Kepler Reconnaissance of Ultracool Dwarfs

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ABSTRACT

I discuss the possibilities for "ultracool" (late-M and L) dwarf science using a two-wheel Kepler Mission. There is approximately one nearby ultracool dwarf per Kepler pointing, allowing this science to serve as an "add-on" to a variety of possible missions. The results will include characterization of rotation periods, condensate cloud weather, stellar radius, starspots, flare activity, and even transiting planets in the habitable zone.

1. Introduction

The term "ultracool dwarf" (UCDs) was coined to describe the late-M (M7-M9.5) and then frontier L dwarf types, though the usage now sometimes includes the more recently discovered cooler T and Y dwarf spectral classes. I will use UCDs to mean M7 to L5 dwarfs, or $T_{eff} \approx 2700$K to 1600K, since few cooler objects are bright enough to be observable with Kepler. The "transition" from type M to L is not a mere human convention with no physical meaning, but rather a temperature range with four dramatic astrophysical transitions:

1. **The Hydrogen-Burning Limit**: The hydrogen fusion limit of $\sim 0.07 M_{\odot}$ (Chabrier & Baraffe 2000), caused by degeneracy in the core, corresponds to $T_{eff} \approx 1800$K, or spectral type L4, for old stars. UCDs thus represent a mixture of "true" hydrogen-fusing stars, which can be very old, and younger brown dwarfs which will continue to cool to T and Y types. Model radius predictions can be tested by the statistics of spectroscopic $v \sin i$ and Kepler rotation periods.

2. **Clouds**: Condensates can form at temperatures below 2600K, and indeed are the key reason that the L dwarf spectra look qualitatively different than the TiO-dominated M dwarf class (Kirkpatrick 2005). The properties of the resulting dust clouds are a key factor in the spectra of ultra cool dwarfs and gas-giant planets, but difficult to predict from first principles alone. Kepler could measure "weather" due to clouds (or cloud holes).

3. **Magnetic Activity**: Chromospheres, corona, flares, and other consequences of magnetic fields generated in a convective dynamo disappear over the UCD spectral range. Mohanty et al. (2002) pointed out the increased resistance and low ionization fraction of UCDs, but it also seems possible that a entirely different dynamo mechanism is operating (Chabrier & Küker 2006). Morin et al. (2011) report evidence of dynamo bistability amongst late-M dwarfs, pointing to two possible dynamo states. Starspots and flares can be measured by Kepler.

4. **Rapid Rotation**: The angular momentum evolution of UCDs is qualitatively different from lower main sequence stars, with braking apparently weak to non-existent. Thus, while old, cool neighbors like Prox Cen (M5) or Barnard's Star (M4) have rotation periods longer than the Sun, even old UCDs have rotation periods less than one day, as deduced by $v \sin i$ measurements (Reiners & Basri 2008). Most UCDs should have periods in the range 3-10 hours.

As this list shows, photometric monitoring is a key tool to investigate the atmospheric properties of UCDs. Ground-based observations typically achieve uncertainties of a few percent, resulting a wide variety of claimed behaviors (Bailer-Jones & Mundt 2001; Clarke et al. 2002; Gelino et al. 2002; Clarke et al. 2003; Koen 2003, 2005, 2006; Lane et al. 2007): periodic, periodic with varying amplitudes, varying periods from run-to-run, aperiodic variations, but mostly non-detections. Bailer-Jones & Mundt (2001) suggested that (cloud) surface features in early L dwarfs evolve on timescales of hours and "mask" the underlying rotation curve in I-band. It is important to note that in the very bright Luhman-16 L8/T0 binary the I-band shows a complex, rapidly varying light curve (Burgasser et al. 2013), but this is likely related to the dramatic cloud changes at the L/T transition that produce large amplitude variations in a narrow spectral class (Radigan et al. 2012). On the other hand, the Kepler light curve for the L1 dwarf W1906+40 (Gizis et al. 2013, submitted) is periodic and stable over 21 months, suggesting there is either a wide variety of cloud/starspot properties or that the ground-based observations are unreliable. Indeed, most L dwarfs are faint, the timescales are well matched to telluric weather and the night sky rotation, and they are spectrally a poor match to background reference stars.

