A Gyrochronology and Microvariability Survey of the Milky Way's Older Stars Using *Kepler*'s Two-Wheels Program

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ABSTRACT

Even with the diminished precision possible with only two reaction wheels, the *Kepler* spacecraft can obtain mmag level, time-resolved photometry of tens of thousands of sources. The presence of such a rich, large data set could be transformative for stellar astronomy. In this white paper, we discuss how rotation periods for a large ensemble of single and binary main-sequence dwarfs can yield a quantitative understanding of the evolution of stellar spin-down over time. This will allow us to calibrate rotation-based ages beyond $\sim$1 Gyr, which is the oldest benchmark that exists today apart from the Sun. Measurement of rotation periods of M dwarfs past the fully-convective boundary will enable extension of gyrochronology to the end of the stellar main-sequence, yielding precise ages ($\sigma \sim$10%) for the vast majority of nearby stars. It will also help set constraints on the angular momentum evolution and magnetic field generation in these stars. Our *Kepler*-based study would be supported by a suite of ongoing and future ground-based observations. Finally, we briefly discuss two ancillary science cases, detection of long-period low-mass eclipsing binaries and microvariability in white dwarfs and hot subdwarf B stars that the *Kepler* Two-Wheels Program would facilitate.

1. Introduction

Measuring the age of main-sequence (MS) stars in the Galactic field is, at best, an imprecise art (Soderblom 2010). Even for solar-type stars, for which we can tether the scale to the single precise measurement that exists—that of the Sun—the uncertainties are $\sim$1 Gyr or larger. Based on the underlying premise that stars are born with an initial distribution of rotation periods and slow down over time as they shed angular momentum (Skumanich 1972; Pallavicini et al. 1981; Soderblom et al. 1993), Barnes (2003, 2007, 2010) have suggested a framework for measuring stellar ages from their rotation periods. This empirical paradigm, gyrochronology, works well for solar-type stars in young clusters (e.g., Meibom et al. 2009, 2011b) and, apart from asteroseismology, is the most precise way to measure stellar ages of individual stars. Asteroseismology is not practical for a large number of stars and is impossible for the fainter ones. Figure 1 shows the results of the *Kepler* open cluster study of NGC 6811 that extended the gyro-age calibrations to $\sim$1 Gyr (Meibom et al. 2011a; Janes et al. 2013). Beyond that age, there remains a lack of measured rotation periods as the periods are longer, the photometric variations smaller, and open clusters further away

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and therefore fainter. Among the *Kepler* open clusters, it may be possible to measure rotation periods of MS stars for the ∼2.5 Gyr old NGC 6819 but not for the ∼9 Gyr old NGC 6791.

The current gyrochronology age calibration breaks down once the stars become fully-convective at the spectral type of ∼M3–M4. In solar-type dwarfs the rotational shear between the convective and radiative zones is believed to be central in generating magnetic fields. The spots at the stellar surface are modulated to the same periods. In fully-convective dwarfs, no such rotational shear exists. The magnetic fields are presumed to be driven by a turbulent dynamo (e.g., Browning 2008). However, they seem to possess strong magnetic fields of kilogauss scales that give rise to chromospheric and/or coronal activity seen in the UV, optical, and X-rays. The active M dwarfs do not always exhibit rotational modulation (Donati et al. 2006; West & Basri 2009), perhaps because the convection flows on the stellar surface are small-scale (Browning 2008). The magnetic activity in the fully-convective dwarfs lasts
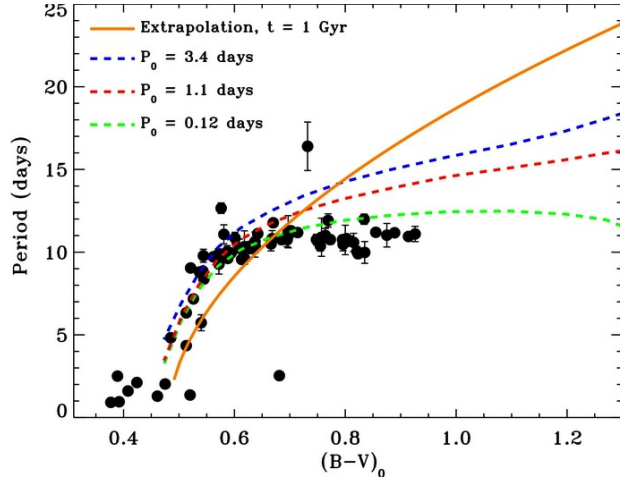

