The 2010 early outburst spectrum of the recurrent nova U Scorpii

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ABSTRACT

Aims. We present optical spectra of the fast recurrent nova U Sco during its recent outburst, obtained within 24 h of maximum light.
Methods. We use medium resolution ($R \sim 4000$) spectra taken with the with the MagE spectrograph on the Magellan (Clay) 6.5 m telescope of the Las Campanas Observatories.
Results. The spectrum is notable for its lack of a low ionization transient heavy element absorption system that is visible in the large majority of novae near maximum light. We suggest that this may be due to the dominance of inner Lagrangian L1 mass transfer and the absence of a circumbinary gas reservoir in this object.

Key words. novae, cataclysmic variables – stars: individual: U Sco

1. Introduction

Recurrent novae (RNe) are semi-detached binary systems consisting of a massive white dwarf (WD; $M_{WD} \geq 1.2\ M_{\odot}$) accreting material from a companion, with mass transfer rates of $\geq 10^{-7}\ M_{\odot}$/year (Hachisu et al. 2000). With total system mass exceeding the Chandrasekhar mass limit, they are prime candidates for SNeIa progenitors, therefore they are monitored diligently. Their "recurrent" designation reflects the fact that they exhibit multiple nova eruptions on time scales of several decades – more frequent than classical novae whose eruptions have been observed only once. Therefore they are excellent natural test beds for the study and understanding of stellar explosions in accreting systems and, of course, the mechanism of mass accumulation on a near-Chandrasekhar limit WD. An excellent recent review on the properties of RNe can be found in Schaefer (2010).

The object of this work, U Sco, is one of the most well-studied recurrent novae, not only for its short intra-outburst rate[1] but also because it is an eclipsing binary with an orbital period of 1.23 days (Schaefer 1990; Schaefer & Ringwald 1995). It consists of a massive WD ($M_{WD} \geq 1.2\ M_{\odot}$; Anupama & Dewangan 2000) and a subgiant mass-losing companion whose spectral type ranges between F8 (Johnston & Kulkarni 1992) and K2 (Anupama & Dewangan 2000; also, Hanes 1985; Schaefer 1990). Because of its total mass exceeding the Chandrasekhar mass limit of 1.4 $M_{\odot}$, it is considered a favorable candidate for a SN Ia progenitor. In quiescence, its optical magnitude ranges from $V \sim 18$ (outside eclipse) to $V \sim 19$ in eclipse (Schaefer et al. 2010); the maximum brightness in outburst reaches $V \sim 8.0$ mag. Its rapid decline by 3 mag from maximum light occurs in 4 days (Fig. 1) making it a very fast recurrent nova. The

principal mechanism leading to the eruption is believed to be a thermonuclear runaway on the mass-accumulating WD, enriching the ISM with CNO-enhanced material.

This short communication presents one of the earliest U Sco 2010 outburst spectra, obtained at moderate spectral resolution within 24 h of discovery and peak brightness and showing strong, wide Balmer lines with fast variability and blueshifted/redshifted velocities reaching 3000 km s^{-1}.

2. Observations

The recent U Sco outburst was announced as an AAVSO[2] and VSNet alert on 2010-Jan.-28.438 (UT)[3] and was confirmed soon thereafter. Our data were obtained on 2010-Jan.-29.354 (UT), about 24 h after outburst maximum. The AAVSO light curve (presented in Fig. 1) indicates that U Sco was at $V \sim 8$ mag the night of our observations. We used the Magellan Echelette (MagE) optical spectrograph on the Clay telescope of the Las Campanas observatories[4], with an 1″ slit, providing $R \sim 4000$. The 14 orders of the spectrograph provided effective coverage between 3000 and 9000 Å. During the night of observations, the sky was clear but the moon was high in the sky (albeit setting at the times of our U Sco observations). A total of 50 spectra were acquired sequentially with exposure times of 10 s each and a cadence of minutes. Although the spectrograph is very stable our object observations were bracketed by observations of a ThAr lamp to improve our wavelength calibration. Finally, the white

