The Spectroscopic Variations of the FU Orionis Object V960 Mon

Yuhei Takagi1,2, Satoshi Honda2, Akira Arai2,3, Kumiko Morihana4, Jun Takahashi2, Yumiko Oasa5, and Yoichi Itoh2

1Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoku Place, Hilo, HI 96720, USA; takagi@nao.jo
2Nishi-Harima Astronomical Observatory, Center for Astronomy, University of Hyogo, 407-2, Nishigaichi, Sayo, Sayo, Hyogo 679-5313, Japan
3Koyama Astronomical Observatory, Kyoto Sangyo University, Momyama, Kamigamo, Kita-ku, Kyoto, 603-8555, Japan
4Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi, 464-8602, Japan
5Faculty of Education, Saitama University, 255 Shimo-Okubo, Sakura, Saitama 388-8570, Japan

Received 2017 October 16; revised 2017 December 31; accepted 2018 January 2; published 2018 February 1

Abstract

We present the results of the spectroscopic monitoring of the FU Orionis type star V960 Mon. Spectroscopic variations of an FU Orionis type star will provide valuable information of its physical nature and the mechanism of the outburst. We conducted medium-resolution ($R \sim 10,000$) spectroscopic observations of V960 Mon with the 2 m Nayuta telescope at the Nishi-Harima Astronomical Observatory, from 2015 January to 2017 January, for 53 nights in total. We focused on Hα line and nearby atomic lines, and we detected the strength variations in both absorption and emission lines. The observed variation in the equivalent width of the absorption lines corresponds to a decrease in effective temperature and increase in surface gravity. These variations were likely to originate from the luminosity fading of the accretion disk due to the decrease in mass accretion rate.

Key words: protoplanetary disks – stars: formation – stars: pre-main sequence

1. Introduction

Circumstellar materials accreting into a young star via a protoplanetary disk form a photosphere. The luminosity of a pre-main-sequence star shows an irregular variation due to the unstable mass accretion, clumpy materials in the protoplanetary disk, and presence of spots in the photosphere (e.g., Herbst et al. 1994). In addition, these stars infrequently undergo episodic outbursts, during which the visual brightness of the star increases by several (4–6) mag. They are categorized as FU Orionis type stars (FUors).

The mechanism of outburst in the FUors is important for our understanding of the star formation process and the mass accretion. FUors outbursts are observed to occur during the Class I/II phase of the pre-main-sequence stage (Quanz et al. 2007). The typical optical spectrum of FUors is similar to those of F- to G-type supergiants with broad absorption lines (Herbig 1977). By contrast, their spectrum in the near-infrared is similar to that of M-type supergiants (e.g., Mould et al. 1978; Sato et al. 1992). Moreover, the profiles of their absorption lines are generally double-peaked (e.g., Hartmann & Kenyon 1985). On the basis of these facts, the model that outbursts occur in the accretion disk, in which the mass accretion rate dramatically increases by several orders of magnitude, was proposed (Hartmann & Kenyon 1996) and has been generally accepted. The spectroscopic characteristics of optical and near-infrared absorption lines in FUors are explained with the spectrum arising from the atmospheres of luminous accretion disks. The episodic outburst of the accretion rate could be the main factor to solve the “luminosity problem” in low-mass protostars (Audard et al. 2014). On the other hand, there is a case that the spectroscopic characteristics are explained via a rapid rotating photosphere. Petrov & Herbig (2008) argued that the rapid rotating central star with large spots can explain the absorption profiles in the optical wavelength, as in the case of V1057 Cyg. Due to the rarity of FUors, well-studied FUors are limited to several pre-main-sequence stars (e.g., FU Ori, V1057 Cyg, V1515 Cyg). Therefore, further studies of other FUors are necessary to understand the detail of their outburst mechanism.