Space based observations for a few days with $\sim 0.5\%$ precision are needed to obtain reliable periods for typical ultracool dwarfs. Kepler, Spitzer (Heinze et al. 2013) and Hubble (Buenzli et al. 2012) have all proven to be capable of detecting rotation periods, but Spitzer and Hubble observations require that the telescope be dedicated to a single target with little value for other science projects due to their small fields of view. In their Spitzer white paper, Triaud et al. (2013) have proposed spending over two hundred days to observe a sample of one hundred UCDs to measure rotation periods and transiting planets in the habitable zone down to Mercury size, which would represent most of a cycle; the outcome of this proposal is not yet known. A similar Hubble allocation seems highly unlikely. *Kepler, however, could make these measurements for a large number of UCDs while executing other science programs.*

2. Case study: W1906+40

The L1 dwarf W1906+40 (Gizis et al. 2011) is an ordinary UCD which happens to lie in the Kepler Mission field of view. Only 16.4 parsecs distant, it has an SDSS magnitude of $g = 22.4$, far fainter than primary Kepler targets. Nevertheless, because the Kepler filter extends to nearly 900 nm and W1906+40 is so red ($g - z = 6.8$), it is observable (Figure 1). Our observations are summarized here but described in Gizis et al. (2013, submitted). In a nine pixel aperture W1906+50 produces 660 counts in thirty minutes, or about 66000 photons. The signal-to-noise ratio is ~ 200, consistent with the observed scatter about the periodic signal. In the short (one-minute) cadence, the S/N is ~ 50. W1906+40 shows a periodic signal with period 0.37015 days and peak-to-peak amplitude of 1.4% that has remained consistent throughout the 21 months it was monitored. A small number of white light flares were observed, but otherwise the aperiodic variations reported in other early-L dwarfs were not observed.

We examined each three-day subset of the full Kepler monitoring, and found that in all cases the 8.9 hour period is easily detected in an L-S periodogram, with no other significant periods [spurious or real] detected. This suggests that Kepler pointings of four days, the limit announced in the call for white papers, would allow the periods of UCDs to be reliably determined, and even if the UCD remains on the detector for only two days the periods could be measured. A sample four day period of W1906+40 is shown in Figure 2. Short cadence data can resolve flares, which range from a 10% brightening for a few minutes to a 300% brightening that was detectable for hours. The one quarter of short cadence monitoring of W1906+40 yielded 0.9 white light flares per four days, though whether this is representative of other UCDs is completely unknown. As a comparison, we also show four days of Kepler short cadence observations of the M4 dwarf GJ 1243 (Gizis et al., in prep.; 0.6 day period) in Figure 3.

3. Proposed Kepler Survey

3.1. Suitability of Kepler

The proposed survey of field UCDs is an ideal add-on project to any Two-Wheel Kepler Mission that observes targets spread over the sky. (An example is the proposed white dwarf survey posted on astro-ph by Kilic et al. (2013).) Ultracool dwarfs are in many ways well-suited to the Kepler capabilities described in the call for proposals. The rotation periods of several hours allows enough rotations to be detected in a 2-4 day observing window that the period can be determined, but are long enough that 30-minute sampling is adequate. The amplitudes of $\sim 1\%$ are extremely challenging from the ground, for the reasons already discussed, so a space telescope is needed. The faint targets are poisson-count limited to $\sim .2-.7\%$ accuracy anyway, so the degradation of the photometry as the target drifts across pixels is acceptable and has little impact on this science. (I also expect that such a drift could be distinguished from the periodic signal.) Even a small mask (3x3 or 5x5) would be acceptable, with an appropriate set chosen to follow the drift, but one could use larger masks if that is more efficient for sampling the target path. The project requires no flight software modifications and is a negligible fraction of the data download budget.

The density of ultra cool dwarfs on the sky is low but well matched to the Kepler field of view: there is one UCD within 20 pc per 150 square degrees (Cruz et al. 2007). In any given pointing motivated by whatever science is desired, there is a good chance to have a suitable UCD dwarf already cataloged suitable to for monitoring during the up-to-four day observing window. We note that these UCDs (within 20 parsecs) are the fundamental sample for understanding this class of objects, and have been the targets of a variety of observational surveys (low and high resolution spectroscopy, radio emission, optical polarization, trigonometric parallaxes, etc.).

One-minute cadence for the UCD targets would be highly desirable since it opens up the flare science, but is not necessary for the rotation and weather aspects. The FAQ's state that this capability will still be software-limited to five hundred targets, so feasibility of this depends on the other science targets and how many masks are necessary.

3.2. Goals

A survey of science targets distributed over the sky would allow the following goals to be met:

1. Measure Rotation Periods: The rotation periods would the angular momentum

evolution to be investigated and allow correlation with other observable properties. While $v \sin i$'s are measured for many UCDs, the interpretation is complicated by the unknown inclination; comparison of the two statistically will yield radii constraints.