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[1] The system has 10 recorded nova outbursts, starting in 1863, with an average inter-erruption interval of a decade; it also holds a record short inter-eruption interval of 7.88 years (1979 to 1987).
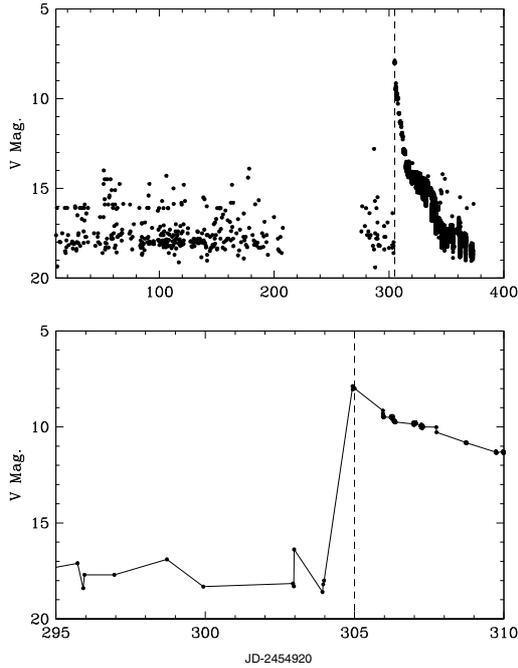
[3] The 2010 outburst was discovered by two amateur astronomers, Barbara Harris of New Smyrna Beach and Shawn Dvorak of Clermont, who were part of the AAVSO network.

[4] http://www.lco.cl/

Fig. 1. AAVSO light curve of U Sco, with the time of our spectroscopic run marked. The zoomed-in version (*bottom panel*) clearly demonstrates that at the time of our observations the nova was at maximum light.
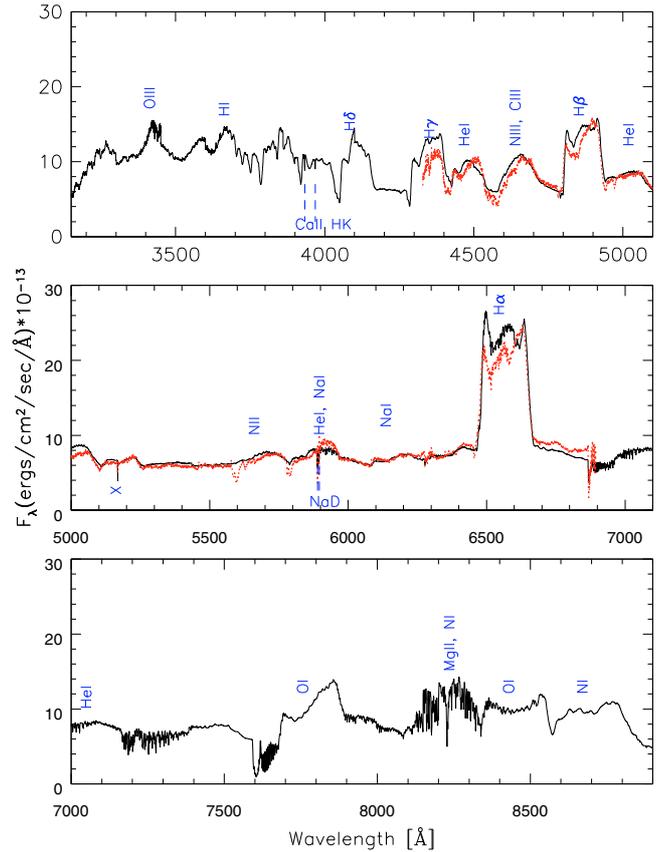

Fig. 2. Average MagE spectrum of U Sco, with the main features labeled. Overplotted with a red dashed line is the 1999 spectrum from Iijima (2002) for comparison.

dwarf LTT 4364 (GJ 430) was observed for flux calibration. For data processing and reduction we used IRAF's[5] echelle package.

3. Data analysis and discussion

Figure 2 presents our averaged spectrum of U Sco with the main features labeled. Using the photometric ephemeris of Schaefer & Ringwald (1995), HJD = 2 447 717.6061(32) + 1.2305631(30)E, the observations cover orbital phases between 0.47 and 0.5, corresponding to inferior conjunction of the white dwarf. The spectrum is almost certainly formed in the optically thick ejecta of the white dwarf. Indeed, the spectral features are very strong, full of line blends and velocity-broadened line profiles. Narrow interstellar Na I D and Ca II H&K are the only absorption lines present that are not associated with the expanding ejecta. The most prominent spectral features are attributed to N III, C III and He I in the ejecta. They do not show any measurable radial velocity variations within the roughly 2 h time period of the MagE observations.

