K2 Ultracool Dwarfs Survey. I. Photometry of an L Dwarf Superflare

John E. Gizis\(^1\), Rishi R. Paudel\(^1\), Sarah J. Schmidt\(^2\), Peter K. G. Williams\(^3\), and Adam J. Burgasser\(^4\)

\(^1\) Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
\(^2\) Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, D-14482, Potsdam, Germany
\(^3\) Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
\(^4\) Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA

Received 2016 November 21; revised 2017 February 17; accepted 2017 February 17; published 2017 March 20

Abstract

We report on K2 Campaign 8 measurements of a huge white light flare on the L1 dwarf SDSSp J005406.55-003101.8 (EPIC 220186653). The source is a typical L1 dwarf at a distance of \(\sim50\) pc, probably an old hydrogen-burning star rather than a young brown dwarf. In the long (30-minute) cadence photometry, the flare peak is 21 times the flux of the stellar photosphere in the broad optical Kepler filter, which we estimate corresponds to \(\Delta V \approx -7.1\). The total equivalent duration of the flare is 15.4 hr. We estimate that the total bolometric energy of the flare was \(4 \times 10^{33}\) erg, more powerful than the previously reported Kepler white light flares for the L1 dwarf WISEP J190648.47+401106.8, but weaker than the \(\Delta V = -11\) L0 dwarf superflare ASASSN-16ae. The initial (impulsive) cooling phase is too rapid to resolve with our 30-minute cadence data, but after 1 hour the gradual cooling phase has an exponential time constant of 1.8 hr. We use template fitting to estimate that the total time-width-at-half-amplitude of the light curve is \(<10\) minutes and that the true flare maximum reached \(\sim70\) times the stellar photosphere, or \(\Delta V \approx -8\). This flare is comparable to the most powerful Kepler flares observed on the active M4 dwarf GI 1243.

Key words: stars: activity – stars: chromospheres – stars: flare – stars: individual (SDSSp J005406.55-003101.8) – stars: low-mass

1. Introduction

Building on the long history of ground-based photometry of flares from main sequence stars (see Gershberg 2005 for a complete overview), the precision and time coverage of the Kepler mission (Koch et al. 2010) has revitalized the study of white light flares (Walkowicz et al. 2011). Davenport (2016) has recently published a catalog of over 850,000 stellar flares detected on 4041 stars during the original Kepler mission. Important Kepler-based studies include the characterization of “superflares” (with bolometric energy \(>10^{33}\) erg) on solar-type stars (Maehara et al. 2012; Candelaresi et al. 2014; Maehara et al. 2015) and flares on both active and inactive M dwarf stars (Hawley et al. 2014). Perhaps the best studied flare star with Kepler is the rapidly rotating, nearby M4 dwarf GI 1243, which was monitored for 11 months in short (1-minute) cadence mode, resulting in the detection of numerous well-characterized flares with Kepler-band energies \(10^{29}-10^{33}\) erg (Ramsay et al. 2013; Davenport et al. 2014; Silverberg et al. 2016). The extended K2 mission (Howell et al. 2014) allows many new fields to be monitored with the Kepler photometer, enabling studies of additional nearby M dwarfs (Ramsay & Doyle 2015; Stelzer et al. 2016).

White light flares from L dwarfs are rare enough that targeted ground-based photometric campaigns have not detected them (Koen 2013; Ramsay et al. 2015), but Gizis et al. (2013) detected 21 white light flares from the nearby L1 dwarf WISEP J190648.47+401106.8 (hereafter W1906+40) in three months of Kepler short cadence monitoring. These flares had estimated bolometric energies in the range \(6 \times 10^{29}\) to \(1.6 \times 10^{32}\) erg. A much more powerful L dwarf flare was later discovered during a ground-based supernova search: the flare ASASSN-16ae on the L0 dwarf SDSS J053341.43+001434.1 (hereafter S0533+00) was observed at \(\Delta V = -11\) magnitudes (Schmidt et al. 2016). Its total estimated bolometric energy of \(>6.2 \times 10^{34}\) erg is only a lower limit to the flare energy since the light curve was sparsely sampled. These flares must be related to chromospheric and coronal activity, as in active GKM main sequence stars, yet Hα chromospheres and X-ray coronae are known to weaken and disappear for cooler L dwarfs (Gizis et al. 2000; Berger et al. 2010; Schmidt et al. 2015), as the stellar rotation-activity relation breaks down (see Cook et al. 2014 and references therein.) High-resolution spectroscopy suggests all L0-L1 dwarfs are rapid rotators, implying they do not significantly spin-down even over billions of years (Reiners & Basri 2008). Some 90% of L0 dwarfs and 67% of L1 dwarfs show chromospheric Hα emission when observed at sufficiently high resolution and signal-to-noise, but the strength of their chromospheres as measured by \(L_{\text{H}\alpha}/L_{\text{bol}}\) is an order of magnitude weaker than in dMe stars, implying early-L dwarfs have cooler chromospheres with lower filling factors (Schmidt et al. 2015). The underlying physical reasons for this decline in traditional activity indicators are thought to be the increasing neutrality and resistance of the outer atmosphere (Mohanty et al. 2002), but additional factors such as changes in the mode of magnetic reconnection (Mullan 2010) or dynamo modes (Cook et al. 2014) may play important roles. We note as well that the Hα emission of some ultracool dwarfs may be auroral, rather than chromospheric, in nature (Hallinan et al. 2015; Pineda et al. 2016).

