CHARACTERIZING A DRAMATIC $\Delta V \sim -9$ FLARE ON AN ULTRACOOL DWARF FOUND BY THE ASAS-SN SURVEY*

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ABSTRACT

We analyze a $\Delta V \sim -9$ magnitude flare on the newly identified M8 dwarf SDSS J022116.84+194020.4 (hereafter SDSSJ0221) detected as part of the All-Sky Automated Survey for Supernovae. Using infrared and optical spectra, we confirm that SDSSJ0221 is a relatively nearby ($d \sim 76$ pc) M8 dwarf with strong quiescent H$\alpha$ emission. Based on kinematics and the absence of features consistent with low-gravity (young) ultracool dwarfs, we place a lower limit of 200 Myr on the age of SDSSJ0221. When modeled with a simple, classical flare light curve, this flare is consistent with a total $U$-band flare energy $E_U \sim 10^{34}$ erg, confirming that the most dramatic flares are not limited to warmer, more massive stars. Scaled to include a rough estimate of the emission line contribution to the $V$ band, we estimate a blackbody filling factor of $\sim 10\%-30\%$ during the flare peak and $\sim 0.5\%-1.6\%$ during the flare decay phase. These filling factors correspond to flare areas that are an order of magnitude larger than those measured for most mid-M dwarf flares.

Key words: brown dwarfs – stars: chromospheres – stars: flare – stars: individual (SDSS J022116.84+194020.4) – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

M dwarfs are well known for their quiescent H$\alpha$ emission (e.g., Hawley et al. 1996) and dramatic flare events with emission spanning the entire electromagnetic spectrum (e.g., Osten et al. 2005). Though flares can be found across the entire M spectral class, flares are most often observed on mid-M dwarfs. Early-M dwarfs are on average less active than mid-M dwarfs, while late-M dwarfs are too faint for most flare-monitoring campaigns. Despite a low number of detected flares, quiescent activity is observed in a larger fraction of late-M dwarfs than mid-M dwarfs. In the solar neighborhood, $\sim 80\%$ of M8 dwarfs show H$\alpha$ emission compared to $20\%$ of M3 dwarfs (West et al. 2011).

The increase in the active fraction with spectral type is consistent with a changing relationship between activity, age, and rotation (Reiners & Basri 2010). Active early-M dwarfs are found, on average, closer to the Galactic plane than active late-M dwarfs, indicating that late-M dwarfs are active for a longer portion of their lifetimes (West et al. 2008). Mid-M dwarfs that flare are found, on average, at lower Galactic heights than those with only H$\alpha$ emission (Kowalski et al. 2009), implying that the average flare lifetime is shorter than the quiescent activity lifetime. The age of flaring late-M dwarfs is particularly interesting because the M7-M9 spectral types include the most massive brown dwarfs at ages $< 1$ Gyr (Burrows et al. 1997).

Flares on early- and mid-M dwarfs follow well-characterized patterns; small flares ($E_U \sim 10^{28}$–$10^{30}$ erg) typically occur hourly or daily, while larger flares ($E_U \sim 10^{32}$–$10^{34}$ erg) typically occur no more often than weekly (Lacy et al. 1976). These patterns vary with both spectral type and base activity level (Hilton 2011; Davenport et al. 2012), but it is unclear whether late-M dwarfs flare more or less frequently than mid-M dwarfs. With $< 20$ total detected late-M dwarf flares events (e.g., Rockenfeller et al. 2006; Hilton 2011; Berger et al. 2013), the patterns followed by late-M dwarfs are unclear.

On UT 2013 August 14, SDSS J022116.84+194020.4 (hereafter SDSSJ0221) was flagged as transient ASASSN-13cb in the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2013) with a flare peak emission of $\Delta V \sim -9$. We present follow-up observations and use models based on mid-M dwarf flares to estimate the properties of the flare. In Section 2, we present our observations and characterize SDSSJ0221, in Section 3 we examine the flare, and in Section 4 we place SDSSJ0221 in the context of late-M dwarf magnetic activity.
2. OBSERVATIONS AND SURVEY DATA

In addition to the detection of the flare, we examined the photometry available from sky surveys and obtained follow-up spectroscopy to investigate the properties of SDSSJ0221. Those data are described below.

2.1. Photometric Data

ASAS-SN is an optical transient survey that images the sky visible from Haleakala, Hawaii, every ~5 days down to $V \sim 17$, using two 14 cm telescopes in a common mount (see Shappee et al. 2013). The V-band images (2 x 90 s exposures per field) are automatically processed through a difference imaging pipeline that produces transient candidates within ~1 hr of the initial observation. We discovered the bright transient ASASSN-13cb (R.A. = 02 21 16.92, decl. = 19 40 19.90) on UT 2013 August 14.52 (Stanek et al. 2013). The transient faded by $\Delta V \sim 0.5$ between the two discovery images and by $\Delta V \sim 3.5$ in confirmation images obtained 2.3 hr later. The photometry of ASASSN-13cb, presented in Table 1, was obtained using magnitudes of several stars from the AAVSO Photometric All-Sky Survey.