The characteristics of the different outbursts of U Sco seem to be very similar to each other, if we compare the properties of the various emission lines, e.g., intensities and line profiles, with those of Anupama and Dewangan (2000) obtained 11 h after the 1999 outburst maximum, Iijima (2002) obtained 16 h after the 1999 outburst maximum, Lepine et al. (1999) obtained 5 days after the 1999 maximum, and Munari et al. (1999), obtained 0.64 to 19.8 days after the 1999 visual maximum. Of those, Iijima (2002) presents spectra only 16 h after the outburst with similar resolution and S/N to the data presented here, and Munari et al. (1999) present multi-epoch spectra that explore the time

evolution of the Balmer emission lines. Our spectrum is quite similar in its general characteristics to that of Iijima taken the same time after outburst, although there are small differences that are apparent. Figure 2 includes the Iijima (2002) spectrum (ref dotted lines) for comparison to ours. The Iijima (2002) spectrum is dominated by a rich group of N II lines. The Hα line has three main emission components, with the redder one being the strongest, and multiple satellite absorption features are present at high velocities (reaching –4850 km s^{-1}). The Hβ line is double-peaked, reaching velocities comparable to those of Hα. The evolution of the 1999 Balmer lines is better demonstrated in Munari et al. (1999), where the Hα line's red peak strengthens with time and the line exhibits three strong peaks 18d after the outburst.

In the 2010 MagE data the line profiles seem to be different – a common phenomenon in postoutburst novae. Both the Hα and Hβ lines are triple peaked, and the red and blue peaks reach similar velocities, indicating that they originate from the same part of the ejecta. The Hγ and Hδ line profiles seem to also have multiple components which are not resolved due to blending with other transitions. This is likely the reason for their velocity deviation with respect to the velocities of Hα and Hβ in Table 1. The blueshifted absorption components of the Hα line identified by Iijima (2002) are absent in our MagE spectra. A blueshifted emission hump at 6420 Å is also identified by Iijima (2002) as a secondary component of NII, reaching velocities of –2880 km s^{-1}; in the 2010 MagE spectra the same feature is blueshifted by –3056 km s^{-1}. Multiple high-velocity absorption components from the ejecta are present in the rest of the Balmer lines and their relevant velocities are listed in Table 1.

Table 1. Kinematic characteristics of the main line profiles in the U Sco spectrum.

Line	Rest wavelength (Å)	Velocities of line components[a]			EW[b] (Å)	$FWHM$[c] (Å)	Em/abs	Notes
		Blue (km s^{-1})	Red (km s^{-1})	center of line (km s^{-1})				
Hα	6563	−2915	3283	150	−309 ± 5	109	em	ejecta
NaD1	5896	−44	–	–	0.231 ± 0.003	1.11	abs	IS
		−206	–	–	0.044 ± 0.002	1.34	abs	IS
NaD2	5890	−45	–	–	0.313 ± 0.003	1.15	abs	IS
		−174	–	–	0.016 ± 0.003	0.85	abs	IS
Hβ	4874	−2966	3287	−390	−145 ± 5	129	em	ejecta
		−3854	–	–	–	–	abs	ejecta
		−5864	–	–	–	–	abs	ejecta
Hγ	4342	–	–	584	−138 ± 6	99	em	ejecta
		−3806	–	–	–	–	abs	ejecta
		−5864	–	–	–	–	abs	ejecta
Hδ	4100	–	–	370	−110 ± 10	87	em	ejecta
		−3786	–	–	–	–	abs	ejecta
		−4304	–	–	–	–	abs	ejecta
CaII H	3968	−45	–	–	0.115 ± 0.012	0.937	abs	IS
		−187	–	–	0.009 ± 0.002	0.618	abs	IS
		−1547	–	–	2.340 ± 0.050	14.92	abs	ejecta
CaII K	3934	−49	–	–	0.181 ± 0.023	0.902	abs	IS
		−187	–	–	0.018 ± 0.005	0.617	abs	IS
		−1106[d]	–	–	3.580 ± 0.060	10.32	abs	ejecta