2. Search for Weather: The claims that weather is present on the timescales of hours (already confirmed in cooler L and T dwarfs) would be confirmed or rejected, and any weather properties can be correlated with other characteristics (rotation, magnetic fields, metallicity). These would be a new class of observation for substellar cloud modeling to confront.

3. Characterize the nature of variability. It has been difficult to distinguish whether variations are caused by magnetically confined starspots or some cloud formation, but each suggests different correlations with the presence or absence of strong magnetic field activity and with effective temperature.

4. Measure White Light Flares: The white light flare rate of W1906+40 is comparable to the Sun but two orders-of-magnitudes lower than rapidly rotating dMe GJ 1243. The flare rate may be a function of the spectral type (temperature), quiescent chromospheric activity, and rotation rates, and would be a new probe of magnetic activity and the dynamo. The rate for W1906+40 was 0.9 detectable white light flares per 4 day period.

5. Search for planetary transits: Because the physical size of all UCDS is ~ 1 jupiter radius, planetary transits are much larger amplitude than on sun-like stars. Although one could not detect Earth-size or smaller planets, as in the Triaud et al. (2013) Spitzer project, Neptunes or super-Earths should be achievable, and as they point out the habitable zone planetary period is $\sim 3 - 4$ days and the probability of transit is $\sim 4\%$. While a null result may not be very meaningful, a transiting planet around an intrinsically dim UCD would offer interesting follow-up opportunities for JWST and other telescopes.

3.3. Other Proposal Designs

Prioritizing UCDs for one year: One could observe one hundred different UCDs for 3.5 days each even if only 40% of the sky is accessible, while executing other science with the many additional pixels. This would allow rigorous statistics and offer a good chance of detecting a transiting planet, but is probably not the compelling use of Kepler, especially since small rocky planets would not be detectable. One can easily scale project by the available time to include the most important bright L dwarfs, and then rely on the proposed piggyback strategy.

Repeated visits: If fields are repeated due to some other science project, any additional observations of UCD targets would be of interest for weather and flare statistics.

Visits to Original Kepler Field: Continued long-cadence or short-cadence monitoring of W1906+40 would be invaluable for assessing the stability and lifetime of the surface features. There are other fainter UCDs of interest, which were accepted for a Cycle 5 GO proposal (PI Martìn), which could be monitored.

Large Scale, Slow-Paced Surveys: One could certainly include UCDs in any slow-cadence, wide-field program, but to me there seems to be little advantage over ground-based photometry for known UCDs in determining the optical Spectral Energy Distribution, no match to the intrinsic rotation periods, and no competitiveness in discovering unknown UCDs.

Extension to dMe Stars: While four day observations of old M0-M6 dwarfs will be much shorter than their periods, younger dMe stars have rotation periods less than four days and flare. Hawley et al. (1996) reported 321 dMe stars (out of 2063 M dwarfs) within 25 parsecs. These too are distributed over the entire sky, giving ~ 1 per pointing, though some will be too bright for Kepler. Kepler short cadence data for GJ 1243 (M4e, at 12 pc) is shown in Figure 3. I have presumed that M dwarfs would be discussed in other white papers.

4. Summary

The combination of their low intrinsic luminosity, low temperature, few hour periods, and $\sim 1-2$ percent amplitudes means that the photometric variations of ultracool dwarfs are best investigated from space, but their low density on the sky means that amassing large sample requires observing them one-by-one. Kepler can break through this barrier by observing UCDs during other science projects.

It should be noted that, as suggested in the call, not all relevant works are cited as they would be in a full proposal or refereed paper.

REFERENCES

Bailer-Jones, C. A. L., & Mundt, R. 2001, A&A, 367, 218

Buenzli, E., Apai, D., Morley, C. V., Flateau, D., Showman, A. P., Burrows, A., Marley, M. S., Lewis, N. K., & Reid, I. N. 2012, ApJ, 760, L31

Burgasser, A. J., Faherty, J., Beletsky, Y., Plavchan, P., Gillon, M., Radigan, J., Jehin, E., Delrez, L., Opitom, C., Morrell, N., Osten, R., Street, R., Melis, C., Triaud, A., & Simcoe, R. 2013, ArXiv e-prints