We have been monitoring L dwarfs that lie in each K2 campaign field of view in both long and short cadence mode, with the aim of detecting flares, transits, and cloud variability. Here we report the detection of a white light flare on an L1 dwarf with a total bolometric energy of \(4 \times 10^{33}\) erg, and measure the gradual decay phase of an L dwarf flare for the first time. We present the target and K2 data in Section 2, fit model flare templates in Section 3, and discuss the results in Section 4.
Table 1
Properties of S0054–00

| Parameter | Value |
|-----------|-------|
| \(r\)     | 22.50 ± 0.15 |
| \(i\)     | 20.09 ± 0.03 |
| \(K_p\)   | 20.5 ± 0.1   |
| \(z\)     | 18.25 ± 0.02 |
| \(J\)     | 15.73 ± 0.05 |
| \(H\)     | 14.89 ± 0.05 |
| \(K_s\)   | 14.38 ± 0.07 |
| W1        | 14.00 ± 0.03 |
| W2        | 13.76 ± 0.05 |

Kinematic

| Parameter | Value |
|-----------|-------|
| \(d(M_\odot - K_p)\) [pc] \(^*\) | 50.9 ± 9.6 |
| \(\mu_v\) [mas yr\(^{-1}\)] | 194.14 ± 18.24 |
| \(\mu_i\) [mas yr\(^{-1}\)] | -148.01 ± 37.83 |
| \(V_{\text{rad}}\) [km s\(^{-1}\)] | 58.9 ± 14.3 |
| \(V_{\text{rad}}\) [km s\(^{-1}\)] | -14.4 ± 14.3 |
| \(U\) [km s\(^{-1}\)] | 7.1 ± 8.0 |
| \(V\) [km s\(^{-1}\)] | -45.5 ± 13.4 |
| \(W\) [km s\(^{-1}\)] | 4.6 ± 13.7 |

Note. 
\(^*\) Based on S. J. Schmidt et al. (2016, in preparation).

2. Target Characteristics and Data

2.1. Properties of SDSSp J005406.55–003101.8

The discovery of the L1 dwarf SDSSp J005406.55–003101.8 (hereafter S0054–00) was first reported by Schneider et al. (2002) and Hawley et al. (2002), who each presented optical spectra. Schmidt et al. (2015) presented a higher signal-to-noise Baryon Oscillation Spectroscopic Survey (BOSS) optical spectrum that confirmed the L1 spectral type. Cross-correlating this spectrum with the Schmidt et al. (2014) L1 dwarf template, we measure \(v_{\text{rad}} = -14.4 ± 14.3\) km s\(^{-1}\). We set a 3σ limit of 5 Å on the equivalent width of the H\(_\alpha\) emission, which implies \(\log(L_{\text{H\alpha}}/L_{\odot}) < -5.0\). The Schmidt et al. (2015) survey found the average \(\log(L_{\text{H\alpha}}/L_{\odot}) = -5.31\) for L1 dwarfs, so S0054–00 was not unusually active when the BOSS spectrum was taken, and indeed may have a typical chromospheric activity level. Bardalez Gagliuffi et al. (2014) obtained a near-infrared spectrum and also classified S0054–00 as an L1 dwarf and found no evidence of a cooler unresolved companion in their spectral fitting. We measure the proper motion from a linear fit to the 2MASS (Skrutskie et al. 2006), SDSS (Alharla et al. 2011), and WISE (Wright et al. 2010) positions. From the observed SDSS optical and 2MASS infrared magnitudes, the Dupuy & Liu (2012) parallax compilation, and the latest color-absolute-magnitude relations (S. J. Schmidt et al. 2017, in preparation), we estimate a distance of \(d = 50.9 ± 9.6\) pc. The observed and derived properties of the target are given in Table 1. From its colors and spectra, S0054–00 appears to be a typical field L1 dwarf, and with a galactic space component motion \(V = -46 ± 13\) km s\(^{-1}\), it is most likely to be an old (age > 1 billion years) hydrogen-burning star (see Dieterich et al. 2014). From the \(V-J\) colors of other L1 dwarfs (Dahn et al. 2002; Dieterich et al. 2014) we estimate that the apparent magnitude is \(V ≈ 24.1\).