Spectroscopic monitoring observations give valuable information to understand the physical nature of FUors. Powell et al. (2012) conducted a high-resolution spectroscopic monitoring of FU Ori and discussed the nature of the disk and the wind, investigating the periodic variation of the wing structure of the strong absorption lines. Petrov et al. (1998) found the variations in the emission features of V1057 Cyg and discussed the formation and the evolution of the surrounding shell features. Because the spectroscopic and photometric characteristics of FUors vary among them, monitoring observations of other FUors is important.

V960 Mon (2MASS J06593158-0405277) is an FU Ori type star that was identified in 2014 November (Maehara et al. 2014). The progenitor is a typical Class II object with a spectral type of late K and a mass of 0.75$M_\odot$ (Kóspál et al. 2015). Results of photometric observations were presented in several studies. According to the results of Hackstein et al. (2015), the maximum magnitude of V960 Mon was observed on 2014 October 6, which was 10.8 and 10.2 mag in the Sloan r- and i-bands, respectively. The brightness of V960 Mon gradually decreased by 0.5–1 mag in the optical wavelength between 2014 October and 2015 April. After V960 Mon had became observable during 2015 September, Semkov (2015) reported that the brightness of V960 Mon was comparable to that in April.

Several spectroscopic observations were conducted after the outburst. Hillenbrand (2014) conducted high-resolution spectroscopic observations and found that the optical spectrum matches that of an early F-type giant or supergiant. In addition, the P Cygni profile in the Hα line and the asymmetric profile of Hβ, Ca II triplet, NaD doublet show evidence of outflow. Li absorption is also seen in its spectrum. From the near-infrared spectroscopic observations (Pyo et al. 2015; Reipurth & Connelley 2015), CO absorption bands and broad H$_2$O absorptions were found, which are characteristic of late-type stars. The spectral type inconsistency between optical and near-infrared is a well-known characteristic of FUors (Hartmann & Kenyon 1996; Jurdana-Šepić & Munari 2016). Therefore,
V960 Mon is classified as FUors in previous studies; however, it is important to keep in mind that it may be a different type of eruptive star compared to a typical FUors due to its small brightness increase.

We conducted medium-resolution optical spectroscopic monitoring observations of V960 Mon with the Nayuta Telescope at the Nishi-Harima Astronomical Observatory. The spectra of $6300–6750 \, \text{Å}$ were obtained from 2015 January to 2017 January. The details of the observations are described in Section 2. The variations found in both absorption lines and emission lines are summarized in Section 3. In Section 4, we discuss the mechanism of the spectroscopic variations.

### 2. Observations and Data Reductions

The spectroscopic observations of V960 Mon were conducted with the Medium And Low-resolution Longslit Spectrograph (MALLS; Ozaki & Tokimasa 2005) equipped on the Nasmyth focus of the 2 m Nayuta telescope at the Nishi-Harima Astronomical Observatory. Three gratings (150, 300, and 18001/mm) and five slits with different widths (0.8, 1.2, 1.6, 5.0, and 8.0 arcsec) are mounted on this spectrograph. We used the 1800 1/mm grating and the 0.8 arcsec slit to achieve the resolution power of $R \sim 10,000$ at 6500 Å. The dispersed light was corrected with a 2K × 2K back-illuminated CCD detector (15 $\mu$m pixel) with a spectral coverage of $\sim 450$ Å. The grating angle was set to a proper amount to obtain the spectral features of the Hα line (6562.8 Å), Li absorption (6707.8 Å), and several neighboring atomic lines, such as Fe i, Fe ii, and Ca i. The total observation nights were 53, between 2015 January 27 and 2017 January 31. The exposure time in a single frame was from 300 to 1200 s. Exposures were repeated several times in order to improve the signal-to-noise ratio (S/N). As an image rotator is not installed on the Nasmyth focus and the MALLS, the position angle of the slit was different in each exposure. The typical seeing of the observations was 1.5 arcsec, and therefore the spectrum of V960 Mon was obtained by separating the close-by star 2MASS J06593168-0405224 with a separation of 5.7 arcsec (Kóspál et al. 2015). Table 1 shows the observation log. For comparison, the spectrum of $\beta$ Aqr (G0Ib, $\sim 5500$ K) was also obtained as a standard star on 2015 June 16 with the same instrumental settings, because the smoothed $\beta$ Aqr spectrum is known to be comparable to those of FUors.