Notes. [a] The blue/red velocities in the line profiles presented here were measured from the average spectrum with a Gaussian fit; the average error in the velocities is 2 km s^{-1}. The velocities of the central components of the Balmer lines were measured with IRAF/splot's task "e", providing an average error of 5 km s^{-1}. [b] Measured from the average spectrum. Following the conventional IRAF nomeclature, negative EW values correspond to emission lines. The errors in the measurements correspond to uncertainties in the determination of the line continuum. [b] Measured from the average spectrum; the error in $FWHM$ measurements is less than 1 Å in all cases. [d] Blend with Hϵ components.

It is interesting to compare the Balmer emission line profiles with those of eclipsing cataclysmic variable accretion disk line profiles, in which the blue and the red anse of the disk produce blueshifted and redshifted components of the Balmer lines with respect to the observer. In the case of U Sco, the red/blue velocities are much higher than those expected from an accretion disk surrounding the WD, so this line shape likely represents the projected geometry of the ejected shell on the orbital plane. The exact shape of the ejected material is not known for U Sco, however modeling of HST and radio observations of the recurrent nova RS Ophiuchi argues for an hourglass shape of the ejecta (Ribeiro et al. 2009). It is possible that the U Sco ejecta are also lobe-like, expanding perpendicular to the orbital plane of the binary. Interestingly, the 1999 U Sco outburst spectra of Lépine et al. (1999), of Munari et al. (1999) and of Iijima (2002) indicate that over a period of a few days the velocities of those peaks decline. In this case, the central line velocity represents the projected velocity of the ejected blobs as material is accelerated perpendicular to the orbital plane. This would present an obvious similarity of the recurrent nova ejecta with those of bipolar planetary nebulae, suggesting that the explosion dynamics may be similar.

The blue region of the spectrum is dominated by broad emission components of Fe II, O III, He I, C III and various unresolved blends. Iijima (2002) identifies a suite of N II lines together with their various blue/red- shifted components between 5450 and 6400 Å, but these are not present in our 2010 MagE spectra. Instead, this spectral region is dominated by pronounced wide emission troughs at 5998, 6012, 6027, 6042, and 6064 Å (Fig. 3, bottom) likely due to Fe II (at $\lambda\lambda$5997.8, 6012.2, 6027.1, 6042.1, 6065.5 respectively). The NaID lines are the only absorption lines that are present in this wavelength interval. The top panel of Fig. 3 presents the CaII H&K lines,

demonstrating that each line component is accompanied by two blueshifted absorption dips. The lower velocity components (at −45 and −49 km s^{-1} for the Ca II H and the Ca II K lines respectively) are interstellar in nature, consistent with the low-velocity components of the NaID lines. Note that in 1999 the latter are also accompanied by a red emission component (Fig. 3, bottom).

The medium velocity components[6] for both CaII H&K and NaID are likely to be due to interstellar clouds along the line of sight. The high velocity components of the CaII H&K lines correspond to the velocities of the ejecta. Similar components should be present in th NaI D lines (especially since the NaI ionization potential is much lower at 5.1 eV), however the relevant spectral region is dominated by HeI, FeII, NII and NaI emission which mask possible high velocity absorption components from NaID.

It is worth noting that variable Na I D absorption components from expanding circumbinary gas clouds have been recently detected in the vicinity of three supernovae Ia (SNe Ia), originating from ionized circumstellar clouds, irradiated by the SN and interacting with the explosion ejecta (Patat et al. 2007). The absence of expected accompanying CaII H&K lines was attributed to the stronger radiation required to excite CaII H&K with respect to NaI. In any case, such observations from the SNeIa community are pointing to the single degenerate scenario for SNeIa progenitors. Similar well-documented observations of high-velocity variable NaI and CaII lines in recurrent novae (such as U Sco), present a mechanism for replenishing circumbinary gas with such clouds, providing a bridge between this class of SNe and their progenitors.