We retrieved photometry from the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Two-Micron All Sky Survey (2MASS; Skrutskie et al. 2006), and the Wide-field Infrared Sky Explorer mission (WISE; Wright et al. 2010) based on a coordinate cross-match to the ASAS-SN position. Each survey returned only one source within our 5" search radius. Poor-quality flags were not set in any bands, but the uncertainties on the $u$, $W3$, and $W4$ measurements were sufficiently high to indicate unreliable magnitudes. The $grizJHK_{S}W1W2$ magnitudes are listed in Table 2.

The colors of SDSSJ0221 are consistent with the median color of M8 dwarfs in the $g$ through $W2$ bands. It is not peculiar in its $g-r$ color (used to select metal-poor M dwarfs; Lépine & Scholz 2008) or its $J - K_{S}$ color (consistent with young ultracool dwarfs; Cruz et al. 2009). Distances calculated using the Bochanski et al. (2010) color–magnitude relations are given in Table 2, with uncertainties including both magnitude uncertainties and the scatter in the relations. We adopt a mean distance of $d = 76 \pm 6$ pc; the uncertainty is dominated by the dispersion of the three distance estimates.

We measured a proper motions of $\mu_{\alpha} = -96.0 \pm 6.7$ mas yr$^{-1}$ and $\mu_{\delta} = -36.3 \pm 7.9$ mas yr$^{-1}$ based on the difference between SDSS and 2MASS coordinates. The combination of the distance and proper motion results in a tangential velocity of $37 \pm 8$ km s$^{-1}$, placing it slightly faster than the median $V_{\text{tan}}$ for ultracool dwarfs near the Sun (e.g., Faherty et al. 2009). Based on the Bayesian statistical proper motion models of Malo et al. (2013), the kinematics of SDSSJ0221 are not consistent with any of the seven closest and youngest moving groups, implying an age > 100 Myr.

2.2. Spectroscopic Data

We obtained low-resolution ($R \sim 800$) optical spectra of SDSSJ0221 on three different nights (UT 2013 August 30 and September 1–2) using the Dual Imaging Spectrograph (DIS) on the Astrophysical Research Consortium 3.5 m telescope at Apache Point Observatory and the Wide Field CCD Camera and Spectrograph (WFCCD) on the du Pont 2.5 m telescope at Las Campanas Observatory. We used the B400/R300 gratings and a 1.5" slit (3500–10,000 Å) with DIS and the 400 lines mm$^{-1}$ grism and a 1.7" slit with WFCCD (3700–9500 Å). The spectra were reduced using Lacosmic (van Dokkum 2001) for cosmic ray rejection and standard techniques in the IRAF twordspec and onedspec packages for spectral extraction and wavelength+flux calibration. The median combined spectrum is shown in Figure 1.

From these spectra, we obtain a spectral type of M8 for SDSSJ0221 using the automatic Hammer routines (based on spectral indices; West et al. 2004; Covey et al. 2007).

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Table 1

| Time (h:m:s) | $V$ Magnitude | $F_{V}$ (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) |
|------------|--------------|----------------------------------|
| 00:00:00   | 12.84 ± 0.03 | (2.68 ± 0.07) × 10$^{-14}$        |
| 00:01:57   | 13.33 ± 0.04 | (1.69 ± 0.06) × 10$^{-14}$        |
| 2:20:19    | 16.70 ± 0.14 | (7.65 ± 0.96) × 10$^{-16}$        |
| Quiescent  | 22.09 ± 0.26 | (5.45 ± 1.52) × 10$^{-18}$        |

Table 2

| Parameter | Value |
|-----------|-------|
| R.A. (2005.933) | 02 21 16.84 |
| Decl. | +19 40 20.4 |
| $g$ | 22.80 ± 0.13 |
| $r$ | 21.24 ± 0.05 |
| $i$ | 18.65 ± 0.02 |
| $z$ | 17.08 ± 0.02 |
| 2MASS (1997.805) | 02 21 16.77 |
| Decl. | +19 40 20.1 |
| J | 15.00 ± 0.04 |
| H | 14.44 ± 0.04 |
| $K_{S}$ | 13.91 ± 0.05 |

Properties of SDSSJ0221 in Quiescence

Spectral type M8

$L_{\text{bol}}/L_{\text{bol}}$ 36 ± 11 Å

$\nu_{\text{tan}}$ 37 ± 8 km s$^{-1}$

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14 http://www.astronomy.ohio-state.edu/~assassin/index.shtml

15 http://www.aavso.org/apass

16 The astrometric calibration of SDSS and 2MASS shows very good agreement (~0.006) within typical coordinate uncertainties (~0.1’; Pier et al. 2003).