Data reductions were performed with the Image Reduction and Analysis Facility (IRAF) software package. Overscan subtraction, dark subtraction, cosmic ray rejection, flat fielding, distortion correction, and scattered light subtraction were conducted before the spectrum was extracted. After the wavelength were corrected to heliocentric wavelength, we estimated the radial velocity of V960 Mon. We compared the observed peak wavelength of the Fe i 6393.6, Fe i 6411.6, and Ca i 6439.1 lines to those at rest wavelength to calculate the radial velocity. The estimated radial velocity was $38.1 \pm 0.5 \, \text{km s}^{-1}$. Continuum normalization was conducted after all of the spectra collected in a single night were combined into a single spectrum. The S/N was calculated from the continuum regions, which we set at the wavelength bands of 6616–6622 Å, 6650–6659 Å, and 6683–6694 Å. The S/Ns of the extracted spectra are shown in Table 1.

### 3. Results

During our observation campaign spanning two years, V960 Mon showed long-term photometric and spectroscopic variations. According to the photometric data of the monitoring observations produced by the American Association of...
Variable Star Observers (AAVSO), the brightness of V960 Mon decreased by $1.07 \pm 0.01$ and $0.79 \pm 0.01$ mag in the V- and I-bands, respectively, from 2015 January 27 to 2017 January 31. In the following subsections, we focus on the variation of intensity of some absorption and emission lines of V960 Mon. We combined the spectra taken for several days to several weeks into a single spectrum to achieve high S/Ns (>50). The total number of the created combined spectra was 21. All of the investigations and measurements mentioned in the following sections are based on these combined spectra.

### 3.1. Absorption Lines

The typical FU Ori type star has broad atomic absorption lines in its spectrum, and the strengths of these lines are similar to those in the spectra of F- to G-type supergiants. The averaged spectrum of V960 Mon over the full two years observations were comparable to those of a spun-up β Aqr spectrum with a rotational velocity of ~50 km s$^{-1}$. On the other hand, the comparison of combined spectra of “early phase” (2015 January 27, 28, February 14, 15, and 18) and the “late phase” (2016 November 25, December 11, 2017 January 10 and 31) showed that the peak depths of absorption lines varied during our observation period (Figure 1). The peak depth of neutral atomic lines such as Fe I and Ca I in the late phase were deeper than those in the early phase spectrum. The peak depth increased by up to 10%. Meanwhile, the peak depth of the ionized Fe lines in the late phase spectrum were shallow compared to those in the early phase spectrum. Their peak depth dropped by ~5% in the late phase. Because the peak depth of the neutral and ionized lines showed the opposite trends in variation, their variations cannot be explained only with the continuum excess fluctuation, such as veiling, which is frequently observed in pre-main-sequence stars.

### 3.2. Hα Line

The P Cygni profile in the Hα line appears in most of the obtained spectra (Figure 2). We interpret that the Hα line constitutes several components, such as blueshifted absorption feature due to the outflow, absorption near the velocity (v) of 0 km s$^{-1}$, which corresponds to a atmospheric absorption similar to other atomic absorption lines, and the red emission. The time-variation in the blueshifted absorption indicates the evolution of the intense wind. Hillenbrand (2014) reported a variation in blueshifted absorption in strong lines (e.g., Hα, Hβ, NaD lines) with high-resolution spectroscopic observations for two nights (2014 December 9–10). A large fluctuation in the blueshifted absorption of Hα was also found in our spectra, which was especially prominent in the spectrum obtained from 2015 January to 2015 October. The blue edge of this absorption extended to ~200 to ~300 km s$^{-1}$, and the main peak was at roughly ~150 km s$^{-1}$. In the latter phase of the observation, the blueshifted absorption was difficult to resolve. Meanwhile, the intensity of the redshifted emission gradually increased during the observation period with a nearly constant peak velocity.

