

DISCOVERY AND OBSERVATIONS OF ASASSN-13db, AN EX LUPI-TYPE ACCRETION EVENT ON A LOW-MASS T TAURI STAR

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ABSTRACT

We discuss ASASSN-13db, an EX Lupi-type (“EXor”) accretion event on the young stellar object (YSO) SDSS J051011.01–032826.2 (hereafter SDSSJ0510) discovered by the All-Sky Automated Survey for SuperNovae (ASAS-SN). Using archival photometric data of SDSSJ0510 we construct a pre-outburst spectral energy distribution and find that it is consistent with a low-mass class II YSO near the Orion star forming region ($d \sim 420$ pc). We present follow-up photometric and spectroscopic observations of the source after the $\Delta V \sim -5.4$ mag outburst that began in 2013 September and ended in early 2014. These data indicate an increase in temperature and luminosity consistent with an accretion rate of $\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$, three or more orders of magnitude greater than in quiescence. Spectroscopic observations show a forest of narrow emission lines dominated by neutral metallic lines from Fe I and some low-ionization lines. The properties of ASASSN-13db are similar to those of the EXor prototype EX Lupi during its strongest observed outburst in late 2008.

Key words: stars: activity – stars: individual (SDSS J051011.01–032826.2) – stars: pre-main sequence

Online-only material: color figures, supplemental data

1. INTRODUCTION

Young stars are often variable (e.g., Herbst et al. 1994), and are known to undergo significant eruptions marking substantial increases in their accretion rates (e.g., Herbig 1977; Hartmann & Kenyon 1996), during which they are thought to accrete a significant fraction of their total mass. A class of young stellar objects (YSOs) that repeatedly undergo these eruptions, named “EXors” after the prototype EX Lupi (e.g., Herbig 1989, 2008), has been the subject of recent studies (e.g., Sicilia-Aguilar et al. 2012; Lorenzetti et al. 2012; Antonucci et al. 2013; Kóspál et al. 2014). The physical mechanisms responsible for triggering these outbursts remain poorly understood (e.g., Sicilia-Aguilar et al. 2012; Kóspál et al. 2014), but a recent study of the 2008 EX Lupi outburst by Kóspál et al. (2014) suggests that a sub-stellar binary companion could be involved. Other possible causes include the magnetorotational instability (e.g., Bae et al. 2013), disk fragmentation (e.g., Vorobyov & Basu 2005), and instabilities

at the disk truncation radius from the stellar magnetosphere (e.g., D’Angelo & Spruit 2010).

Among the defining characteristics of EXors are that they erupt every few years with variable peak luminosities, typical visual amplitudes of up to ~ 4 mag, and outburst durations of a few months to a year. At minimum light, EXors resemble classical T Tauri stars (TTs) with absorption spectra like those of late K- or early M-dwarfs and a strong Li I line at 6707 Å (Herbig 2008). At maximum light, their spectra are dominated by a hot continuum and quiescent absorption features appear as emission lines, indicating increased accretion (Herbig 1989, 2008; Lorenzetti et al. 2012).

In this Letter we describe the discovery and follow-up observations of a new EXor-type outburst, ASASSN-13db. The transient was discovered by the All-Sky Automated Survey for SuperNovae (ASAS-SN²⁰), a long-term project to monitor the whole sky on a rapid cadence to find nearby supernovae and other transients (see Shappee et al. 2013 for details). Our transient source detection pipeline was triggered on

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²⁰ <http://www.astronomy.ohio-state.edu/~assassin/index.shtml>