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[6] −186 and −187 km s^{-1} for Ca II H and the Ca II K lines respectively and −206 and −174 km s^{-1} for NaI D1 and D2 respectively.
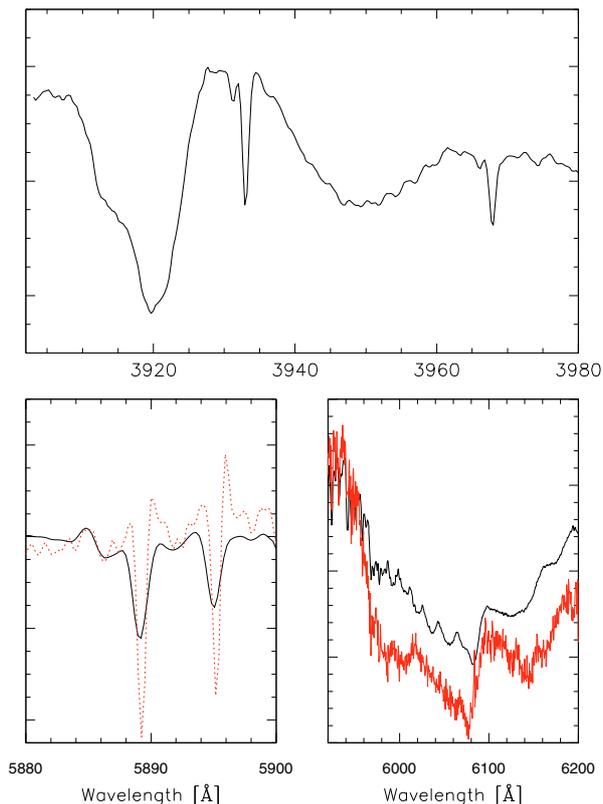
Fig. 3. Close-ups of the CaII H&K line region (3920–3980 Å; *top panel*) and the region between the HeI 5876 Å and Na I D and the Hα region (5900–6200 Å; *middle panel*). Overplotted, are the relevant spectral regions of the 1999 spectrum from Iijima (2002) for comparison, when available.

Fig. 4. Representative snapshots of Balmer lines: Hα (*bottom, right*), Hβ (*bottom, left*), Hγ (*top, right*) and Hδ (*top, left*). $t_2 = t_1 + 672$ s, $t_3 = t_1 + 1301$ s and $t_4 = t_1 + 1453$ s. A constant offset was applied to the spectra for presentation purposes. Overplotted, are the relevant spectral regions of the 1999 spectrum from Iijima (2002) for comparison, when available.

Finally, at this very early stage in the postoutburst nova there is no indication of forbidden lines or coronal lines in the 2010 U Sco MagE spectra, unlike other recurrent novae, e.g., RS Oph (Rosino 1987), which have giant secondary stars. Furthermore, there are no hints of the weak Mg I b feature (at 5174 Å) and the Fe II blend (at 5270 Å) which were used to secure the spectral classification of the secondary star by Anupama & Dewangan (2000).

3.0.1. Line variability

In a nova explosion the accretion disk surrounding the WD is believed to be swept up by the much more massive ejecta, and the outer layers of the WD are ejected replenishing the surrounding ISM with heavier elements. As discussed before, the velocities of the Balmer emission line components decline with time. In the time-resolved MagE spectra there are no changes in the velocities of the blue and red peaks of the Hα and Hβ lines. However, real variability in the line profile *shapes* is evident in Fig. 4, in which four snapshots of observations of the Balmer lines are presented. Using the notation of the figure, $t_2 = t_1 + 672$ s, $t_3 = t_1 + 1301$ s and $t_4 = t_1 + 1453$ s. More notable variations are presented in the equivalent width of the lines. Although the amplitudes of the variations are not large, they are nevertheless real (within error) and they lack periodicity. The amplitude of those variations is larger in the Hα line (of the order of 20 ± 5 Å), declining for the rest of Balmer lines. The probable cause is variations of the emissivity as the ejecta expand. It is interesting that these fast variations are reminiscent of accretion disk flickering,
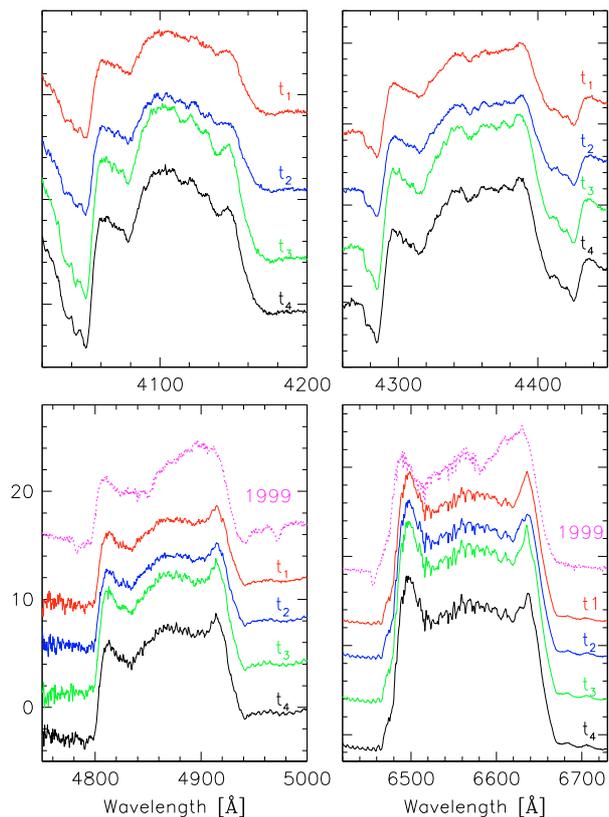
although the accretion disk should not be visible at the time of the 2010 MagE observations, which is only one day after the peak of the outburst maximum.

