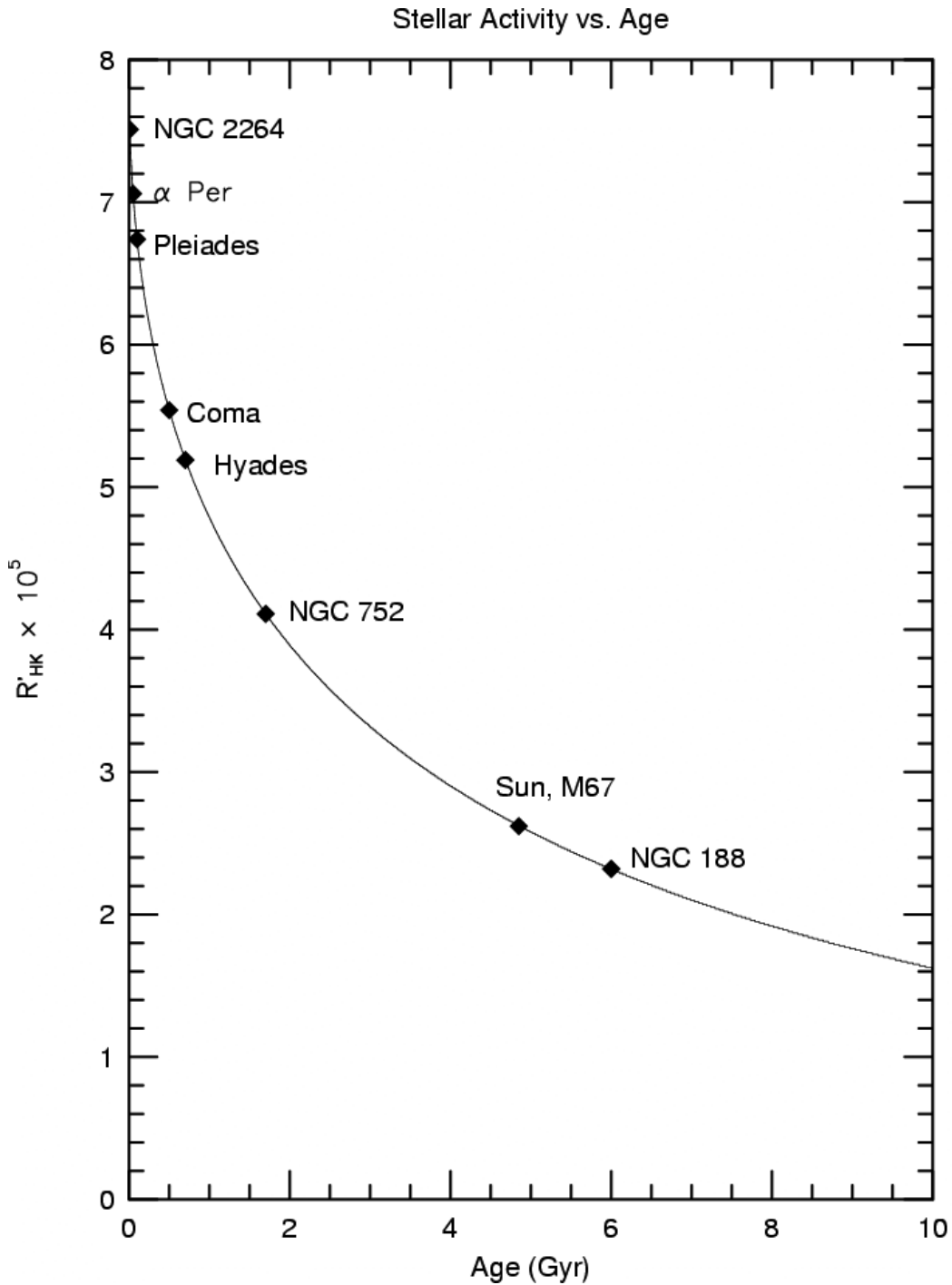


Fig 1: The mean level of magnetic field-related activity of solar-type stars in open clusters of known age. The index R'_{HK} is the chromospheric component of Ca II H&K line emission normalized by the stellar bolometric (total) flux. The amplitude of brightness variability and the frequency of powerful flare events are generally correlated with chromospheric and coronal activity in late-type dwarf stars. *Figure adapted from Walter and Barry (1991)*

TABLE 1. Open Clusters for *Kepler* Sun-in-Time Program

Cluster	Age (Myr)	RA (h-m)	DEC (° ')	Angular Diameter (arcminutes)	V (Sun)
Pleiades	100	03-44	+24 00	120	10.5
Coma	400	12-23	+26 00	300	9.4
Hyades	700	04-17	+15 31	400	7.8
NGC 752	1700	01-55	+37-26	75	12.8
M 67	4000	08-48	+12-00	30	14.6
α Per	50	03-20	+49-00	240	11.3
NGC 2264	< 10	06-38	+09-56	30	14.3