Fig. 1.— The rotation period–color diagram for the open cluster NGC 6811 as measured by *Kepler* (Meibom et al. 2011a). The orange curve is an extrapolation of data from younger open clusters to 1 Gyr, assuming the Skumanich $P \propto \sqrt{t}$ spin-down, while the green, red, and blue curves are $t = 1$ Gyr gyrochrones (Barnes 2010) for initial periods of 0.12, 1.1, and 3.4 days, respectively. The gyro-age of NGC 6811 was measured to be 1.00 ± 0.17 Gyr (Janes et al. 2013), which represents the oldest calibration of gyrochronology, except for the Sun. Beyond that age, there are few measured rotation periods as the known open clusters are too far away and faint.

much longer, up to 7–8 Gyr for mid–late M dwarfs (West et al. 2011). The relationship between stellar rotation, magnetic activity, and their evolution with age is much more complex in fully-convective stars. The magnetic activity has important ramifications for the habitability of planets around low-mass stars and serves as a probe of the internal mechanisms controlling magnetic field generation and stellar atmospheric heating. In addition, a reliable age determination is key to understanding the evolution of exoplanet orbits.

The *Kepler* spacecraft, even with only two operational reaction wheels, is capable of acquiring data to higher precision (∼mmag) and for fainter stars than small- to medium-aperture, ground-based telescopes. Moreover, as the stellar rotation periods are longer and the photometric variations have smaller amplitudes, the necessary cadence and time baseline cannot be provided by ground-based instruments.

In this white paper for the Kepler Two-Wheels Program (KTWP), we describe how *Kepler*-measured rotation periods of FGKM dwarf binary systems and single M dwarfs will enable the calibration of gyrochronology for older dwarfs in the Galactic field than currently available and for the fully-convective dwarfs at the end of the stellar MS. This will help establish precise determinations of stellar ages, to ∼10% for all dwarfs that have measurable surface rotations. The impact of age measurements in stellar astrophysics as well as in tracing the formation history of the Milky Way cannot be overstated. In addition, the presence of a rich, time-resolved photometry of a large number of stars will enable many ancillary projects. We briefly describe two objectives (i) to identify long-period M dwarf eclipsing binaries to determine the role of magnetic fields and surface rotation on stellar radii and (ii) to characterize micro-variability among cool white dwarf (WD) and hot subdwarf B (sdB) stars.

2. Calibrating the Stellar Rotation–Age Paradigm Using Wide MS Binaries in the *Kepler* Field

Binary (or multiple) star systems are essentially small open clusters, albeit with just two members. While not able to provide the statistical power of the dozens of stars typical in an open cluster, an ensemble of binary systems in the Galactic field can be even more powerful as they span a range of ages, metallicities, and evolutionary histories that provide a truly heterogeneous population. Past the age of ∼1 Gyr, binaries are also much closer and brighter than open clusters. As all but the most massive open clusters, which are further away and fainter, become unbound after ∼1 Gyr, their utility is limited as lower-MS dwarfs tend to escape first, limiting their availability as age benchmarks. Therefore, to test and calibrate gyrochronology for older stars, binary and multiple systems represent powerful keystones.