2.2. K2 Photometry

\(K2\) measured S0054–00 as EPIC 220186653 during Campaign 8 (2016 January 3–2016 March 23) in long cadence (30-minute) mode (Jenkins et al. 2010). There are 3445 good quality measurements over 78.6 days (\(\text{Kepler}\) mission dates 2559.11 to 2637.75); each data point is the average flux during a 29.4-minute period. We measure aperture photometry from the pixel files using the Astropy-affiliated photutils package. Rather than center on the noisy target in each frame, we adopt the best position based on the median of all centroid measurements, and then adjust it for each observation using the spacecraft motion estimate calculated by the mission (recorded as POS_CORR1 and POS_CORR2 in the FITS file headers). For the eight hours before the flare, the median count rate is 84.5 count s\(^{-1}\) through both 2-pixel and 3-pixel apertures; we adopt the 2 pixel aperture photometry for our analysis.

The broad \(\text{Kepler}\) filter extends from 430 nm to 900 nm. As discussed by Gizis et al. (2013), an L1 dwarf photosphere contributes significant counts only from the reddest part of this range, but hot flares contribute through the range and therefore have a higher mean energy per observed count. Because the principal goals of the original \(\text{Kepler}\) mission did not require absolute calibration of the photometry, the mission relied on \(K_p\), an AB-magnitude system that used ground-based \(gri\) photometry to predict what magnitude \(\text{Kepler}\) would observe (Brown et al. 2011). \(K_p\) values for \(K2\) fields have been determined by Huber et al. (2016), who remarked that the predicted magnitudes of red M dwarfs are too bright. We therefore do not expect the catalog value \(K_p = 17.2\) for the extremely red S0054–00 to be useful. Lund et al. (2015), Aigrain et al. (2015), and Libralato et al. (2016) found that for most (AFGK) stars, \(K_p\) predicts the observed \(K2\) count rate well, with a zero-point of 25.3 for a 3-pixel aperture. To clearly distinguish between the ground-based, catalog \(K_p\), value, and the actual space-measured magnitude of S0054–00, we follow Lund et al. (2015) in defining

\[\hat{K}_p = 25.3 - 2.5 \log(\text{count rate})\]

Under this system, \(\hat{K}_p = 20.5\) for our target before the flare. Our observed signal-to-noise per 30-minute cadence, 13, is consistent with other \(K2\) stars (Libralato et al. 2016) of similar magnitude. The \(K2\) photometry of our target does show long-term drifts, which we believe are instrumental effects, and which we do not consider further in this paper. There is no evidence of rotational modulation, and only one flare is evident in the data set.

At \(\text{Kepler}\) mission day 2595.784194, the target brightens to 1880 count s\(^{-1}\) (\(\hat{K}_p = 17.1, \Delta \hat{K}_p = 3.4\)); by the next 30-minute cadence, it faded to 380 count s\(^{-1}\); and then continued to decline over the next several hours (Figure 1). The fast rise and slow/exponential decline is typical of stellar flares in the \(\text{Kepler}\)-band. Davenport et al. (2014) described the \(\text{Kepler}\) light curve of an M4 flare star as double exponential, consisting of both an “impulsive” decay component that dominates at early times and a “gradual” decay component that dominates at late times. We adopt this terminology. The initial impulsive rise and decay is not resolved in our time series, implying the full time-width at half the maximum flux (\(t_{1/2}\)) is less than 30 minutes, but a gradual decay component is clearly detected. Maehara et al. (2015) define the “duration” of the flare as the “e-folding decay time of flare intensity after its
peak,” which also must be less than 30 minutes; our fits discussed in the next section suggest a value of ~7–10 minutes. Hawley et al. (2014) defined “duration” instead as the difference between the start and end times, meaning the times when the flare flux is detectable above the photospheric flux. The duration under this definition is 5 hr.