### 3.3. Forbidden Lines

Some of the weak forbidden lines were also detected in our spectra (Figure 3). The [S II]6731 line was clearly observed. The equivalent widths (EWs) of the [S II]6731 were measured in all of the combined spectra, and the derived average value was $-0.093 \pm 0.035$ Å. No significant strength variation was found. By contrast, the [O I]6300 line was hardly detected, presumably because it is intrinsically weak and is blended with the telluric lines. The [S II]6716 line was not detected due to the nearby absorption of Ca I and Ti II in 6718 Å. However, the fact that the observed line profiles of the blended Ca I and Ti II line were not symmetric suggests the presence of the neighboring [S II] 6716 emission. These forbidden lines have rarely been observed in FUors (e.g., V2494 Cyg; Magakian et al. 2013).
4. Discussion

4.1. Variations of the Absorption Lines

To investigate the strength time-variations of the absorption lines during the two-year observation period, we measured the EWs of each of the 21 combined spectra. We used four lines that were not heavily blended with nearby lines: Fe I 6393.6, Fe I 6411.6, Ca I 6439.1, and Fe II 6456.4. Nevertheless, some weak absorption lines exist close to the three atomic lines. Therefore, note that the measured EWs of these lines are the sum of the target atomic line and the adjacent lines. Moreover, Fe II 6456.4 was blended with nearby Ca I. However, we adopted this line for the EW measurement because the trends in variation were contrastive between the neutral and ionized lines. We fitted each line profile with a Gaussian function, using the SPLOT task of IRAF, and measured the EW. The error of the equivalent width (δEW) was determined using the equation given by Cayrel de Strobel & Spite (1988), 

\[ \delta EW = 1.6(w \delta \chi) / \epsilon \]

where \( w \), \( \delta \chi \), and \( \epsilon \) are the width of the line, pixel size, and reciprocal of S/N, respectively.

We found that the EW of Fe II 6456.4 gradually decreased during the two-year monitoring (Figure 4). The EWs of the Fe I lines were nearly stable, or increased marginally. The dispersion in each EW may imply a short-term variation; however, high time resolution observations are needed to confirm this variation. The FWHM of each combined spectrum was estimated by averaging the measured FWHM of the Fe I 6393.6, Fe I 6411.6, and Ca I 6439.1 lines. The FWHM was constant during the observation period, and the averaged FWHM of the entire period was 1.9 ± 0.1 Å.

We also measured the half-width at half-depth (HWHD; Petrov & Herbig 2008; Lee et al. 2015) of both the shortward and longward sides of the Fe I 6393.6, Fe I 6411.6, Ca I 6439.1, and Fe II 6456.4 lines in each combined spectrum, to figure out the presence of the variations in line profile. The HWHDs of
the shortward and longward sides were nearly equal in each line during the observation period. Therefore, wind-driven blueshifted absorption features that were detected in several lines of HBC 722 (Lee et al. 2015) were not seen in these four lines. Due to their symmetric profiles, we interpret that these lines arise from the rapid rotating atmosphere and the spectroscopic variations originate from the change in effective temperature ($T_{\text{eff}}$) and surface gravity ($g$) in the atmosphere.

4.2. Estimating the $T_{\text{eff}}$ and $g$ Variations

A general method to figure out the value of $T_{\text{eff}}$, $g$, and also the metal abundance from a spectrum is based on EWs measurements of Fe I and Fe II lines, taking into account the equality of the abundance estimated from Fe I and Fe II. Several tens of absorption lines are usually used for this investigation, to estimate $T_{\text{eff}}$ and $g$ with no dependency on depths and excitation potentials of absorption lines. However, as the wavelength range ($\sim$450 $\AA$) of our spectra is limited, it is difficult to make an accurate estimate of these parameters with the standard method. In order to estimate the approximate $T_{\text{eff}}$ and $g$ in the spectra of the early phase and late phase (as defined in Section 3.1), we first derived the EW variability of the Fe I 6393.6, Fe I 6411.6, Ca I 6439.1, and Fe II 6456.4 lines in the synthetic spectrum generated with an atmospheric model.