The *Kepler* FOV contains a large number wide, MS binary systems. Figure 2 shows the $g - i$ color distribution, with the inferred spectral types marked along the top x-axis, for ∼1600 candidate binary pairs for which at least one
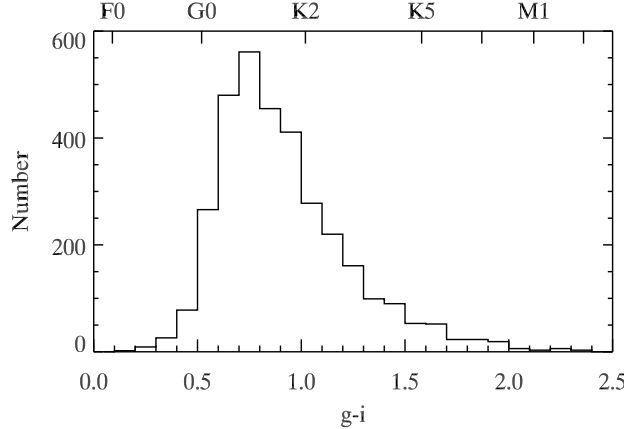

Fig. 2.— The $g - i$ color distribution, with the spectral types shown along the top x-axis, for the candidate common proper motion binaries with at least one component observed by *Kepler*. The candidate binaries were identified by cross-matching KIC with UCAC4 proper motions (K. Weisenburger, *priv. comm.*. Known binaries in the Washington Double Star Catalog (Mason et al. 2001) are also included (K. Janes, T. Mizusawa, *priv. comm.*). The lack of M dwarf binaries reflects *Kepler's* selection effect and not the dearth of M dwarf binaries in the *Kepler* FOV. With a wider spread of age and metallicity than available among nearby open clusters, these binary systems are central in our efforts to benchmark gyrochronology (Barnes 2003; Barnes & Kim 2010) as well as the chromospheric activity–age relations. With a photometric precision and temporal coverage that far exceeds what is available from the ground, *Kepler* will be critical in measuring rotation periods for these older stars where rotation periods can be several months long and photometric amplitudes are very small.

component has been observed by *Kepler* (K. Weisenburger, *priv. comm.*). They were identified by matching the *Kepler* Input Catalog (KIC; Batalha et al. 2010) with the UCAC4 proper motion catalog (Zacharias et al. 2013) using the algorithm outlined in Dhital et al. (2010). In addition, we found 40 binaries in the Washington Double Star Catalog (Mason et al. 2001) within the *Kepler* FOV (K. Janes, *priv. comm.*; T. Mizusawa, *priv. comm.*). As *Kepler* observes only a small fraction of the over 13.2 million stars in the KIC, there are presumably many more binaries that could be added to the list of stars observed by *Kepler*. The current observed *Kepler* stars are predominantly FGK dwarfs; thus, the added targets should be biased towards the mid–late M dwarfs. Given the baseline of many months and photometric precision of approximately a mmag, *Kepler* could measure rotation periods for one or both components of hundreds of binary systems that span the FGKM spectral types, even accounting for observed binaries that will not be rotating.

Apart from being the one precise age measurement of a star available to us, the Sun is also the only age datum we have past ∼1 Gyr. There exist no age measurements that can be used to calibrate gyrochronology, once rotation periods have been measured. Therefore, to calibrate the rotation–age relationship, we will have to empirically solve the three-dimensional plane of rotation period, color (age), and age. In other words, we will need to identify the tangent field of rotational isochrones. As this will necessarily be completely empirical, a solution will require measurements for more than a hundred binaries. Stellar metallicity is also known to affects magnetic activity levels (e.g., Bochanski et al. 2011). If sufficient rotation periods are measured, we could possibly extend the solution into the fourth dimension to include metallicity.