Chabrier, G., & Baraffe, I. 2000, ARA&A, 38, 337

Chabrier, G., & Küker, M. 2006, A&A, 446, 1027

Clarke, F. J., Oppenheimer, B. R., & Tinney, C. G. 2002, MNRAS, 335, 1158

Clarke, F. J., Tinney, C. G., & Hodgkin, S. T. 2003, MNRAS, 341, 239

Cruz, K. L., Reid, I. N., Kirkpatrick, J. D., Burgasser, A. J., Liebert, J., Solomon, A. R., Schmidt, S. J., Allen, P. R., Hawley, S. L., & Covey, K. R. 2007, AJ, 133, 439

Gelino, C. R., Marley, M. S., Holtzman, J. A., Ackerman, A. S., & Lodders, K. 2002, ApJ, 577, 433

Gizis, J. E., Troup, N. W., & Burgasser, A. J. 2011, ApJ, 736, L34+

Hawley, S. L., Gizis, J. E., & Reid, I. N. 1996, AJ, 112, 2799

Heinze, A. N., Metchev, S., Apai, D., Flateau, D., Kurtev, R., Marley, M., Radigan, J., Burgasser, A. J., Artigau, É., & Plavchan, P. 2013, ApJ, 767, 173

Kilic, M., Agol, E., Loeb, A., Maoz, D., Munn, J. A., Gianninas, A., Canton, P., & Barber, S. D. 2013, ArXiv e-prints

Kirkpatrick, J. D. 2005, ARA&A, 43, 195

Kirkpatrick, J. D., Reid, I. N., Liebert, J., Cutri, R. M., Nelson, B., Beichman, C. A., Dahn, C. C., Monet, D. G., Gizis, J. E., & Skrutskie, M. F. 1999, ApJ, 519, 802

Koch, D. G., Borucki, W. J., Basri, G., Batalha, N. M., Brown, T. M., Caldwell, D., Christensen-Dalsgaard, J., Cochran, W. D., DeVore, E., Dunham, E. W., Gautier, T. N., Geary, J. C., Gilliland, R. L., Gould, A., Jenkins, J., Kondo, Y., Latham, D. W., Lissauer, J. J., Marcy, G., Monet, D., Sasselov, D., Boss, A., Brownlee, D., Caldwell, J., Dupree, A. K., Howell, S. B., Kjeldsen, H., Meibom, S., Morrison, D., Owen, T., Reitsema, H., Tarter, J., Bryson, S. T., Dotson, J. L., Gazis, P., Haas, M. R., Kolodziejczak, J., Rowe, J. F., Van Cleve, J. E., Allen, C., Chandrasekaran, H., Clarke, B. D., Li, J., Quintana, E. V., Tenenbaum, P., Twicken, J. D., & Wu, H. 2010, ApJ, 713, L79

Koen, C. 2003, MNRAS, 346, 473

—. 2005, MNRAS, 360, 1132

—. 2006, MNRAS, 367, 1735

Lane, C., Hallinan, G., Zavala, R. T., Butler, R. F., Boyle, R. P., Bourke, S., Antonova, A., Doyle, J. G., Vrba, F. J., & Golden, A. 2007, ApJ, 668, L163

Mohanty, S., Basri, G., Shu, F., Allard, F., & Chabrier, G. 2002, ApJ, 571, 469

Morin, J., Delfosse, X., Donati, J.-F., Dormy, E., Forveille, T., Jardine, M. M., Petit, P., & Schrinner, M. 2011, in SF2A-2011: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, ed. G. Alecian, K. Belkacem, R. Samadi, & D. Valls-Gabaud, 503–508

Radigan, J., Jayawardhana, R., Lafrenière, D., Artigau, É., Marley, M., & Saumon, D. 2012, ApJ, 750, 105

Reid, I. N., Kirkpatrick, J. D., Gizis, J. E., Dahn, C. C., Monet, D. G., Williams, R. J., Liebert, J., & Burgasser, A. J. 2000, AJ, 119, 369

Reiners, A., & Basri, G. 2008, ApJ, 684, 1390

Triaud, A. H. M. J., Gillon, M., Selsis, F., Winn, J. N., Demory, B.-O., Artigau, E., Laughlin, G. P., Seager, S., Helling, C., Mayor, M., Albert, L., Anderson, R. I., Bolmont, E., Doyon, R., Forveille, T., Hagelberg, J., Leconte, J., Lendl, M., Littlefair, S., Raymond, S., & Sahlmann, J. 2013, ArXiv e-prints

Walkowicz, L. M., Basri, G., Batalha, N., Gilliland, R. L., Jenkins, J., Borucki, W. J., Koch, D., Caldwell, D., Dupree, A. K., Latham, D. W., Meibom, S., Howell, S., Brown, T. M., & Bryson, S. 2011, AJ, 141, 50