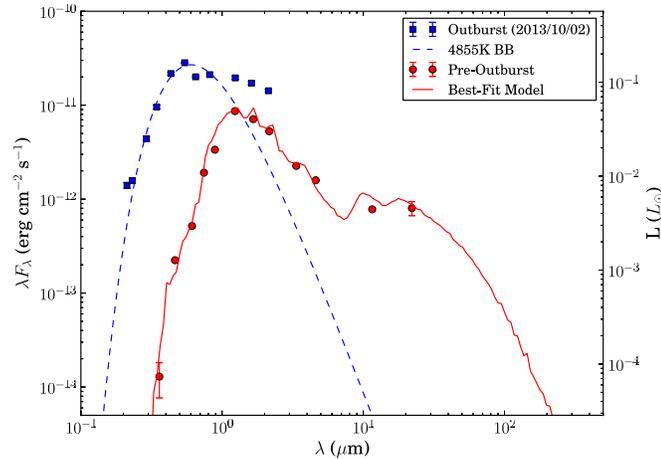


Figure 1. Spectral energy distribution of SDSSJ0510 before and during its outburst. The red circles indicate pre-outburst photometric data and the blue squares indicate outburst data. Error bars are shown, but in most cases they are smaller than the points. The solid red curve shows the best fit to the pre-outburst data from the models of Robitaille et al. (2007; model ID 3016557). We also estimate an additional thermal emission component by fitting a $T = 4855$ K blackbody curve to the outburst data (dashed blue curve).

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

2013 September 24, detecting a change in V -band magnitude from $V \sim 19.4$ to $V \sim 14$ over a span of ~ 15 days in the red source SDSS J051011.01–032826.2 (hereafter SDSSJ0510). The source is located roughly $6^\circ.6$ (~ 50 pc) from the Orion Nebula and roughly $1^\circ.4$ (~ 10 pc) from the L1615/L1616 cloud, both regions of star formation at a distance of ~ 420 pc (averaging recent estimates from Menten et al. (2007), Hirota et al. (2007), and Sandstrom et al. (2007)). We assume this distance for SDSSJ0510. Follow-up spectroscopic observations with the Magellan Echellette spectrograph (MagE; Marshall et al. 2008) on 2013 September 26 showed a highly unusual spectrum with a plethora of emission lines, and we began a follow-up campaign in order to characterize this transient.

In Section 2 we describe pre-outburst archival observations, including a previous outburst recorded in 2010–2011, and new data taken during and after the outburst as part of our follow-up campaign. In Section 3 we analyze these data and describe the properties of the star in quiescence and in outburst. Finally, in Section 4 we compare these properties to those of known EXors and the prototype EX Lupi.

2. OBSERVATIONS AND SURVEY DATA

Here we summarize the available archival data in quiescence and outburst as well as our new photometric and spectroscopic observations.

2.1. Photometry in Quiescence

We retrieved archival photometry of SDSSJ0510 in quiescence spanning the optical to the mid-infrared (IR) 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 Survey Explorer* (Wright et al. 2010) based on a coordinate cross-match to the ASAS-SN position. There are no *Spitzer*, *Herschel*, or *AKARI* observations of the source. We used the *ugriz*, *JHK_s*, and *W1W2W3W4* magnitudes in Section 3.1 to construct a spectral energy distribution (SED) for the progenitor, as shown in Figure 1. From the SDSS data,

and using M-dwarf templates from Bochanski et al. (2007), we estimate the quiescent V -band magnitude to be $V \sim 19.4$.

2.2. Prior Outburst

After the discovery of ASASSN-13db, we examined existing data for SDSSJ0510 from the Catalina Real-Time Transient Survey (CRTS; Drake et al. 2009), the Mobile Astronomical System of Telescope Robots (MASTER), and the Near-Earth Asteroid Tracking program (NEAT). The NEAT data indicate that SDSSJ0510 did not have any eruptions between 2000 December and 2003 February, but we found that it had a previously unreported outburst in late 2010 and early 2011 that was observed by CRTS and MASTER (D. Denisenko et al. 2013, private communication). SDSSJ0510 had $V > 17$ on 2010 November 8 (CRTS) and 2011 October 2 (CRTS), but had $V \sim 15.1$ in 2010 December (multiple CRTS epochs) and was brighter than the present outburst with $V \sim 13.2$ on 2011 January 22 (MASTER). The length and magnitude of this previous outburst are consistent with a large EXor-type event.

