Early Spectroscopy of the 2010 Outburst of U Scopii

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Abstract

We present early spectroscopy of the recurrent nova U Sco during an outburst in 2010. We successfully obtained time-series spectra during the period of \( t_1 = 0.37-0.44 \text{d} \), where \( t_1 \) is the time that elapsed since the discovery of the present outburst. This is the first time-resolved spectroscopy on the first night of U Sco outbursts. At \( t_1 \approx 0.4 \text{d} \), the H\( \alpha \) line consists of a blue-shifted \((-5000 \text{km s}^{-1} \) ) narrow absorption component and a wide, triple-peak emission line: blue \((\sim -3000 \text{km s}^{-1} \) ), central \((\sim 0 \text{km s}^{-1} \) ), and red \((\sim +3000 \text{km s}^{-1} \) ). The blue and red peaks developed more rapidly than the central one for the first night. This rapid variation would be caused by the growth of aspherical wind produced during the earliest stage of the outburst. At \( t_2 = 1.4 \text{d} \), the H\( \alpha \) line has a nearly flat-topped profile with weak blue and red peaks at \( \pm 3000 \text{km s}^{-1} \). This profile can be attributed to a nearly spherical shell, while the asphericity growing on the first night still remains. The wind asphericity is less significant after \( t_3 = 9 \text{d} \).

Key words: stars: individual (U Scorpii) — stars: novae, cataclysmic variables — techniques: spectroscopic

1. Introduction

U Sco is a recurrent nova (RN) whose outburst occurs every 8–12 yr. The recurrence time of U Sco is the shortest in all known RNe. U Sco is also known as a very fast nova defined by \( t_3 < 10 \text{d} \), where \( t_3 \) is the elapsed time when the object faded by 2 mag from the outburst maximum (Payne-Gaposchkin 1958). Because of the rapid evolution, the earliest phase \((t<1 \text{d})\) of the outburst of U Sco is still poorly known, in spite of its relatively short recurrence period.

Schaefer and Ringwald (1995) performed photometry of U Sco in its quiescent phase, and found that it is an eclipsing binary having an orbital period of 1.23 d. The eclipse was also observed in the outburst in 1999 (Matsumoto et al. 2003). Hachisu et al. (2000) successfully reproduced a light curve including the eclipse, using their theoretical model with a very massive white dwarf (WD) close to the Chandrasekhar limit. Hence, U Sco is suggested to be a system in the final stage of binaries evolving to Type Ia supernovae (Hachisu et al. 1999, 2008).

Thanks to the network for circulating the discovery reports and observations of transient objects (see Kato et al. 2004 for review), observations just after the outburst maximum of U Sco were first performed in 1999 (Munari et al. 1999; Anupama & Dewangan 2000; Iijima 2002). Munari et al. (1999) and Iijima (2002) reported that the Balmer emission lines had triple peaks, where the red peak is stronger than both the blue and the central peak at \( t_4 \approx +0.65 \text{d} \), where \( t_4 \) is the elapsed time from the peak of the outburst. The width of the emission lines gradually decreased with each day. Anupama and Dewangan (2000) took an earlier spectrum at \( t_5 = +0.45 \text{d} \), in which the red peak of H\( \alpha \) was weaker than the central one. These observations imply that a rapid change in the line profile would have occurred within only a few hours after the maximum brightness. This could be attributed to a temporal change in the structure of the earliest wind. A time-series spectroscopy in the earliest phase is required to probe the nature of the U Sco outburst.

We successfully obtained spectroscopic and photometric data of U Sco in the earliest phase just after the outburst discovery in 2010. In this letter, we present the result of spectroscopic observations in an early stage of the outburst. The result of photometric and late-time spectroscopic observations will be published in a forthcoming paper.

2. Observations and Reduction

The tenth outburst of U Sco was independently discovered at \( V = 8.05 \) on 2010 January 28.4385 UT by S. Dvorak and at a visual magnitude of 8.8 by B. G. Harris (Schaefer et al. 2010a). In this letter, we use the epoch, \( t_0 \), which is the elapsed time from the discovery date by S. Dvorak.1 We started our observations of the outburst just after the discovery.

We performed spectroscopic observations of U Sco on

\[ t_1 = 0.37-0.44 \text{d} \]

1 Schaefer et al. (2010b) suggest that the peak time of the 2010 outburst would be January 28.19 UT with an uncertainty of 0.07 d from the similarity among the light curves in individual eruptions of RNe.
8 nights from 2010 January 28.86 to February 19.86 using HOWPol (Hiroshima One-shot Wide-field Polarimeter; Kawabata et al. 2008) installed in the 1.5 m Kanata telescope at Higashi-Hiroshima Astronomical Observatory (HHAO). The wavelength coverage was 4200–9000 Å and the spectral resolution was \( R = \lambda / \Delta \lambda \approx 400 \) at 6000 Å. On the first night, we performed time-resolved spectroscopy during the period of January 28.84–28.91 with HOWPol. We also performed low-resolution spectroscopy with FBSPEC II attached to a 40 cm reflector from January 28.84 to February 5.83 at Fujii Kurosaki Observatory (FKO). Its wavelength coverage was 3800–8400 Å and its spectral resolution was \( R = \lambda / \Delta \lambda \approx 500 \) at 6000 Å. Additional spectra were observed with SBIG DSS7 attached to the 28 cm reflector on 2010 January 28.84 and 29.86 at the observatory in Okayama University of Science (OUS). The wavelength coverage was 4200–8200 Å and the spectral resolution was \( R = \lambda / \Delta \lambda \approx 400 \) at 6000 Å. The log of our spectroscopic observations is summarized in table 1. Data reductions were performed in the standard procedure by using IRAF.\(^2\) The wavelength calibration was performed by using the sky emission line taken in the same frame.