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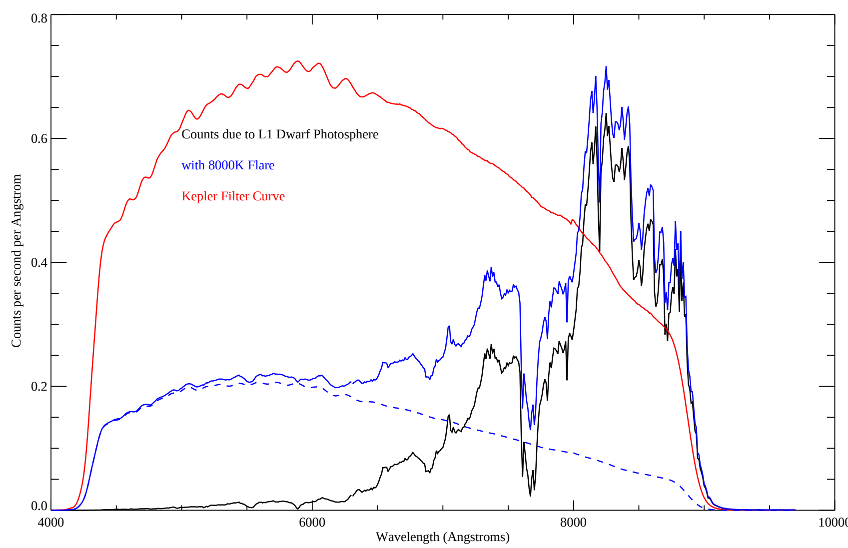

Fig. 1.— Predicted count rates as a function of wavelength for the Kepler photometer. We use the L1 standard 2MASS J14392836+1929149 (Kirkpatrick et al. 1999) for $\lambda > 6300$ Åand the L0.5 dwarf 2MASS J07464256+2000321 (Reid et al. 2000) for $\lambda \leq 6300$Å in order to completely cover the Kepler filter sensitivity range. The counts are weighted by the average Kepler filter response (Koch et al. 2010), which is also plotted by itself. The integrated count rate is normalized to give 660 DN per second, which matches the pipeline reported count rate for Quarter 10. Also shown is a hypothetical 8,000K blackbody flare (Walkowicz et al. 2011) that contributes an equal number of counts.

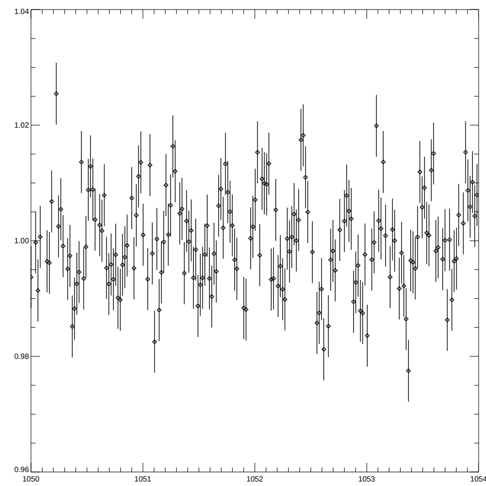

Fig. 2.— W1906+40 (L1) Kepler light curve for Mission Days 1020-1024. The 0.37 day period is obvious. Similar quality data could be obtained for dozens of nearby ultracool dwarfs while executing other science missions.

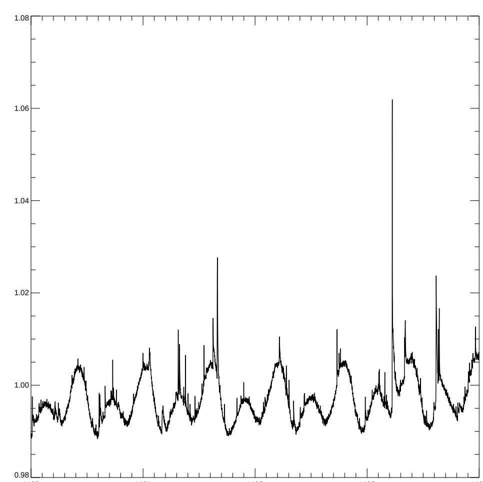

Fig. 3.— GJ 1243 (M4e) Kepler light curve for Mission Days 1100-1104 at short cadence, illustrating the potential of short cadence observations of dMe stars. The rotation period is 0.6 days.