17 Using the Web-based tool at http://www.astro.umontreal.ca/~malo/banyan.php.
optical spectrum is shown compared to the M7 and M8 templates from Bochanski et al. (2007) in Figure 1. Visual comparison shows that the spectral features of SDSSJ0221 place it between the two types, but the spectrum is a better match to the M8 template, indicating an M8 type. We were unable to measure radial velocities from the individual spectra due to their low resolution.

We measure the Hα equivalent width (EW) of the individual spectra using the Hammer (West et al. 2004; Covey et al. 2007), obtaining a mean and standard deviation of $36 \pm 11 \text{ Å}$ (listed in Table 2) for seven total spectra. Using a $\chi$ value from Schmidt et al. (2013, in preparation), we calculate an activity strength of $L_{\text{H}\alpha}/L_{\text{bol}} = 1.5 \times 10^{-4}$. This is well above the median and dispersion for Hα emission from M8 dwarfs (West et al. 2011). The full range of the measured Hα EWs (22–54 Å; (0.9–2.3) $\times 10^{-4}$) is larger compared to its mean Hα EW than the range seen for an average late-M dwarf (Bell et al. 2012), but not remarkable given the strong emission and observed flare.

We obtained a low-resolution ($R \sim 150$) infrared spectrum on 2013 September 3 using SpeX (Rayner et al. 2003) on the Infrared Telescope Facility, as well as standard calibration frames and a spectrum of the A0 star HD 16811. The data were reduced and telluric-corrected using SpexTool (Vacca et al. 2003; Cushing et al. 2004). The H$_2$O indices compiled by Allers & Liu (2013) indicate an infrared spectral type of M7, but direct comparison to spectral standards (shown in Figure 1) results in a final infrared spectral type of M8.

The infrared spectrum also includes features that are sensitive to the surface gravity (age) of ultracool dwarfs. We calculated the FeH, VO, K I, and H-cont indices from Allers & Liu (2013); the combined score from all four indices indicates features consistent with a typical field dwarf, placing a rough lower limit of 200 Myr on the age of SDSSJ0221. While the Li I absorption line could provide an additional limit on the age of SDSSJ0221, the optical spectrum does not have sufficient signal-to-noise ratio and resolution to place limits on Li I.

3. PROPERTIES OF THE FLARE

We calculated a quiescent V-band magnitude of $V = 22.09 \pm 0.26$ for SDSSJ0221 by calibrating the M8 template spectrum to the SDSS r-band magnitude and then integrating the spectrum over a V-band filter curve. This quiescent magnitude results in $\Delta V = -9.25 \pm 0.26$ for the observed peak magnitude (shown in Figure 2). It is unlikely that we observed the flare at its true peak. However, more energetic flares occur are increasingly infrequent (Lacy et al. 1976), so it is also unlikely that the flare was much larger than observed. Kowalski et al. (2013) includes flares with impulsive decays lasting from 0.02 to 0.2 hr. If we assume a linear impulsive decay, this range of decay times is consistent with a range of peak magnitudes from the observed $\Delta V \sim -9.25$ (at $t = 0 \text{ hr}$) to a $\Delta V \sim -12$ (at $t = -0.18 \text{ hr}$) peak. For simplicity, we assume that the observed peak is also the total flare peak.

3.1. The Flare Light Curve

Classical flares have a characteristic shape: an “impulsive” phase that includes a fast rise and decline (well approximated as
linear changes in magnitude with time) and a “gradual” phase typically modeled by an exponential decay. Flare light curves have a wide variety of morphologies beyond simple, classical flares; some show multiple peaks (e.g., Hawley & Pettersen 1991) or complex structures in their decay phase (e.g., Kowalski et al. 2010). With only three detections of SDSSJ0221 during 1991) or complex structures in their decay phase (e.g., Kowalski et al. 2010), both at just over $E_U = 10^{34}$ erg. While the $E_U$ calculated for the flare on SDSSJ0221 is slightly larger, its uncertainties due to the estimation of the flare shape and the use of scaling relations are likely to be an order of magnitude. Extrapolating the flare frequency distributions of Hilton (2011) to $E_U = 10^{34}$ erg, flares this large should occur on active mid-M dwarfs monthly, and active late-M dwarfs once per year.

3.2. Emission in the V Band

At optical and UV wavelengths, flare emission originates from two components. The major contributor is a $T \sim 10,000$ K blackbody (e.g., Hawley & Fisher 1992) thought to originate deep in the stellar atmosphere near the foot points of the magnetic field loops. Atomic emission lines (e.g., Fuhrmeister et al. 2010) and hydrogen Balmer continuum (Kunkel 1970) are emitted as part of a second, lower density component. The continuum emission dominates the overall optical/UV energy budget of the flare, contributing 91%–95% of the total during the impulsive phase and 69%–95% during the gradual phase (Hawley & Pettersen 1991).