2.3. New Photometric Observations

The emission lines seen in the initial follow-up spectrum of ASASSN-13db indicated that it must be hot and should have increased ultraviolet (UV) emission. Based on this, we requested and were granted a series of *Swift* X-ray Telescope (XRT; Burrows et al. 2005) and UltraViolet and Optical Telescope (UVOT; Roming et al. 2005) target of opportunity (ToO) observations. The *Swift* UVOT observations of ASASSN-13db were obtained in six filters: V (5468 Å), B (4392 Å), U (3465 Å), $UVW1$ (2600 Å), $UVM2$ (2246 Å), and $UVW2$ (1928 Å) (Poole et al. 2008). We used the UVOT software task *uvotsource* to extract the source and background counts from a $5''.0$ radius region and a sky region with radius of $\sim 20''.0$. The UVOT count rates were converted into magnitudes and fluxes based on the most recent UVOT calibration (Poole et al. 2008; Breeveld et al. 2010). The UVOT data are shown along with other photometric data in Figure 2.

The XRT was operating in Photon Counting mode (Hill et al. 2004) during our observations. The data were reduced and combined with the software tasks *xrtpipeline* and *xselect* to obtain an image in the 0.3–10 keV range with total exposure time of 5388 s. We used a region with a radius of 20 pixels ($47''.1$) centered on the source position to extract source counts and a source-free region with a radius of 100 pixels ($235''.7$) for background counts. We measured seven counts in the source region and 113 counts in the background region, giving an expected number of counts in the source region of 4.5. We do not detect X-ray emission from ASASSN-13db to a 3σ upper limit (Kraft et al. 1991) of 2.5×10^{-3} counts s^{-1} , equivalent to $\sim 1.3 \times 10^{-13}$ erg cm^{-2} s^{-1} . This is not strongly constraining, as the source’s emission drops strongly at sub-UV wavelengths, so we do not use this limit when fitting the outburst SED.

In addition to the *Swift* observations, we obtained optical and near-IR photometry from a number of ground-based observatories. *VRI* observations were obtained at the Las Cumbres Observatory Global Telescope Network (LCOGT) 1 m facilities in Cerro Tololo, Chile and Sutherland, South Africa (Brown et al. 2013) and with the Ohio State Multiobject Spectrograph (Martini et al. 2011) on the MDM 2.4 m telescope. *VRIJHK* observations were obtained with ANDICAM on the CTIO 1.3 m telescope. All images were reduced following standard procedures. The *VRI* aperture magnitudes were calibrated using SDSS

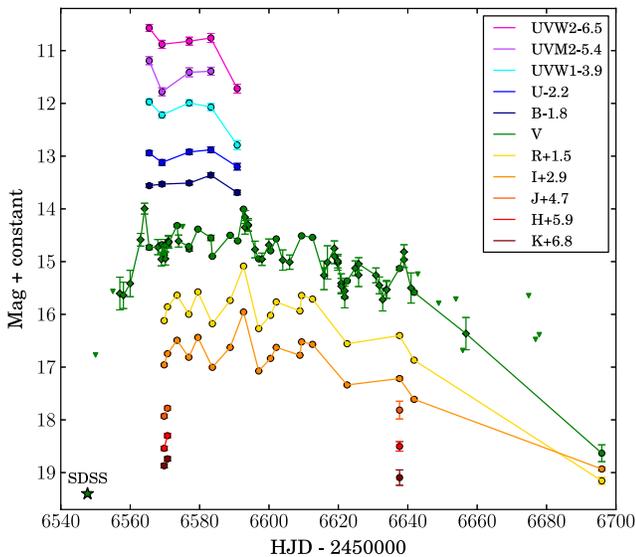


Figure 2. Light curve of ASASSN-13db, starting two weeks prior to discovery and spanning ~ 4.5 months. Data obtained from *Swift* (UV + optical), LCOGT 1 m (optical), MDM 2.4 m (optical), and SMARTS 1.3 m (optical + near-IR) are shown as circles while data from ASAS-SN (*V*-band) are shown as diamonds. 3σ upper limits are shown as triangles for epochs where the source was not detected. The approximate quiescent *V*-band magnitude calculated from SDSS data is shown as a star in the bottom-left. The source exhibited day-to-day fluctuations of up to a magnitude and remained 4–5.5 mag brighter in *V*-band than in quiescence for the duration of the outburst.