We used the software SPTOOL\(^7\) developed by Y. Takeda to create a synthetic spectrum, which is based on Kurucz’s ATLAS9/WIDTH9 atmospheric model (Kurucz 1993). We first assumed that the continuum excess did not change between the early and the late phases. The metal abundance was set to the solar value, and the oscillator strength ($gf$) of the four lines was calibrated to fit the solar spectrum presented by Hinkle et al. (2000). Synthetic spectra were created with SPTOOL by varying the parameters $T_{\text{eff}}$ from 4500 K to 7500 K and log $g$ from 1.0 to 3.6. Microturbulence ($\xi$) were set to a value calculated by the following empirical relations among $T_{\text{eff}}$, $g$, and $\xi$ from the result of Gray et al. (2001)

\[
\begin{align*}
\xi & = 6.02 g^{-0.08} \quad (\text{for } T_{\text{eff}} = 7000–7500 \text{ K}) \\
\xi & = 10.58 g^{-0.17} \quad (\text{for } T_{\text{eff}} = 6500–7000 \text{ K}) \\
\xi & = 12.57 g^{-0.23} \quad (\text{for } T_{\text{eff}} < 6500 \text{ K}),
\end{align*}
\]

which were derived from the observed physical parameters of late A- to early G-type stars.

The EW of Fe I 6393.6, Fe I 6411.6, Ca I 6439.1, and Fe II 6456.4 lines in the created synthetic spectrum were measured with the SPLIT task of IRAF. As mentioned in Section 4.1, the absorption lines of V960 Mon are broad, and the measured EWs of four lines also include the components of adjacent lines. Therefore, prior to the EW measurements of synthetic spectra, we first defined the wavelength range for each four absorption lines. This wavelength range was determined based on the blue-end and the red-end of the absorption line in the observed V960 Mon spectrum. The EW measurement of the four lines in the synthetic spectrum was conducted by summing up the absorption components included in this wavelength range, and then the variabilities of these lines were estimated (Figure 5). Note that the bumps that appear in the temperature range of $T_{\text{eff}} \sim 6500$ K are due to the switch of the equations adopted for $\xi$ estimations. The $T_{\text{eff}}$ and log $g$ can be estimated from the convergence of the four lines shown in panels (e) and (f) of Figure 5. The approximate parameters for V960 Mon in the early phase were estimated to be $T_{\text{eff}} \sim 7000$ K and log $g \sim 1.2–1.5$. In the late phase, $T_{\text{eff}}$ decreased to $\sim$5800–6000 K and log $g$ increased to $\sim$2.2. Although the estimated $T_{\text{eff}}$ and $g$ have uncertainties due to the limited number of absorption lines and the $\xi$ estimated from the empirical relationship, a decreasing trend in $T_{\text{eff}}$ and increasing trend in $g$ was shown from our observed spectra.

EW variations may occur by the change in continuum excess such as veiling; therefore, there is a possibility that the EW