Furthermore, a few wide MS+WD pairs exist in the KTWP field. These evolved pairs offer an opportunity to independently test the gyrochronology ages obtained from MS stars. The cooling ages and masses of the WD components can easily be derived from spectral line profile fits from ground-based spectroscopy which we are conducting at NOAO in an ongoing study (e.g., Zhao et al. 2011). The WD cooling age alone provides an absolute lower limit to the companion MS star's rotationally inferred age. With masses determined from ground-based spectral line fits, correction for the MS lifetime of the WD component can be made, providing an independent check on the total systemic age derived from rotation and/or activity. Thus, this subset of wide pairs in the KTWP field offers a valuable independent consistency check on the relative ages provided by gyrochronology among MS+MS pairs.

2.1. Comparing the Stellar Rotation–Age and Activity–Age Relations in FGKM Dwarfs

We propose a rigorous test of two competing approaches to the measurement of stellar ages: rotation and chromospheric activity. These methods often give conflicting results; and there is much current debate in the scientific community about how best to determine stellar ages, especially for those not found in the very limited of accessible clusters (Barnes 2009; Soderblom 2010). In the *Kepler* field, we have identified a large sample of wide common proper motion pairs, each consisting of two MS stars (Figure 2). Such pairs provide a very robust basis for determining rotational age of each pair via gyrochronology enabled by the photometric micro-variability ($<1\%$) imposed by rotation of spotted stellar surfaces. The photometric precision and temporal coverage of the *Kepler* field, even in its extended mission, far exceeds what is available from ground-based investigations of the rotation–mass–age relation. This is particularly important for pairs older than the Sun where rotation periods can be several months and photometric amplitudes are very low. In parallel to the analysis of the proposed *Kepler* photometric data, we plan to do follow-up spectroscopic observations of these pairs to confirm spectral types (mass), to measure activity proxies such as CaII H and K and Hα, and to determine their metallicity (e.g., Zhao et al. 2011). The *Kepler* data alone will provide a robust test of gyrochronology theory and the assumption that such pairs are coeval. Combined with our ongoing spectroscopy conducted at NOAO, the *Kepler* data will also support a definitive comparison between rotation–age and activity–age relations, and how each depends upon mass and metallicity.

2.2. Extending gyrochronology beyond the fully-convective boundary

M dwarfs are the most numerous stellar constituents of the Milky Way ($\gtrsim 70\%$; Henry & McCarthy 1993) and appear to be the most numerous hosts of terrestrial planets (Howard et al. 2012; Dressing & Charbonneau 2013). However, until the recent advent of all-sky surveys, their intrinsic faintness had long limited our ability to study M dwarfs. As a result, large discrepancies exist in the empirical (when they exist) and theoretical values of their masses, radii, and metallicity. Obtaining robust empirical constraints for these properties, as well as on age, is critical to characterization of the orbiting, terrestrial planets.

There are only $\sim$3,000 M dwarfs ($\sim$2%) among the observed *Kepler* stars, almost all of which are of early–mid spectral types (Batalha et al. 2010). Thus, while more than 1,500 rotation periods for M dwarfs were measured from *Kepler* Q3 data (McQuillan et al. 2013; Nielsen et al. 2013; Reinhold et al. 2013), only 10–30 were for fully-convective M dwarfs. The vast majority of measured rotation periods for the $>$M3–M4 dwarfs come from the MEarth survey (Irwin et al. 2011a), with a few from Kiraga & Stepien (2007). The period distribution is bimodal with peaks at $\sim$1 d and $\sim$180 d, with amplitudes of $\sim$0.01–0.05 mag. The latter peak corresponds to older stars, possibly associated with the Milky Way's thick disk. The MEarth survey was able to measure the rotation periods from a ground-based telescope. With the expected mmag precision, a higher cadence, and a similar/longer time baseline, KTWP should be able to measure these rotation periods for the older M dwarfs. In fact, McQuillan et al. (2013) detected rotation periods for 63% of the early–mid M dwarfs in the *Kepler* sample. As the late M dwarfs are more likely to be active for a longer time, the yield could be even higher.