Because the ASASSN-16ae flare on S0533+00 was observed in the V-band, we estimate the V-band properties of our S0054−00 flare. At the peak of the flare, S0054−00 would have become a blue source rather than an extremely red one. Taking an A star photosphere as a proxy for the hot emission of a flare, we find that $V = K_p - 0.1$ for A stars when we transform from gri to V and $K_p$ (Brown et al. 2011; Huber et al. 2016), implying that the observed peak of the flare was $V = 17.0$ and therefore $\Delta V = -7.1$. The observed peak is the average over a 30-minute period, which likely underestimates the true peak brightness of the flare but the integrated counts are correct. The total “equivalent duration,” which is related to the total energy of the flare and should not be confused with the duration previously discussed, is equal to the total integrated counts of the flare divided by the photosphere count rate (Gershberg 1972; Hawley et al. 2014), 15.4 hr in the Kepler filter. Equivalent duration is bandpass-dependent: in the V-band, the equivalent duration was ~17 days.

A number of different approaches have been used to describe the energy of flares detected by Kepler. Walkowicz et al. (2011) and Candelaresi et al. (2014) report bolometric (UV, visible, and infrared, but not X-ray) energies. The flare spectral energy distribution is extrapolated beyond the Kepler filter by assuming the flare is a blackbody of temperature 10,000 K. Using the L1 dwarf and 10,000 K blackbody calibrations described by Gizis et al. (2013), we find a total flare energy of $E_{bol} \approx 4 \times 10^{33}$ erg. This extrapolation to bolometric energy is uncertain to at least the ~20% level (see Table 3 of Gizis et al. 2013). It is also useful to instead consider the observed energies through the Kepler filter. Hawley et al. (2014) report “Kepler energies” ($E_K$) that are tied to the observed spectrum of the M4 flare dwarf GJ 1243 and its input catalog magnitude, and do not extrapolate to include the ultraviolet or infrared. These cannot be directly compared to our analysis because the L1 dwarf is much cooler than GJ 1243, but we can follow their procedure to compute $E_K$ using the S0054−00 spectrum.

Convoluting the S0054−00 photosphere spectrum with the Kepler response function, we find that the stellar photospheric flux is $9.9 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, but a 10,000 K blackbody is 1.3 times more energetic for the same count rate. Following the same procedure as Hawley et al. (2014), we multiply by the width of the filter (4000 Å), $4\pi d^2$, and the Kepler equivalent duration. After applying our energy correction factor of 1.3, we find $E_K = 9 \times 10^{32}$ erg for the flare.

3. Template Fitting

With a total estimated energy of $4 \times 10^{33}$ erg, the S0054−00 flare lies between the strongest flare observed on the L dwarf W1906+40 ($\sim 1.6 \times 10^{32}$ erg, Gizis et al. 2013; we hereafter call this “the W1906+40 flare”) and the strongest L dwarf flare, ASASSN-16ae ($\sim 6.2 \times 10^{34}$ erg, Schmidt et al. 2016). The ASSASN-16ae curve was only sparsely sampled; the advantage of the S0054−00 flare is that the full light curve, especially the gradual decay phase, was observed. This allows

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{K2 photometry of a flare on SDSSp J005406.55-003101.8. Time zero on this plot is Kepler mission day 2595.78419378. The cyan curve shows our fit to the late-time exponential decay (Equation (1)); the extrapolation back to the time of the flare is shown as the dashed curve. The count rate outside of the flare was 84.5 count s$^{-1}$.}
\end{figure}
us to characterize the late cooling phases of such an energetic flare for the first time.