\[^7\] takeda

\[^8\] http://optik2.mtk.nao.ac.jp/~takeda/sptool/

---

**Figure 4.** EWs of the absorption lines. The error bar in the x-axis shows the periods when the spectra were collected to create a combined spectrum for EW measurement. The open circle indicates the EW measured with a poor fitting due to a low S/N (S/N $\sim$ 45).
variations may not be only caused by $T_{\text{eff}}$ and $g$ variations. As the EW of Fe I shows an increasing trend and Fe II shows a decreasing trend during our observation period, it is difficult to explain these EW variations with the fluctuation in the veiling, but we conducted an alternative investigation to derive the $T_{\text{eff}}$ and $g$ variations. An unequivocal way to resolve the variability of the stellar parameters from EW variations with no contamination of veiling is to use the EW ratios among the lines. EW ratios calculated with the lines within a limited wavelength are fine indicators of the physical parameters, as they are free from veiling (Takagi et al. 2014, 2015). EW ratios composed of atomic and ionized lines (Fe I 6393.6/Fe II 6456.4, Fe I 6411.6/Fe II 6456.4, and Ca I 6439.1/Fe II 6456.4) were employed as indicators. By using the measured EWs of Fe I, Fe II, and Ca I lines of the synthetic spectra, we estimated the relationship between EW ratio, $T_{\text{eff}}$, and $g$, as the case of EW. Then the variations of $T_{\text{eff}}$ and $g$ of V960 Mon were estimated by comparing its EW ratio of the early and late phase spectrum to the derived EW ratio–$T_{\text{eff}}$–$g$ relations. All of the EW ratios show the decrease in $T_{\text{eff}}$, which was comparable to the result estimated from the EW variations. On the other hand, it was difficult to confirm the increase in $g$. Therefore, an investigation using more absorption lines is necessary to derive the precise variations of these parameters.

We constrained the cause of the spectroscopic and photometric variations based on $T_{\text{eff}}$ and $g$ variations estimated from the EW variation. According to the previous photometric observations (Hackstein et al. 2015), $T_{\text{eff}}$ decreases and $g$ increases occurred with a decrease in brightness. These variations are difficult to explain with a photospheric pulsation of a variable star or a gravitational contract of a photosphere of young stars. The pulsation of the star photosphere will cause variations in brightness, $T_{\text{eff}}$, and $g$. However, the brightness of the star decreases when the radius of the photosphere increases, resulting in a decrease in both $T_{\text{eff}}$ and $g$. This variation conflicts with that of V960 Mon case. Meanwhile, photospheric contraction in the pre-main-sequence stage causes $T_{\text{eff}}$ and $g$ variations. However, it is again difficult to explain the $T_{\text{eff}}$ and $g$ variations of V960 Mon with this photospheric contraction, as this variation occurred in such a short timescale.

We interpret that the absorption lines in the optical spectrum of V960 Mon arise from the atmosphere of the accretion disk.

---

**Figure 5.** Panels (a)–(d): estimated EWs of the four absorption lines from the synthetic spectra (black solid line). The thick red and thin blue-dashed lines represent the EWs of the combined spectra of V960 Mon obtained in the early and late phases of the monitoring, respectively. The dotted lines indicate the errors of the EWs. Panels (e) and (f): the four red and blue lines in the left and middle panels are superimposed in the respective frames ((e): early phase, (f): late phase). The filled region of each line shows the error range.
The decrease in $T_{\text{eff}}$ during our observation period is evidence of the decrease in the accretion rate. The decreasing trends in both the brightness and $T_{\text{eff}}$ are similar to the variation found in V1057 Cyg. According to the steady accretion disk model, where the disk is considered to be a luminous source, the decrease in brightness and $T_{\text{eff}}$ can be explained by the decreasing mass accretion rate (Kenyon et al. 1988; Kenyon & Hartmann 1991). During our observation period, the $T_{\text{eff}}$ derived from our optical spectra decreased from $\sim$7000 K to $\sim$6000 K. The brightness of V960 Mon also decreased during the observation period but is still bright compared to the pre-outburst phase. Therefore, the decrease in both $T_{\text{eff}}$ and brightness is considered to be caused by the decrease of the accretion rate. The mass accretion rate of V960 Mon reduced nearly 50% from the early phase to the late phase, based on the accretion disk model and the observed $T_{\text{eff}}$ variation. In addition, the increase in $g$ suggests the evolution of the vertical structure in the accretion disk. Clarke et al. (1990) showed that the scale-height of the accretion disk gradually decreases with the disk cooling. This trend is comparable to the variations in both $T_{\text{eff}}$ and $g$ observed in V960 Mon. We conclude that the outburst and the brightness decrease that we observed are the result of a sudden increase and decrease in the mass accretion rate, respectively, in V960 Mon.