(A color version and FITS images of this figure are available in the online journal.)

stars in the field transformed onto the Johnson–Cousins magnitude system using Lupton (2005), while the *JHK* magnitudes were calibrated using a 2MASS star in the field. These data are shown in Figure 2, along with all photometric data from the ASAS-SN pipeline.

2.4. New Spectroscopic Observations

We obtained optical spectra with multiple telescopes and instruments between 2013 September 26 and 2014 January 19. The instruments/telescopes used were CCDS on the MDM 2.4 m, the MagE on the Magellan Clay 6.5 m at Las Campanas Observatory, the Multi-Object Double Spectrographs (MODS; Pogge et al. 2010) on the 8.4 m Large Binocular Telescope (LBT) on Mount Graham, the Dual Imaging Spectrograph (DIS) on the Apache Point Observatory 3.5 m telescope, and the B&C spectrograph on the Steward Observatory Bok 2.3 m telescope at the Kitt Peak National Observatory. The spectra from CCDS, DIS, and B&C were reduced using standard techniques in IRAF. The spectra from MODS were reduced using IRAF and the MODS pipeline in IDL. The spectra from MagE were reduced using the Carnegie pipeline. Figure 3 shows a montage of the flux-calibrated spectra from MODS, CCDS, and the B&C. Figure 4 shows a small section of the MagE intermediate-resolution ($R \sim 5000$) spectra.

3. ANALYSIS

3.1. Spectral Energy Distribution

Figure 1 shows the pre-outburst SED of SDSSJ0510 as compared to its SED during outburst on 2013 October 2. Also shown is the best-fit SED model for SDSSJ0510 generated by the Robitaille et al. (2007) YSO SED fitting tool²¹ (model ID

²¹ <http://caravan.astro.wisc.edu/protostars/sedfitter.php>

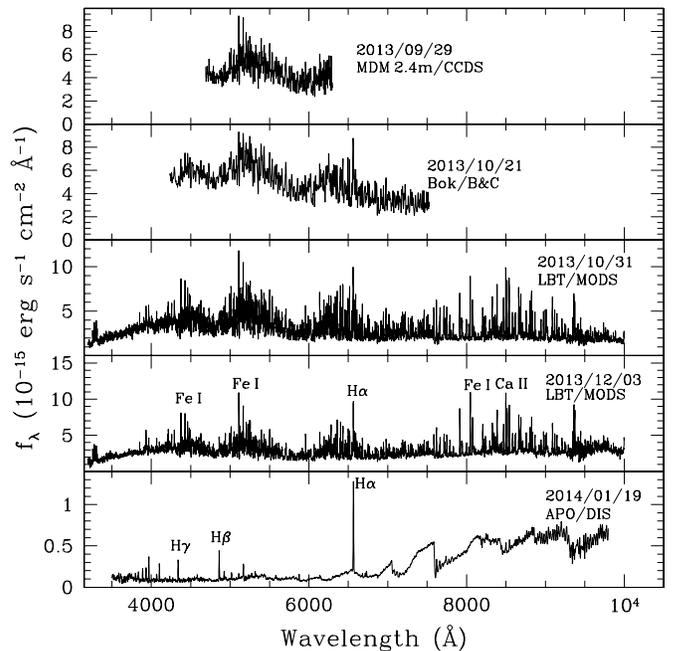


Figure 3. Spectral time-sequence of ASASSN-13db during and after the outburst. Each spectrum shows the UT date and telescope/instrument used. During the outburst, the spectra are dominated by a forest of emission lines, mostly neutral metallic lines from Fe I, with later epochs showing stronger features. Some of the strongest features, such as Fe I, $H\alpha$, and the Ca II infrared triplet, are identified in the 2013 December 3 MODS spectrum. In contrast, the 2014 January 19 spectrum shows features characteristic of a TTS of M5 spectral type, indicating the outburst has likely ended. Note the change in the flux scale between panels.

3016557). The fitting method compares the observed SED to 200,000 model YSO SEDs consisting of pre-main sequence stars with various combinations of stellar parameters embedded in circumstellar disks with outflow cavities in order to sample a large range of parameter space. To account for any variability of SDSSJ0510 in quiescence, we used 10% minimum uncertainties on all input magnitudes.