We first consider the late-time, gradual decay phase of the flare. After normalizing by the non-flaring photosphere (84.5 count s$^{-1}$) and measuring from the time of the flare ($t = t - 2595.78419378$), we fit an exponential decay curve to the 10 data points from 1 to 5.5 hr after the peak:

$$
\Delta F = Be^{-\gamma \Delta t}. \tag{1}
$$

We find $B = 2.94 \pm 0.22$ and $-\gamma = 13.6 \pm 1.0$ days$^{-1}$; this fit is shown in Figure 1. The exponential time constant ($\gamma = 1/\tau$) is 1.8 hr. Silverberg et al. (2016) and Schmidt et al. (2016) analyzed simultaneous spectroscopic and K2 observations of the late exponential decay to conclude that in the case of flares on the M4.5 dwarf GJ 1243, the gradual decay phase should be considered to be due to a “physically distinct” region from the impulsive decay phase, due to perhaps a “different spatial region, different atmospheric layer, or different cooling process.” In the W1906+40 flare, which was observed spectroscopically, the Kepler impulsive and gradual decay phases traced the white light emission and broadened Hα, but atomic (chromospheric) emission lines were much longer lived.

To investigate the impulsive phase of the flare we turn to model templates based on other white light flares to infer what may have happened during the first hour of the flare. Ground-based photometry of flares show a great diversity of light curves, but remarkably, Davenport et al. (2014) found that a single flare template (hereafter the D14 template) fits most Kepler flares on the M4 dwarf GJ 1243, once the flares were scaled by their maximum amplitude ($A$) and full width at half time ($t_{1/2}$). The rapid rise is described by a fourth order polynomial, and their decay template has two exponentials, which we write as:

$$
\Delta F = A_0 e^{-\gamma_0 \Delta t / h_1} + A_1 e^{-\gamma_1 \Delta t / h_2}. \tag{2}
$$

The D14 template parameters are $A_0 = 0.6890 \pm 0.0008$, $A_1 = 0.3030 \pm 0.0009$, $\gamma_0 = 1.000 \pm 0.003$, and $\gamma_1 = 2.783 \pm 0.0007$, so that along with the polynomial parameters, which we do not list here, there are nine fixed parameters common to all flares, plus three free parameters ($A_0$, $t_{1/2}$, and time of flare) that are unique for each flare. This template also fits the W1906 +40 flare, where we find $t_{1/2} = 6.9$ minutes, and was used by Schmidt et al. (2016) to fit ASASSN-16ae to find $t_{1/2}$ in the range 3 (best fit) to 6.2 (minimal fit) minutes. We fit the D14 template to our flare by computing it on a 1-minute cadence timescale and averaging down to the long cadence timescale. Because we are interested in the impulsive phase, we fit to only the first 1.5 hr of the flare (plus 2 hr before the flare, for a total of 7 data points). The results are shown in Figure 2. One hundred randomly drawn model fits from the posterior distribution are shown in red. The three derived parameters are flare amplitude $A = 63.9^{+1.9}_{-0.9}$, $t_{1/2} = 6.69 \pm 0.14$ minutes, and flare time $2595.77636 \pm 0.00017$ days. It is clear from Figure 2 that the late-time evolution is not well fit by this template. We can show this directly from our gradual phase fit. For the D14 template to reduce to Equation (1) at late times, the maximum amplitude of the flare would be $2.94/0.303 = 9.7$ times the photospheric count rate and $t_{1/2} = 0.2783/13.6$ day = 29.5 minutes, but this amplitude is too low and the timescale is too long compared to the K2 observations. Unfortunately, the S0054–00 long cadence data does not contain enough content to allow all the possible flare parameters of Equation (1) to be fit independently. To illustrate alternative possibilities, we also make use of template parameters that were fit to a very impulsive flare on an M4 dwarf based on other white light flares, which is the S0054–00 flare. The light curve for this fit is a better match to the gradual decay phase (Figure 2.) Although our lack of detailed, independent knowledge of the impulsive flare light curve means we cannot be precise on the true amplitude and timescale of the S0054–00 flare, the template fitting exercise suggests that the timescale ($t_{1/2}$) is less than 10 minutes and that the true flare maximum may have been approximately 70 times the mean photospheric value ($\Delta K_s \approx -4.6$), implying $\Delta V \approx -8$, more than 3 times that observed in the data averaged over 30 minutes.