4.3. Variation in H$\alpha$ Line

The H$\alpha$ line shows a P Cygni profile especially in the spectra obtained from 2015 January to 2015 October. The blueshifted absorption feature became weak in the latter phase of the observation period. The decline of the blueshifted absorption feature can be explained by the decreasing mass accretion rate (Kenyon et al. 1988; Kenyon & Hartmann 1991). During our observation period, the $T_{\text{eff}}$ derived from our optical spectra decreased from $\sim$7000 K to $\sim$6000 K. The brightness of V960 Mon also decreased during the observation period but is still bright compared to the pre-outburst phase. Therefore, the decrease in both $T_{\text{eff}}$ and brightness is considered to be caused by the decrease of the accretion rate. The mass accretion rate of V960 Mon reduced nearly 50% from the early phase to the late phase, based on the accretion disk model and the observed $T_{\text{eff}}$ variation. In addition, the increase in $g$ suggests the evolution of the vertical structure in the accretion disk. Clarke et al. (1990) showed that the scale-height of the accretion disk gradually decreases with the disk cooling. This trend is comparable to the variations in both $T_{\text{eff}}$ and $g$ observed in V960 Mon. We conclude that the outburst and the brightness decrease that we observed are the result of a sudden increase and decrease in the mass accretion rate, respectively, in V960 Mon.

Dispersion Echelle Spectrograph showed a good fit. Because absorption lines of these giants are narrow due to their slow rotation, we smoothed their spectra to fit the spectrum of V960 Mon in the respectable phases.

The fraction of the disk component in the observed spectrum of V960 Mon is able to be estimated from the brightness increment of V960 Mon. The brightness increment can be estimated by comparing the brightness of the early and late phase to that of the pre-outburst phase. According to the past photometric observations reported in AAVSO, the approximate brightness increment in 6500 Å is estimated as $\sim$2.8 mag and $\sim$1.8 mag in the early and late phases, respectively, compared to the pre-outburst phase. Hence, the fraction of the disk component in the observed spectrum of V960 Mon was estimated as $\sim$92% and $\sim$80% in the early and late phases, respectively. Based on the estimated fraction, we subtracted the disk component in the spectrum of V960 Mon.

Carattio Garatti et al. (2015) argued that V960 Mon has possibly two companions, which are young stellar objects, and described that Pa$\alpha$ and Br$\gamma$ emissions observed in the near-infrared spectrum are emitted from these companions. Therefore, it is possible that the H$\alpha$ emission also originates from these companions. As the increased brightness of V960 Mon was relatively small, there is a possibility that the emission feature of the companions is relatively easy to observe compared to other FUors in a binary system. On the other hand, a large fluctuation in the blueshifted absorption feature can also affect the EW of the emission. Therefore, the EW error was estimated as $\sim$3 Å, assuming a 0.1 mag uncertainty in the brightness increment. This implies that the emission feature in H$\alpha$ was generally stable during the observation period.

5. Summary

We conducted spectroscopic monitoring observations of the FU Ori type star V960 Mon for two years from 2015 January to 2017 January. The EWs of the absorption and the emission lines were measured. The variations of the EWs of the Fe I and Fe II lines show that $T_{\text{eff}}$ decreased and that $g$ of the luminous source increased. This result suggests that the luminous source of the V960 Mon is the accretion disk and that the mass accretion rate decreased, the latter of which caused $T_{\text{eff}}$ to decrease. The increase in $g$ reflects the evolution of the vertical structure in the accretion disk. Emission lines were also detected in our observations, which may be emitted from the nearby companions. Further observations with high spectroscopic resolution and high time resolution are needed to give more constraints on the evolution of the disk and wind structures of V960 Mon.