3.1. Observing Strategy

The observing program would consist of 1 month of continuous observation per cluster per year in the Long Cadence (LC) mode for the first four clusters in Table 1. One month of continuous observing should yield sufficient data to statistically characterize short-term variability in solar-type stars during one or more rotation periods. Two months of continuous observation would be required for M67 since its solar-age members are expected to have rotation periods of ~ 30 days. This gives a total of 6 months per year. The optional addition of the young clusters, α Per and NGC 2264, each observed continuously for one month, would increase the program duration to 8 months per year. The total program duration is 2 years. Two years of observation would yield statistical information on longer-term variability that may arise from stellar cycles for the aggregate of stars in a cluster. Therefore, the total amount of observing time is 12 months for the first five clusters and 16 months of equivalent continuous observing in total over 2 years for all the clusters in Table 1. We expect $\sim 100 - 200$ stellar point sources per field.

4. Scientific Impact

We do not know if the results of this program of cluster observations of solar-type stars over evolutionary time scales will yield fundamentally new and different results from those already obtained from observations in the *Kepler* field. However, we do know that studying open clusters is a coherent and systematic approach based on homogeneous samples of stars of known age and properties that may be representative of the host stars of exoplanetary systems. The characterization of the conditions of the ambient variable radiative and energetic particle fields in the Habitable Zones of solar-type stars extending over a range of ages is an appropriate and logical step in the progression from discovery of extrasolar planetary systems to their investigation in the context of emergent or existent life elsewhere in the universe.

The results will provide critical quantitative context for the development of models of exoplanetary atmospheres from the early stages of planetary system evolution to more mature stages equivalent to our own solar system. *Kepler* now presents us with an unprecedented opportunity to embark on such a pioneering program.

TECHNICAL PROPOSAL

5. Drifting Apertures (DRIFTAP): A New Data Collection Mode of Operation for *Kepler*

The scientific proposal outlined above would greatly benefit if the Kepler Mission were to create a new data collection mode in order to simplify the design and implementation of observations during the Two-Wheel Kepler Mission.

According to the *Call for White Papers: Soliciting Community Input for Alternate Science Investigations for the Kepler Spacecraft* (2 August 2013) (hereafter CWP2013), two possible point-drift mode observations would have a rate of drift that is estimated to be approximately 0.9 arcsec/minute which translates to ~ 1 pixel every ~ 5 minutes (see Fig. 2). Currently 30 short cadence (SC) observations (58.85 seconds; Gilliland et al. 2010) are combined together to make a single long cadence (LC) observation (29.42 minutes; Gilliland et al. 2010). During the Kepler Mission, small “circular” apertures with radii of 1.5 to 4 pixels were typically used; these small apertures typically had between 7 and 50 pixels that needed to be stored after every SC observation.

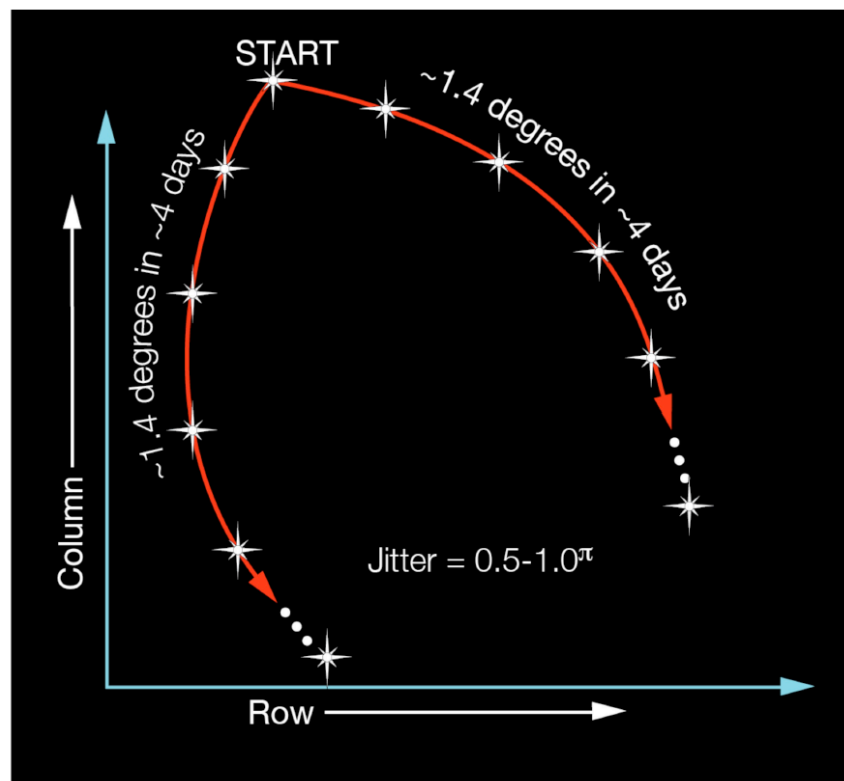


Figure 2: Schematic view of two possible point-drift mode observations on a CCD. During a ~ 4 day period the spacecraft can hold a target to within a jitter of $\sim 0.5-1.0$ arcsec along a drift line that is estimated to be ~ 1.4 degrees in length. A reset of the pointing brings the observation back to near the start point. The rate of drift is estimated to be approximately 0.9 arcsec/minute (~ 1 pixel in ~ 5 minutes) or possibly less. The path of a target during this time period will inscribe an arc shape on the focal plane. *Source: Figure 3 of CFP2013*