The properties of SDSSJ0510 before and during outburst are summarized in Table 1. The pre-outburst SED is well-modeled as a class II YSO at a distance of ~ 420 pc. The best-fit model is consistent with a luminosity of $\sim 0.1 L_{\odot}$, $T_{\text{eff}} \sim 3100$ K, and $M_{*} \sim 0.15 M_{\odot}$. In addition to the properties of the best-fit model, we also list the minimum and maximum values for each parameter taken from all models with $\chi^2 - \chi^2_{\text{min}} < 3$ for all individual data points, as suggested in Robitaille et al. (2007). While most parameters are well-constrained, some are not. For example, the best fitting accretion rate is $\dot{M} = 2 \times 10^{-12} M_{\odot} \text{ yr}^{-1}$, but realistically this should be viewed as an upper limit of $\dot{M} \lesssim 10^{-10} M_{\odot} \text{ yr}^{-1}$. Similarly, the distribution of inner disk radii is bimodal, at 0.02 and 0.5 AU, and only the latter is consistent with estimates for EX Lupi (Sipos et al. 2009). None of the models are consistent with SDSSJ0510 having an envelope.

Other EXors in outburst have shown additional thermal emission (Lorenzetti et al. 2012; Sicilia-Aguilar et al. 2012). Fitting a blackbody curve to the outburst SED assuming the same extinction as before the outburst ($A_V = 0.04$ for the best-fit model), we find that the bluer outburst data are well-fit by a $T = 4855$ K blackbody curve, slightly higher than the typical range of 1000–4500 K (Lorenzetti et al. 2012). The near-IR outburst data are not well-fit by this blackbody

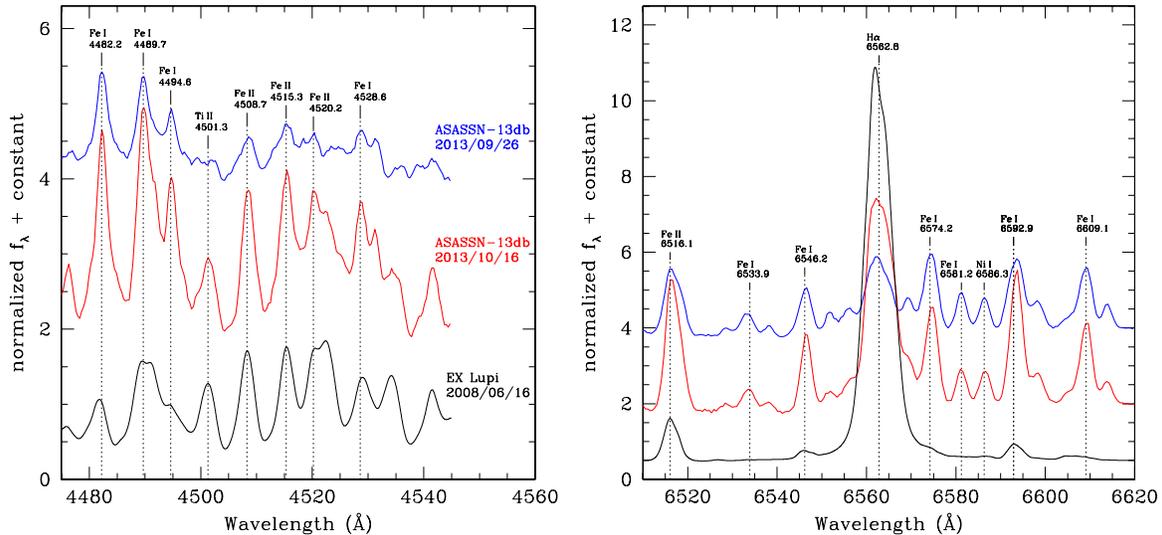


Figure 4. Continuum normalized spectra of ASASSN-13db compared to a spectrum of EX Lupi during its latest and strongest eruption in 2008 June (Sicilia-Aguilar et al. 2012). We have convolved the high-resolution spectrum of EX Lupi with a Gaussian to match the intermediate resolution of the Magellan/MagE spectra. All identified emission features of EX Lupi are present in the ASASSN-13db spectra, but ASASSN-13db also shows many features not seen in EX Lupi, some of which are identified in the figure (e.g., the Fe I lines at 6533.9 Å and 6581.2 Å). We used a low-order polynomial to fit the minimal continuum between the emission lines and normalize the spectra.