To include more M dwarfs in KTWP, we conducted a preliminary search for M dwarfs in KIC. First, we required $r - z > 0.89$ ($\sim$M0; West et al. 2011) and $r < 19.0$. Then, to select against M giants, we required $J - H > 0.7$ (Covey et al. 2007) and total proper motion > 20 mas yr^{-1} (USNO; Monet et al. 2003). Figure 3 shows the $r - z$ color distribution for the resultant sample of $\sim$7,500 M dwarfs. It is highly biased towards the early–mid M dwarfs, with only $\gtrsim$350 later than M4. This reflects the blue bias of the USNO proper motions, whose photographic plates were not sensitive enough for the later M dwarfs. However, a sample of >15,000 M dwarfs, that includes a significant number of mid–late ones, has been identified from KIC using PanStarrs proper motion (see
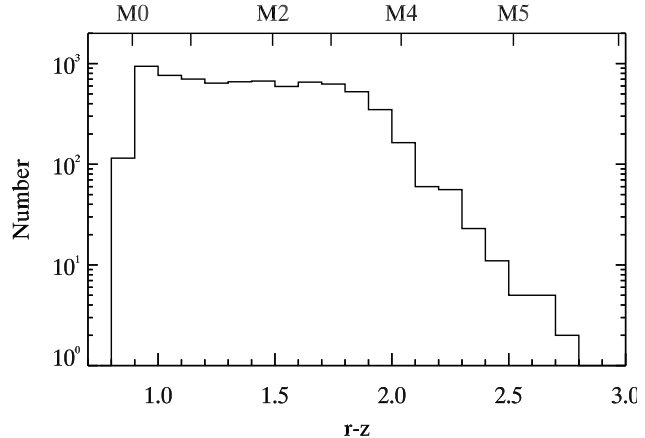

Fig. 3.— The $r - z$ color distribution, with spectral subtypes indicated along the top x-axis, for $\sim$7,500 M dwarfs in the KIC. This preliminary sample was based on USNO proper motions (to select against M giants), which have a known bias against the mid–late M dwarfs (Monet et al. 2003). A larger sample of M dwarfs has been identified using proper motions from the PanStarrs survey (see recently approved *Kepler* GO proposal; E. Gaidos & A. Mann), which should be preferentially included in KTWP.

recently approved *Kepler* GO proposal; E. Gaidos & A. Mann). These should be preferentially included in KTWP target lists.

3. Ancillary Science Goals

While the focus of this proposal is on measuring the rotation ages of lower MS stars, two other projects can be undertaken in parallel using stars in the same KTWP field.

3.1. Long-Period Eclipsing Binaries

Empirical measurements of M dwarf radii are rare (Torres et al. 2010). Those that have measured radii are either near enough for angular diameter measurements with optical long-baseline interferometry (e.g., Lane et al. 2001; Berger et al. 2006; Ségransan et al. 2003; Boyajian et al. 2012), or are short-period eclipsing binary stars (e.g., Stassun et al. 2007, 2008; Morales et al. 2009). There currently exist significant discrepancies between the radii measured in short-period eclipsing binary M dwarfs and predictions from evolutionary models (Baraffe et al. 1998). Chabrier et al. (2007) suggested that M dwarfs in short-period eclipsing binaries may have inflated radii due to effects from rapid rotation and magnetic fields; however this hypothesis has yet to be empirically verified.

Determining the role of rotation in radius inflation is of crucial importance to current and future NASA exoplanet missions. If, in fact, rapidly rotating M dwarfs are inflated compared to slowly rotating M dwarfs, we must then take this into account when determining the radius of exoplanets detected by Kepler or NASA's future TESS mission. We can test the Chabrier et al. (2007) hypothesis by searching for and characterizing long-period eclipsing binary M dwarfs (orbital periods of greater than 10 days), where the component stars are not synchronously rotating. *Kepler* is uniquely suited to this search, as it can observe stars nearly-continuously and detect the several-hour eclipse signature within a light curve spanning months to years and can observe thousands of M dwarfs at once. Searching for long-period eclipsing binaries from the ground

is extremely challenging with only one detection to date (LSPM J1112+7626, P = 41 days; Irwin et al. 2011b).