An LC observation during the Two-Wheel Kepler Mission would see the target drift about 6 pixels during the 30 minute duration of an LC observation. If a circular aperture with a radius of R pixels was previously used to observe a point source during the Kepler Mission, then an

“optimal” *static* aperture to use for an LC observation during the Two-Wheel Kepler Mission would have the circular aperture of R pixels *split in half* with an additional *rectangular midsection of $2R \times 6$ pixels*. The orientation of these oblong apertures should, of course, be along the drift direction — any other orientation would require more pixels in order not to lose photometric precision. The required number of pixels to be stored using optimal static apertures would range from 25 pixels ($R=1.5$ pixels) to 98 pixels ($R=4$ pixels); the new aperture sizes are between 1.96 times ($R=4$ pixels) and 3.57 ($R=1.5$ pixels) larger than in the case of the standard Kepler Mission. The significantly larger oblong apertures would, of course, suffer from a greater probability of contamination by nearby stars in crowded fields.

During the Two-Wheel Kepler Mission, one could alternatively use a nearly-circular aperture with a radius R pixels split in half with an additional rectangular midsection of just one “column” of $2R$ pixels with an orientation along the drift direction. These slightly-oblong apertures would be optimal for exposure times of about 5 minutes (i.e., 5 SC observations) where the target would drift by about 1 pixel. The required number of pixels to be stored using optimal static apertures would range from 10 pixels ($R=1.5$ pixels) to 58 pixels ($R=4$ pixels); the new aperture sizes are between 1.16 ($R=4$ pixels) to 1.43 ($R=1.5$ pixels) larger than in the case of the standard Kepler Mission. This modest expansion of aperture size would minimize contamination from nearby stars.

During the Two-Wheel Kepler Mission, a new medium cadence (MC) observation mode could be created that would combine five SC observations *using the same nearly-circular aperture*. For long time series, the aperture would be shifted by ~ 1 pixel in the drift direction after every fifth MC observation (every 5 minutes). If the guest observer wanted all targets as MC observations, then the number of MC targets would likely drop from $\sim 150,000$ for LC targets (during the Kepler Mission) to $\sim 25,000$. This reduction in potential targets could be quite acceptable for many observing proposals for the Two-Wheel Kepler Mission. The time resolution of a MC time series would, of course, be 6 times better than current LC observations.

During the Two-Wheel Kepler Mission, a new version of the LC observation mode could be created that would combine six five-minute MC observations. From a practical point of view, it may well be possible to reuse almost all of the existing flight software used currently for LC observations with little modification (i.e., modest capital expenditure in implementation labor costs). Assuming that the pixel data from each pixel in each aperture in a SC observation is currently stored in memory by aperture number, then the only change required could be to *change the origin information* of each aperture to be extracted from each SC observation after every fifth SC observation; this will work if the pixels used in a given aperture are defined *relative to a point of origin* on the CCD (say at the lower-left corner of a rectangular pixel region). Alternatively, if the *absolute* pixel locations to be extracted are stored in memory, then all of the aperture pixel locations would need to be updated after every fifth SC observation. This new mode of LC observation would effectively be made of the combination of 6 MC observations.

We call this scheme **drifting apertures** (DRIFTAP). It would be a new data collection mode for the Kepler Mission. DRIFTAP would improve photometric precision with regards to significant linear image motion expected in the Two-Wheel Kepler Mission. By keeping to the current SC/LC observing times, observing operations would essentially be the same. The programming changes required for onboard data storage processing of observed pixel should be minor if the current spacecraft operations system is efficiently designed.

If the DRIFTAP data collection mode of operation is chosen for implementation for the Two-Wheel Kepler Mission, then some careful consideration will need to be given to edge effects when apertures (over observations lasting up to 4 days) would shift from one CCD to another CCD along the drift direction. This could be simply implemented as a new bit in the SAP_QUALITY FITS header keyword. If the new SAP_QUALITY bit is set to one, then the aperture is at least partially off the CCD — thus indicating that that particular observation should not be used for scientific analysis.

We think that implementing the DRIFTAP data collection mode of operation would benefit most scientific proposals that will be submitted in response to this call for white papers.

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