4. Discussion

All three L dwarfs with observed white light flares appear to be old, hydrogen-burning stars with ages measured in the billions of years; indeed, S0533+00 (ASASSN-16ae) is likely a thick-disk star, perhaps 10$^9$ years old. White light flares and superflares may be common to all early-L dwarfs, regardless of age. Evidently the rapid rotation and weak spin-down of this class of stars supports a dynamo that generates robust magnetic fields and reconnection events that can exceed solar flare energies. Maehara et al. (2015) calculated that superflares of energy 10$^{33}$ erg occur about once every 70 yr on the Sun, which contrasts with the 1 superflare observed in 1/5 of a year of monitoring S0054–00 with K2. However, a more realistic, and lower, flare rate will come by considering all ($\sim 20$) of the early-L dwarfs monitored during the full K2 mission. Long-term monitoring of S0054–00 may reveal additional flares—we note that the Catalina Real-Time Transient Survey (Drake et al. 2009) found S0054–00 to be approximately 1 mag brighter than normal in 2006 January (MJD 53744.14) in unfiltered CCD images. This may have been a white light flare. Schmidt et al. (2016) use the ASASSN data to estimate a flare rate of approximately 1/6 yr for L0 dwarf flares with energy 10$^{34}$ erg.

For these three flaring L dwarves, the flare duration as measured by the e-folding timescale is $<10$ minutes for energies 10$^{33}$–10$^{34}$ erg, which agrees with the observed duration of G dwarf superflares (Maehara et al. 2015) with the same energy, despite the much different stellar size and effective temperatures. Given the similarity of the L dwarf flares to G dwarf flares, it is interesting to compare them to the solar flare simulations of Aulanier et al. (2013), which can account for flares and superflares in G dwarfs, although we caution that physical conditions may be different. They find the following scaling of bolometric energy with maximum magnetic field strength and linear separation between the

---

5 All fits reported in this paper are the result of Markov Chain Monte Carlo sampling of at least 1.5 million samples of the posterior function using emcee (Foreman-Mackey et al. 2013) with uniform priors.
bipoles ($L_{\text{dipole}}$):

$$E = 0.5 \times 10^{32} \left( \frac{B_{\text{max}}}{1000 \text{ G}} \right)^2 \left( \frac{L_{\text{dipole}}}{50 \text{ Mm}} \right)^3 \text{erg}.$$ (3)

If we use the radius of the L1 dwarf (0.09 $R_{\odot}$, Dieterich et al. 2014) as the length scale, corresponding to a pair of large starspots (active regions) separated by $\sim$60°, then maximum magnetic field strengths of 6000 G are needed for the S0054−00 superflares. Berger (2006) report magnetic fields of $\sim$1000 G in much less energetic ultracool dwarf radio flares, so such a field in an unusually strong flare seems plausible. For ASASSN-16ae, increasing the volume by a factor of 10 (such as with spots on the opposite sites of the star) and increasing the field to 8000 G could account for the observed energy. While the lengths needed to produce superflares with $E > 10^{35}$ erg may be possible in solar-type stars, the small sizes of single L dwarfs suggest that they will not have higher energy superflares unless extremely strong (>10 kG) magnetic fields are possible.

L dwarf superflares offer significant opportunities to study the later phases of a superflare, particularly the gradual cooling phase. In solar-type stars, the bright photosphere makes even the peak emission at best a few-percent effect, and following the late decay of a superflare in white light would require extraordinary precision. For L dwarfs, however, the photospheric contribution is greatly reduced. In the flare presented here, a trigger from a photometric survey like LSST with a 30-minute response time on a 8 m class telescope would allow hours of spectroscopy of both the gradual phase white light component and atomic emission lines. Such observations could yield new constraints on the cooling of stellar photospheres in response to impulsive energy injections.

We thank James Davenport, Dermott Mullan, and Rachel Osten for helpful discussion of stellar flares. This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. The material is based upon work supported by NASA under award Nos. NNX15AV64G, NNX16AE55G, and NNX16AJ22G. A.J.B. acknowledges funding support from the National Science Foundation under award No. AST-1517177.

This research has made use of NASA’s Astrophysics Data System, the SIMBAD database, and the VizieR catalog access tool, operated at CDS, Strasbourg, France, the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA, and the Mikulski Archive for Space Telescopes (MAST). Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation and from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. This publication also makes use of data from the Sloan Digital Sky Survey. Funding for the Sloan Digital Sky Survey IV has been provided by the
Facility: Kepler.