With eclipse depths of roughly one to several magnitudes, the reduced photometric performance of KTWP will not inhibit the detection of long-period eclipsing binary stars. We propose to search for long-period eclipsing binary M dwarfs within our proposed M dwarf sample. Results will directly feed into the radius determinations of exoplanets detected by Kepler and TESS.

3.2. Variability among Highly Evolved Stars

A photometric investigation of micro-variability among cool white dwarf (WD) and hot subdwarf B (sdB) stars is proposed for the extended Kepler mission. The Kepler data will enable time series observations to be obtained for WD targets with absolute magnitude $M_V > +15$ and color $0.2 < V - I < 1.4$ corresponding to the temperature ($T_{eff} < 6000$ K) and period ($P < 500$ s) regime where micro-variability due to collisionally induced absorption by H_2 and/or C_2 may occur. In the sample of several dozen cool WDs observed so far with ground-based facilities, no periodic variability larger than $\sim 2\%$ has been detected (Rudkin 2004), suggesting such objects have good potential to be used as faint OIR flux standards for large-aperture and space-based telescopes. However, two targets show possible variability near the limit of what can be confirmed from ground-based photometry. The detection of any level of micro-variability (or not) would provide rigorous tests of cool WD models and the equation of state for degenerate matter using asteroseismology techniques.

In a parallel project that can be conducted in the same field, a search for variations in the arrival times of known pulsations in WD and sdB stars can also be investigated. Such periodic changes in the $O-C$ diagrams for V391 Pegasi (Silvotti et al. 2007) revealed the presence of a planet in this post-MS system. Even in its reduced pointing precision mode, the photometric precision and nearly continuous multi-year coverage afforded by Kepler will provide several definitive searches for additional planetary survivors out to several astronomical units from the host stars.

4. Observing Strategy with *Kepler*'s Two-Wheel Program

As a result of only two reaction wheels being in working condition, KTWP will be able to deliver photometric precision of 0.3–0.6 mmag rms to 1 mmag rms depending on the seeing. Even accounting for pixel sensitivity variations, the relative photometry is expected to be ~ 0.3–1%[1] for all stars brighter than ~ 16–17 mag. Photometric variations of FGKM dwarfs, modulated to stellar surface rotation, are typically 0.01–0.05 mag (McQuillan et al. 2013; Nielsen et al. 2013; Reinhold et al. 2013). The rotation periods for dwarfs up to 16–17 mag will be easily detected. In fact, under the best performance scenarios, it might even be possible to detect giant planets. For fainter dwarfs, detection efficiency will be dependent on the precision ultimately delivered by KTWP and the amplitude of their photometric variations.

We have constructed preliminary samples of $\gtrsim 1600$ wide FGKM dwarf binaries and $\gtrsim 7,500$ single M dwarfs in the current *Kepler* FOV. There are a handful of wide WD+MS systems, single WDs, and sdBs as well. While our sample has a distinct lack of mid–late M dwarfs due to its dependence on USNO proper motions, such a sample has recently been constructed (see recently approved *Kepler* GO proposal; Gaidos & Mann). To cover a wide range of parameter space that includes mass, age, activity level, and metallicity, we request a sample of 1000 binary systems and 2000 single M dwarfs be observed. However, the number of targets can certainly be changed to maximize *Kepler*'s utility. All of these targets can be observed with the long cadence (30 min samples) used in the regular *Kepler* operations. Our proposed programs will not be affected by the need to reorient the spacecraft every four days.