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

Table 1
Properties of SDSSJ0510 Before and During Outburst

	Best-fit Model (Pre-outburst)	$\Delta\chi^2 < 3$ Range (Pre-outburst)	During Outburst
Stellar age (yr)	3.5×10^6	$1 \times 10^6 - 2 \times 10^7$	—
Stellar mass (M_\odot)	0.15	0.1–0.4	—
Stellar radius (R_\odot)	1.1	0.7–1.1	—
Effective temperature (K)	3075	2700–3900	4855
Total luminosity (L_\odot)	0.1	0.04–0.4	>0.2
Accretion luminosity (L_\odot)	$< 4 \times 10^{-4}$	—	0.2
Disk accretion rate ($M_\odot \text{ yr}^{-1}$)	2×10^{-12}	$10^{-12} - 10^{-9}$	$\sim 10^{-7}$
Disk mass (M_\odot)	5.6×10^{-5}	$4 \times 10^{-7} - 6 \times 10^{-3}$	—
Disk inner radius (AU)	0.6	0.01–3	—
Disk outer radius (AU)	900	9–8000	—
Disk scale height at 100 AU (AU)	7	1–12	—
Disk flaring power	1.1	0.9–1.2	—

curve, indicating the presence of increased disk emission, but we lack the mid-to-far-IR data needed to fit an additional disk component. Integrating over the blackbody curve gives a lower limit to the total luminosity in outburst of $L = 0.2 L_\odot$.

Assuming the total luminosity in outburst is equivalent to the accretion luminosity, we estimate the mass accretion rate of ASASSN-13db in outburst using two methods. First, we use the scaling from Natta et al. (2004) based on the width of the H α line at 10% of maximum. We measure this width to be $\sim 600 \text{ km s}^{-1}$, which gives an accretion rate of $\dot{M} = 9 \times 10^{-8} M_\odot \text{ yr}^{-1}$. We also use our estimate of the accretion luminosity combined with the stellar mass, stellar radius, and inner disk radius estimates from the SED fits and the method described in Dahm (2008). This gives a lower limit of $\dot{M} = 5.5 \times 10^{-8} M_\odot \text{ yr}^{-1}$. These two estimates are mutually consistent, and we conclude that $\dot{M} \sim 10^{-7} M_\odot \text{ yr}^{-1}$ is a reasonable estimate of the accretion rate during the outburst.

The SED of the source in quiescence and during outburst are both consistent with ASASSN-13db being a large EXor accretion event on a low-mass TTS (e.g., D’Alessio et al. 1999;

Sipos et al. 2009), similar to the 2008 outburst of EX Lupi (e.g., Herbig 2008; Lorenzetti et al. 2012).

3.2. Light Curve of ASASSN-13db

Figure 2 shows the UV, optical, and near-IR light curves of ASASSN-13db from HJD 2546550 (~ 1 week prior to detection) through our latest epoch of observations on HJD 2546695. The ASAS-SN data show SDSSJ0510 brightening by $\Delta V \sim 3.8$ mag, at which point it was flagged by the ASAS-SN detection pipeline. Subsequent follow-up observations show the transient reaching a peak magnitude of $V \simeq 14$ and fluctuating by up to ~ 1 mag across all observed bands on timescales as short as < 1 day. These variation timescales and amplitudes are consistent with other EXor events (e.g., Lorenzetti et al. 2012). SDSSJ0510 showed little variation in NIR colors before and during the outburst, implying the apparent brightening is likely not due a change in circumstellar extinction. During the ~ 4 month outburst, SDSSJ0510 was consistently ~ 4 – 5.5 mag brighter than in quiescence. The star began to exhibit lower

average magnitudes beginning around HJD 2456622, and has faded to $V \sim 18.6$ on HJD 2456695, indicating the outburst has likely ended.