References
Aigrain, S., Hodgkin, S. T., Irwin, M. J., Lewis, J. R., & Roberts, S. J. 2015, MNRAS, 447, 2880
Aihara, H., Allende Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Aulanier, G., Démoulin, P., Schrijver, C. J., et al. 2013, A&A, 549, A66
Bardalez Gagliuffi, D. C., Burgasser, A. J., Gelino, C. R., et al. 2014, ApJ, 794, 143
Berger, E. 2006, ApJ, 648, 629
Berger, E., Basri, G., Fleming, T. A., et al. 2010, ApJ, 709, 332
Brown, T. M., Latham, D. W., Everett, M. E., & Esquerdo, G. A. 2011, AJ, 142, 112
Candelaresi, S., Hillier, A., Maehara, H., Brandenburg, A., & Shibata, K. 2014, ApJ, 792, 67
Cook, B. A., Williams, P. K. G., & Berger, E. 2014, ApJ, 785, 10
Dahn, C. C., Harris, H. C., Vrba, F. J., et al. 2002, AJ, 124, 1170
Davenport, J. R. A. 2016, ApJ, 829, 23
Davenport, J. R. A., Hawley, S. L., Hebb, L., et al. 2014, ApJ, 797, 122
Dieterich, S. B., Henry, T. J., Jao, W.-C., et al. 2014, AJ, 147, 94
Drake, A. J., Djorgovski, S. G., Mahabal, A., et al. 2009, ApJ, 696, 870
Dupuy, T. J., & Liu, M. C. 2012, ApJS, 201, 19
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Gersberg, R. E. 1972, Ap&SS, 19, 75
Gersberg, R. E. 2005, Solar-Type Activity in Main-Sequence Stars (Berlin: Springer)
Gizis, J. E., Burgasser, A. J., Berger, E., et al. 2013, ApJ, 779, 172
Gizis, J. E., Monet, D. G., Reid, I. N., et al. 2000, AJ, 120, 1085
Hallinan, G., Littlefair, S. P., Cotter, G., et al. 2015, Natur, 523, 568
Hawley, S. L., Covey, K. R., Knapp, G. G., et al. 2002, AJ, 123, 3409
Hawley, S. L., Davenport, J. R. A., Kowalski, A. F., et al. 2014, ApJ, 797, 121
Howell, S. B., Sobeck, C., Haas, M., et al. 2014, PASP, 126, 398
Huber, D., Bryson, S. T., Haas, M. R., et al. 2016, ApJS, 224, 2
Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010, ApJL, 713, L120
Koch, D. G., Borucki, W. J., Basri, G., et al. 2010, ApJL, 713, L79
Koen, C. 2013, MNRAS, 428, 2824
Kowalski, A. F., Hawley, S. L., Wisniewski, J. P., et al. 2013, ApJS, 207, 15
Libralato, M., Bedin, L. R., Nardiello, D., & Pietto, G. 2016, MNRAS, 456, 1137
Lund, M. N., Handberg, R., Davies, G. R., Chaplin, W. J., & Jones, C. D. 2015, ApJ, 806, 30
Maehara, H., Shibayama, T., Notsu, S., et al. 2012, Natur, 485, 478
Maehara, H., Shibayama, T., Notsu, Y., et al. 2015, EP&S, 67, 59
Mohanty, S., Basri, G., Shu, F., Allard, F., & Chabrier, G. 2002, ApJ, 571, 469
Mullan, D. J. 2010, ApJ, 721, 1034
Pineda, J. S., Hallinan, G., Kirkpatrick, J. D., et al. 2016, ApJ, 826, 73
Ramsay, G., Doyle, J. G. 2015, MNRAS, 449, 3015
Ramsay, G., Doyle, J. G., Hakala, P., et al. 2013, MNRAS, 434, 2451
Ramsay, G., Hakala, P., & Doyle, J. G. 2015, MNRAS, 453, 1484
Reiners, A., & Basri, G. 2008, ApJ, 684, 1390
Schmidt, S. J., Hawley, S. L., West, A. A., et al. 2015, AJ, 149, 158
Schmidt, S. J., Shappee, B. J., Gagné, J., et al. 2016, ApJL, 828, L22
Schmidt, S. J., West, A. A., Bochanski, J. J., Hawley, S. L., & Kielty, C. 2014, PASP, 126, 642
Schneider, D. P., Knapp, G. R., Hawley, S. L., et al. 2002, AJ, 123, 458
Silverberg, S. M., Kowalski, A. F., Davenport, J. R. A., et al. 2016, ApJ, 829, 129
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 113, 1163
Stelzer, B., Damasso, M., Scholz, A., & Matt, S. P. 2016, MNRAS, 463, 1844
Walkowicz, L. M., Basri, G., Batalha, N., et al. 2011, AJ, 141, 50
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868