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[1] http://keplergo.arc.nasa.gov/News.shtml#TwoWheelWhitePaper

This white paper is predicated upon *Kepler* pointing at the current FOV, which is reasonable given the time and effort already spent in characterizing the stars in this FOV. This was done under the assumption that pointing elsewhere will require either a significant effort in identifying ∼150,000 targets that *Kepler* is capable of monitoring at a time or a dramatic under-utilization of *Kepler*'s capabilities. **However, we would like to note that our science goals are not dependent on where *Kepler* is pointed. There exist large samples of both FGKM binaries (Luyten 1997; Chanamé & Gould 2004; Lépine & Bongiorno 2007; Dhital et al. 2010) and fully-convective dwarfs (Bochanski et al. 2010; West et al. 2011) throughout the sky.** Some parts of the sky, particularly in the Sloan Digital Sky Survey (York et al. 2000) footprint, might even be better due to the extant multi-band data.

5. Conclusion

This white paper outlines several projects which can easily be undertaken with the KTWP within the reduced photometric precision available. None of these projects will require any significant movement of the spacecraft from its present field.

First, we propose the first comprehensive calibration of the rotation–age–mass–metallicity relation to the bottom of the MS and to nearly the age of the Galaxys disk (∼10 Gyr). We have determined that the KTWP field contains hundreds of lower-MS stars that are in widely separated non-interacting common proper motion pairs. Components of a given pair are expected to be of the same age and chemical composition. But are they? The rotational ages derived from the proposed KTWP will provide the first direct test of the notion that such pairs are coeval. Moreover, the range of spectral types (i.e., masses) and metallicities represented by these pairs will permit the first comprehensive examination of the rotation–age–mass–metallicity relation among MS stars of M spectral type across the transition regime where self-generating toroidal fields, like the Suns, give way to turbulent dynamo-driven magnetic fields. In conjunction with ground-based spectroscopy of chromospheric activity among these wide pairs which is already in progress at NOAO facilities, the proposed KTWP observations will allow a detailed comparison of the consistency and precision of ages derived from activity vs. rotation as a function of spectral type (mass). Moreover, combination of the KTWP photometry and ground-based spectroscopy will permit the inclusion of a fourth dimension (metallicity) in the analysis. Finally, a few wide pairs contain a MS paired with a WD. In such cases, the cooling age of the latter provides a firm lower limit to the total age of the system, hence a valuable limit on both the rotational and activity ages.

Our second proposed project involves eclipsing binaries containing late-type MS stars in the KTWP field. Empirical measurements of M dwarf radii are rare, with most coming from short-period eclipsing binaries. However, significant discrepancies ($\gtrsim$10%) exist between the measured radii and the predictions from evolutionary models. As the short-period binaries may have inflated radii, long-period eclipsing binaries are necessary to test the evolutionary models. With similar brightness components, eclipse depths are roughly one to several magnitudes. A large database or time-resolved photometry would be a trove for eclipsing binary searches.

Our third proposed project involves a search for microvariability among evolved stars in the KTWP field. Several WDs and sdB stars are already known to be in the Kepler field. Those already known to exhibit non-radial pulsations will be monitored during the extended time afforded by the KTWP to search for light time modulation of the arriving pulses, the signature of planets or substellar companions. In addition, a few cool WDs in the field may have atmospheric opacities dominated by dissociation of H_2 or C_2 molecules that could drive pulsations. The photometric precision afforded by the KTWP should provide a conclusive test of this hypothesis.

While we hope to conduct all of the above projects in parallel, any one of them can easily be accommodated separately within the constraints of the KTWP scenario. Some modes overlap exists between the

targets already observed over the past several years with Kepler and our proposed sample. In these cases we will be able to look for the signatures of activity/spot cycles. In cases where the photometric modulation has extended over many rotational or pulsational cycles, we will be able to search for the signature of light-time modulation in the O−C diagrams caused by planets or substellar companions.

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