3.3. Spectral Analysis of ASASSN-13db

The spectral time-sequence of ASASSN-13db is shown in Figure 3. The spectra are completely dominated by a forest of emission lines during the outburst. The lines are mostly neutral metallic lines from Fe I, with some low-ionization lines, including Fe II, Ca II, and Ti II. Figure 3 shows some of the strongest lines identified in the MODS spectrum from 2013 October 31, which include Fe I, H α , and the Ca II infrared triplet. In contrast, the latest spectrum shows a strong red continuum and features characteristic of a TTS (M5 spectral type), again indicating the outburst has likely ended. In this spectrum we detect the 6707 Å Li I line, but we are unsure whether SDSSJ0510 is in a fully quiescent state.

The emission line dominated spectra of ASASSN-13db are broadly similar to EXors in outburst, but with an unusually rich set of emission lines and little continuum. In Figure 4 we show two small sections (4470–4560 Å and 6510–6620 Å) of MagE spectra obtained at two different epochs separated by 20 days. For comparison, we also show a spectrum of EX Lupi from Sicilia-Aguilar et al. (2012) obtained in 2008 June during its strongest observed outburst (e.g., Kóspál et al. 2008; Aspin et al. 2010). We identify Fe I, Ni I, Fe II, and Ti II lines in emission, which are clearly present in the spectra of both ASASSN-13db and EX Lupi. The metallic lines in the spectra of ASASSN-13db are resolved with FWHM $\simeq 120$ – 170 km s $^{-1}$, consistent with the broad components of the metallic emission lines in the spectra of EX Lupi during its 2008 outburst. Our spectra of ASASSN-13db do not have enough resolution to show the narrow-line components observed in some emission lines during the EX Lupi outburst (Herbig 2007; Sicilia-Aguilar et al. 2012). ASASSN-13db does not show signs of large amplitude ($\gtrsim 5$ km s $^{-1}$) radial velocity variations.

4. DISCUSSION

Pre-outburst photometry and SED fitting indicate that SDSSJ0510 is likely an $L \simeq 0.1 L_{\odot}$ TTS near the Orion star-forming region at a distance of ~ 420 pc, consistent with its post-outburst spectrum. During the strong outburst from 2013 September–2014 January, it increased in V-band flux by a factor of over 140 and maintained a level of emission 4–5.5 mag greater than in quiescence for much of this time. The magnitude of this outburst, its evolution, and its duration are consistent with those of the 2008 outburst of EX Lupi, the prototype of the EXor variable class. In addition to this outburst, SDSSJ0510 also experienced a similar outburst in late-2010/early-2011. As EXors are known to experience recurring events every few years, this also suggests that SDSSJ0510 is an EXor.

Spectroscopy of SDSSJ0510 during outburst also shows similarities to the spectra of other EXors in the literature (e.g., Sicilia-Aguilar et al. 2012; Herbig 2008; Lorenzetti et al. 2012). In particular, spectra of the source in outburst are dominated by a forest of narrow emission lines at all epochs, primarily Fe I and other low-ionization lines. Comparison with spectra of EX Lupi during its 2008 outburst from Sicilia-Aguilar et al. (2012) shows that the spectra of ASASSN-13db have many of the same emission features as EX Lupi in 2008. However, the spectra of ASASSN-13db also show a number of lines not present in the EX Lupi spectra, indicating possible differences in excitation

temperature and/or abundances between the sources. As of late 2014 January, the spectrum is that of an M5 TTS star.

The similarities between our observations of ASASSN-13db and EXors in the literature lead us to conclude that SDSSJ0510 likely underwent an EXor accretion event. The magnitude of the change in luminosity and the presence of many unique spectral features, however, are unusual for typical EXor outbursts, and more closely resemble the large 2008 outburst in EX Lupi. If this was an EXor outburst, SDSSJ0510 would appear to be one of the lowest mass TTSs with such an event, and it seems to be experiencing large-scale events on a more rapid timescale than the typical EXor.

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