Spectroscopic observations of the $V$ band during flares are rare, in part because there are only two strong emission lines, H/ß and He I 5876. Hawley et al. (2003) calculated an energy budget for four flares on AD Leo with spectra overlapping the $V$-band filter. They found that the continuum contributes 89%–96% of the $V$-band energy budget during the impulsive phase and 0%–95% of the $V$-band energy budget during the gradual phase. The large range of continuum emission in the $V$ band during the quiescent phase is due to the faintness of the blackbody compared to the line emission and stellar flux; in a large flare, the blackbody is likely to remain strong even during the decay phase.

We can examine the range of filling factors and blackbody emission temperatures consistent with the impulsive and gradual phase observations by calculating the blackbody contribution to the flux, $F_\lambda$, as

$$F_\lambda = \pi B_\lambda(T),$$

where $X$ is the filling factor of the blackbody spectrum, $R$ is the stellar radius, $d$ is the distance, and $T$ is the characteristic temperature of the blackbody distribution. We adopt $R = 0.124 R_\odot$ (the radius derived for M8 LP 349-25B; Dupuy et al. 2010) and $d = 76$ pc (Section 2.1) for the radius and distance.

Kowalski et al. (2013) directly fit blackbody functions to blue optical spectra of flaring mid-M dwarfs, obtaining temperatures from $T = 9800$ to 14,100 K for the peak and $T = 5600$ to 8900 K during the decay phase of impulsive flares. As the flare on SDSSJ0221 was larger than most of the flares examined, we adopt the slightly higher values to examine the area coverage of continuum emission; $T = 10,000, 13,000,$ and $16,000$ K for the impulsive phase and $T = 7000$ and $10,000$ K for the gradual phase. The resulting model spectra are shown in Figure 3, both with the blackbody modeled as the only contribution to the flare $V$-band flux and scaled so that the blackbody contributes 95% during the impulsive phase and 50% during the gradual phase.

During the impulsive phase, blackbody emission with a characteristic temperature of $T = 10,000, 13,000$, and $16,000$ K would need to have filling factors of 32%, 16%, and 11% respectively to produce 95% of the observed flare emission. Those

![Figure 2](image-url)
Large flares even at typical thin disk ages. (West et al. 2008), it is possible that ultracool dwarfs can have the persistence of quiescent activity in late-M dwarfs for down of the age–activity relation (Reiners & Basri 2010) and probably a star rather than a brown dwarf. Stars with dramatic of $< 1$ Gyr could be a massive brown dwarf, but with thin disk kinematics, SDSSJ0221 is more likely a few Gyr old and so is probably a star rather than a brown dwarf. Stars with dramatic flares are typically assumed to be young, but with the break down of the age–activity relation (Reiners & Basri 2010) and the persistence of quiescent activity in late-M dwarfs for $< 8$ Gyr (West et al. 2008), it is possible that ultracool dwarfs can have large flares even at typical thin disk ages.

The $E_U \sim 10^{42}$ erg estimate of the energy released is comparable to the highest energies calculated for mid-M dwarf flares (Hawley & Pettersen 1991; Kowalski et al. 2010). The flare is likely to have covered > 10% of the stellar (or possibly brown dwarf) surface at its peak magnitude, significantly larger than the area coverage at the peaks of most flares (Hawley et al. 2003; Fuhrmeister et al. 2008; Kowalski et al. 2013), but comparable to that of the largest flares (Hawley & Pettersen 1991; Kowalski et al. 2010).

The flare on SDSSJ0221 is not the only very large amplitude flare detected on a late-M dwarf; Schaefer (1990) report a very similar flare on CZ Cnc, and strong flares have been observed at other wavelengths (e.g., Tagliaferri et al. 1990; Fleming et al. 2000) and through optical spectroscopy (e.g., Liebert et al. 1999; Schmidt et al. 2007). Overall, however, there are not yet sufficient observations to characterize the flare frequency distribution of M7–M9 dwarfs and investigate the similarity of their emission mechanisms to those on more massive M dwarfs.

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Figure 3. M8 template spectrum calibrated to the SDSS magnitudes of SDSSJ0221 (in quiescence; black) with blackbody emission curves shown to simulate the peak (green, blue, and purple lines) and gradual phase (red and orange lines) magnitudes. The solid lines show filling factors of 100% of the V-band flare emission originating in the blackbody continuum, while the dashed lines show filling factors of 95% (impulsive phase) and 50% (gradual phase) of the V-band emission originating in the blackbody continuum.

(A color version of this figure is available in the online journal.)