3.0.2. THEA systems?

Transient Heavy Element Absorption (THEA) systems were described for novae by Williams et al. (2008), by examining high-resolution ($R \sim 50\,000$) optical spectra of post-outburst nova ejecta. These are transient absorption lines from low ionization Fe-peak and s-process elements that correspond to gas ejected from the secondary star prior to the nova outburst. The observed gas expansion velocities are between 400–1000 km s^{-1}. The corresponding ions responsible for the absorption are Sc II, Ti II, V II, Cr II, Ba II, Sr II, and Fe II (2008). They appear as early as one day after the nova outburst and they evolve with time, having lifetimes of up to 2 months after the explosion. THEA lines have been identified in 13 novae so far (2008; Mason et al. 2010), and the exact origin of the gas responsible for the absorption is still uncertain.

Since the *FWHM* of THEA lines reaches up to 350 km s^{-1}, the 75 km s^{-1} resolution of the MagE U Sco 2010 spectra should be capable of detecting the majority of such systems, if present, and place constraints on their formation mechanism. However, they are not observed in the early outburst spectrum of U Sco.

Thus, U Sco would join the small group of novae in which THEA are absent (V382 Vel/99, V1187 Sco/04, and V5115 Sgr/05; 2008). Williams et al. (2008) point out that these novae,

like U Sco, are all fast novae ($t_3 \leq 13$ d) and therefore the THEA lines may have dissipated by the time of the relevant observations, which were more than 6–9 days after outburst. At the same time, if the THEA system is due to material lingering above the orbital plane of the binary (2008) this material could be bipolar and not spherically symmetric, since it is ejected from the secondary star (it mimics an outflow, but it originates from the secondary star of the binary). Therefore, it would not be easily detected even in very high resolution spectra in high inclination systems such as U Sco. Of course, as gas expands from the binary, the opening angle would tend to increase, so components perpendicular to the orbital plane (and further away form the binary) could be detected. Certainly, high resolution observations of U Sco up to a month after its outburst maximum can provide essential information on the distribution of the gas responsible for the THEA absorption lines, and can contribute critically to determining their formation mechanism.