### 3. Results

#### 3.1. Overall Properties of Early Spectra

In figure 1, we show the spectra obtained on January 28.84 (\( t_d = 0.37 \) d), 28.86 (\( t_d = 0.39 \) d), 29.85 (\( t_d = 1.38 \) d), and February 2.79 (\( t_d = 5.32 \) d). We performed a line identification comparing our spectra with previous studies (Munari et al. 1999; Anupama & Dewangan 2000; Iijima 2002), and show our spectra in figure 1. They are characterized by some strong emission lines having a large FWZI (Full-Width at the Zero-Intensity) of \( \sim 11000 \) km s\(^{-1}\). Blue-shifted narrow absorption lines are accompanied by

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3.2. Spectral Variation on the First Night

As shown in figure 2, the intensity of the blue and red components of Hα increased more rapidly than that of the central one on the first night. The growth of the red component was apparently smooth, while that of the blue component may have been more complicated, or weaker than the red one. Similarly, the Hβ and He I λ 5876 lines showed a rapid increase in their red components. These rapidly evolving components are seen not only around the red peak, but also in a rather wide range of velocity between 1000 and 4000 km s\(^{-1}\) in Hα and He I λ 5876.

In the Hα line, the central peak was stronger than the red and blue ones on the first night, while the whole profile became

Fig. 2. Intranight variability of the peak profiles of Hα, Hβ, and He I λ 5876 in \(t_d = 0.37-0.44\) d. To emphasize the intranight increasing of the blue and red components, the spectra are normalized at the rest wavelength of each line. The total intensity of each emission line gradually becomes stronger by \(\sim 1\%\) within 2 hr from \(t_d = 0.37\) to 0.44 d.

Some strong emission lines at \(t_d = 0.37\) and 0.39 d. They considerably weakened by \(t_d = 1.38\) d and diminished by \(t_d = 5.32\) d. The velocities of the absorption components for the Balmer series, He I, and N II lines are about –5000, –4600, and –4500 km s\(^{-1}\), respectively.

The profile of the Hα emission line consists of central, red, and blue components at \(t_d \approx 0.4\) d. The red and blue components have peaks at \(\sim \pm 3000\) km s\(^{-1}\), as shown in figure 2. The red component is stronger than the blue one. A similar profile is seen in the spectrum in the 1999 outburst at \(t_p = 0.45\) d, which is the earliest spectrum taken in that outburst (Anupama & Dewangan 2000). In figure 3, we show the nightly variation of the whole Hα line on a logarithmic scale. At \(t_d = 1.38\) d, the line profile is described as a nearly flat-topped one with weak blue and red peaks at \(\pm 3000\) km s\(^{-1}\). The red peak is still higher than the blue one, as observed at \(t_d \approx 0.4\) d. Then, the peak wavelength gradually shifts to the rest one between \(t_d \sim 5\) and 9 d. At \(t_d = 9.38\) d, the Hα line had a rather symmetric profile consisting of a flat-topped component and a narrower peak one. In the spectra at \(t_d = 16.36\) and 22.39 d, the flat-topped component diminishes and the line profile is characterized by a single peak having a possible spread wing.

The Hβ, He I λ 5876, and He I λ 7065 emission lines exhibit the same behavior as Hα, except for the relative intensity of the blue and red peaks. The ratio of their blue and red peaks relative to the central one is higher than that of Hα, as can be seen in figure 2.

Fig. 3. Internight variability in the line profile of Hα. The thick black (top in \(t_d = 0.39\), red (bottom), and green (middle) lines show the spectra obtained at HHAO, FKO, and OUS, respectively. The blue lines show the spectra from Anupama and Dewangan (2000) in order to compare it with the profile for 2010 outburst. The values written at the left and right sides of the figure mean the days from the outburst maximum in 1999 and the days from the outburst discovery date in 2010, respectively.
a flat-topped one by \( t_d = 1.38 \) d. Hence, it is expected that the increase in intensity of the blue and red components continued until their intensities became comparable to that of the central component. Thus, our observation on the first night traces the growing phase of the blue and red peaks. The observation epoch would correspond to the period that was overlooked in the case of the 1999 outburst, namely, between \( t_p = 0.45 \) d (Anupama & Dewangan 2000) and 0.65 d (Iijima 2002).