The absence of THEA systems may have implications for outburst models such as those of Hachisu et al. (2000) that predict postoutburst winds, since the winds should produce observable absorption when they achieve a certain column density. What limits does the absence of observed absorption place on the total mass loss due to such winds? An answer to this question is provided by the analysis of the THEA system in the nova LMC 2005 by Williams et al. (2008), where for the best case observed until the present time of a narrow line absorption system a Fe II column density of $\sim 10^{18}$ cm^{-2} and a corresponding shell mass of $\sim 10^{-5}$ $M_\odot$ was deduced, assuming solar abundances. If we assume as an extreme that the LMC 2005 THEA absorption might still have been detectable if it had been 100 times weaker with the same line widths, we could have possibly detected ejected mass of $\sim 10^{-7}$ $M_\odot$, which is roughly what Iijima (2002) estimated for the 1999 U Sco outburst, and is what the Hachisu et al. (2000) models generally predict for early wind mass loss. However, the velocity gradients in the postoutburst winds are not the narrow 50 km s^{-1} THEA widths that were observed for LMC 2005, rather are of order 2000 km s^{-1} for the winds. Thus, any line absorption from winds is likely to be spread over a much greater wavelength interval, rendering the resulting very broad absorption lines more difficult to detect against the continuum. For absorption lines formed over a broad velocity interval, roughly 3×10^{-6} $M_\odot$ of ejected mass would be needed to detect absorption features from the winds. Such a mass is greater than the upper limit normally expected from a wind in the early weeks following outburst and therefore the absence of observed THEA absorption should not normally impose a stringent constraint on wind models. In any event, absorption produced by the outburst ejecta, which are generally more massive, are likely to dominate most absorption from postoutburst winds except in cases of high wind mass loss rates or a situation where the wind continues for many months, because the ejecta and the winds have similar, very large velocity gradients.

The absence of THEA absorption in U Sco within one day of maximum brightness indicates that the circumbinary gas reservoir observed around most novae by Williams et al. (2008) may not be present for this system. Williams & Mason (2010) have

suggested that nova outbursts may be initiated by two types of mass transfer from the secondary star onto the WD: (1) from steady flow via the inner Lagrangian point, L1, and (2) via a more irregular collapse of the large circumbinary reservoir that produces THEA absorption. Outbursts of the first type would not necessarily show any THEA absorption and according to TNR models (Yaron et al. 2005) should be characterized by rapid, smooth declines in visible brightness, especially if these "type 1" outbursts are associated with massive WDs. We suggest here that the rapid, smooth decline of U Sco is a sign of a TNR triggered by inner Lagrangian mass transfer and the absence of a significant circumbinary reservoir in the line of sight.

4. Overview of conclusions

This paper presents the earliest medium-resolution spectrum of U Sco one day after its 2010 outburst, covering the optical region of the spectrum (3000–8500 Å). Wide, multicomponent Balmer emission lines are present, reaching velocities of ~ 3000 km s^{-1}, indicative of an expanding shell resulting from the explosion. Broad emission components of Fe II, O III, He I, C III are identified in the blue part of the spectrum. The THEA complex is not present in U Sco, although the fact that this may be due to our viewing angle of the system can not be ruled out. Time-resolved spectra revealed intrinsic fast variations in the Balmer lines, similar to accretion disk flickering.

References

Anupama, G. C., & Dewangan, G. C. 2000, AJ, 119, 1359
Fluks, M. A., Plez, B., The, P. S., et al. 1994, A&AS, 105, 311
Hanes, D. A. 1985, MNRAS, 213, 443
Hachisu, I., Kato, M., Kato, T., Matsumoto, K., & Nomoto, K. 2000, ApJ, 534, L189
Houdashelt, M. L., Bell, R. A., Sweigart, A. V., & Wing, R. F. 2000, AJ, 119, 1424
Iijima, T. 2002, A&A, 387, 1013
Johnston, H. M., & Kulkarni, S. R. 1992, ApJ, 396, 267
Lépine, S., Shara, M. M., Livio, M., & Zurek, D. 1999, ApJ, 522, L121
Mason, E., Diaz, M., Williams, R. E., Preston, G., & Bensby, T. 2010, A&A, 518, A108
Munari, U., Zwitter, T., Tomov, T., et al. 1999, A&A, 347, L39
Patat, F., Chandra, P., Chevalier, R., et al. 2007, Science, 317, 924
Ribeiro, V. A. R. M., Bode, M. F., Darnley, M. J., et al. 2009, ApJ, 703, 1955
Schaefer, B. E. 1990, ApJ, 355, L39
Schaefer, B. E. 2010, ApJS, 187, 275
Schaefer, B. E., & Ringwald, F. A. 1995, ApJ, 447, L45
Schaefer, B. E., Pagnotta, A., Xiao, L., et al. 2010, AJ, 140, 925
Williams, R., & Mason, E. 2010, Ap&SS, 327, 207
Williams, R., Mason, E., Della Valle, M., & Ederoclite, A. 2008, ApJ, 685, 451
Yaron, O., Prialnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398