4. Discussion

The intranight variation of the blue and red components shown in figure 2 suggests that the emitting region has an aspherical shape that grew rapidly on the first night. Gill and O’Brien (1999) calculated the line profiles using models with aspherical structures of nova ejecta, such as equatorial and tropical rings and polar caps, which generate the blue and red peaks in the line profile. We propose that aspherical winds, such as are suggested in Gill and O’Brien (1999), are the origin of the red (and blue) components. A bipolar jetlike structure has been suggested for U Sco to explain its large expansion velocity (see Kato & Hachisu 2003 and reference therein). A well-collimated narrow jetlike structure is expected to generate emission lines with a narrow velocity range. Since the rapidly growing red components extend in a wide velocity range of 1000–4000 km s\(^{-1}\) (see subsection 3.2), the observed line variation favors a wind-like structure, with a large opening angle, rather than a well-collimated jetlike structure with a small opening angle. In contrast to the blue and red components, the central one, slowly growing relative to the red one, is probably attributed to a slower, nearly spherical wind.

The fact that the red component is stronger than the blue one on the first night implies that the wind is not only aspherical, but also nonaxisymmetric. On the other hand, the blue component could also be suppressed due to the superposition of blue-shifted absorption components. The latter is plausible because blue-shifted absorption components are clearly seen at that phase. In addition, it is interesting that the orbital phase was close to zero during our first observation; phase = 0.05 at \( t_d = 0.37 \), as shown in table 1. This suggests that the secondary star is at near side and might give a partial occultation or a perturbation of the coming wind, leading to weaker blue components. This scenario is plausible only when the secondary star affects the velocity field of the ejecta significantly.

Another noteworthy feature of the line profile on the first night is that H\( \beta \) and He I\( \lambda 5876 \) have strong red components relative to H\( \alpha \). In other words, the central component of H\( \beta \) and He I\( \lambda 5876 \) is relatively weak. This would reflect the difference in temperature of the emitting region. Typically, H\( \beta \) and He I\( \lambda 5876 \) may become stronger relative to H\( \alpha \) in the case of higher electron temperature. The temperatures of the excitations of H\( \beta \) and He I\( \lambda 5876 \) are higher than that of H\( \alpha \). The observed line profiles suggest that the possible asymmetric winds causing the red and blue components are highly excited, compared with the slower, nearly spherical wind causing the central one.

The asymmetry of the nova ejecta has been discussed in literature (e.g., MacDonald 1986; Livio et al. 1990; Porter et al. 1998; Scott 2000; Gill & O’Brien 2000; Harman & O’Brien 2003; Kawabata et al. 2006). In the 1999 outburst of U Sco, a significant polarization change across the H\( \alpha \) emission line was found at \( t_p = 0.3 \) d and then diminished by \( t_p = 2.2 \) d (Ikeda et al. 2000). This result suggests that the earliest wind was asymmetric, which is consistent with the present work.

At \( t_d = 1.38 \) d, the line profile of H\( \alpha \) has a nearly flat-topped structure with weak blue and red peaks. This profile implies that the H\( \alpha \) emission was from a nearly spherical shell on the second night, while the asphericity growing on the first night still remained. At \( t_d \sim 9 \) d, the profile of the H\( \alpha \) line consists of a flat-topped component and another Gaussian component centered at the rest wavelength. The asymmetry in the line profile gradually becomes insignificant by \( t_d \sim 9 \) d. This indicates that the asphericity of the wind was less significant by this time. Since the deceleration of the flat-topped component was not remarkable between \( t_d = 0.39 \) and 9.38 d, the spherical shell was likely to expand freely from the first night. The Gaussian component would be attributed to the decelerating nova wind near the white dwarf. By \( t_d = 16.36 \) d, the flat-topped component diminished. It is noted that the single-peaked H\( \alpha \) line after \( t_d = 16 \) d is similar to that in the same epoch of the 1987 outburst (Sekiguchi et al. 1988), while not being consistent with those in the 1979 and 1999 outbursts (Barlow et al. 1981; Munari et al. 1999). This may suggest that the geometry (shape and/or its axis) of two consecutive outbursts was not always similar to each other. Additionally, the observed maxima of the outbursts in 1999 and 2010 were estimated to be the phases \( \sim 0.41 \) and 0.05, respectively. Assuming that the geometry of the outburst is not axisymmetric and its shape depends on the binary phase at the onset of the outburst, we expect that the apparent nature could change along lines of sight. If this is the case, the high-velocity wind could be seen as the outburst began at around a phase of \( \sim 0.4 \) (Munari et al. 1999).

5. Conclusion

We obtained time-resolved spectra on the first night after discovering the 2010 outburst of U Sco, and found a rapid evolution of the profile of the H\( \alpha \) emission line. This is the first observational sample revealing the intranight variability of the spectral lines just after the maximum brightness. The H\( \alpha \) emission line showed three components: center, blue, and red ones on the first night. The blue and red components rapidly evolved, which would be caused by aspherically structured winds. The line profile becomes rather symmetric, and we cannot find any clear evidence for the wind asphericity after \( t_d = 9 \) d.

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