We used the data obtained at Okayama Astrophysical Observatory, which had been collected through SMOKA operated by the Astronomy Data Center, National.
Astronomical Observatory of Japan. We also used data from the UVES Paranal Observatory Project (ESO DDT Program ID 266.D-5655). This work was supported by JSPS KAKENHI grant Nos. 26103708, 26870507, 25870124, and 17K00960.

Software: IRAF (Tody 1986; Tody et al. 1993), SPTOOL (http://optik2.mtk.nao.ac.jp/~takeda/sptool/).

ORCID iDs
Kumiko Morihana @ https://orcid.org/0000-0002-4895-0908
Yumiko Oasa @ https://orcid.org/0000-0001-7249-6787

References
Audard, M., Ábrahám, P., Dunham, M. M., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 387
Bagnulo, S., Jehin, E., Ledoux, C., et al. 2003, Msngr, 114, 10
Carattio Garatti, A., Garcia Lopez, R., Ray, T. P., et al. 2015, ApJL, 806, L4
Cayrel de Strobel, G., & Spite, M. (ed.) 1988, in IAU Symp. 132, The Impact of Very High S/N Spectroscopy on Stellar Physics (Dordrecht: Kluwer), http://adsabs.harvard.edu/abs/1988IAUS..132....C
Clarke, C. J., Lin, D. N. C., & Pringle, J. E. 1990, MN1RAS, 242, 439
Gray, R. O., Graham, P. W., & Hoyt, S. R. 2001, AJ, 121, 2159
Hackstein, M., Haas, M., Köppl, Á, et al. 2015, A&A, 582, L12
Hartmann, L., & Kenyon, S. J. 1985, ApJ, 299, 462
Hartmann, L., & Kenyon, S. J. 1996, ARA&A, 34, 207
Herbig, G. H. 1977, ApJ, 217, 693
Herbst, W., Herbst, D. K., Grossman, E. J., & Weinstein, D. 1994, AJ, 108, 1906
Hillenbrand, L. 2014, ATel, 6797, 1
Hinkle, K., Wallace, L., Valenti, J., & Harmer, D. 2000, Visible and Near Infrared Atlas of the Arcturus Spectrum 3727-9300 A (San Francisco, CA: ASP)
Jurdana-Šepić, R., & Munari, U. 2016, NewA, 43, 87
Kenyon, S. J., Hartmann, L., & Hewett, R. 1988, ApJ, 325, 231
Kenyon, S. J., & Hartmann, L. W. 1991, ApJ, 383, 664
Köppl, Á, Ábrahám, P., Moór, A., et al. 2015, ApJL, 801, L5
Kurucz, R. 1993, Kurucz CD-ROM No 13 (Cambridge, MA: Smithsonian Astrophysical Observatory)
Lee, J.-E., Park, S., Green, J. D., et al. 2015, ApJ, 807, 84
Maehara, H., Kojima, T., & Fujii, M. 2014, ATel, 6770, 1
Magakian, T. Y., Nikogossian, E. H., Movsessian, T., et al. 2013, MNRAS, 432, 2685
Mould, J. R., Hall, D. N. B., Ridgway, S. T., Hintzen, P., & Aaronson, M. 1978, ApJL, 222, L123
Ozaki, S., & Tokimasa, N. 2005, Ann. Rep. Nishi-Harima Astron. Obs., 15, 15
Petrov, P., Duemmler, R., Ilyin, I., & Tuominen, I. 1998, A&A, 331, L53
Petrov, P. P., & Herbig, G. H. 2008, AJ, 136, 676
Powell, S. L., Irwin, M., Bouvier, J., & Clarke, C. J. 2012, MNRAS, 426, 3315
Pyo, T.-S., Oh, H., Yuk, I.-S., Kim, H., & Davis, C. J. 2015, ATel, 6901, 1
Quanz, S. P., Henning, T., Bouwman, J., et al. 2007, ApJ, 668, 359
Reipurth, B., & Connelley, M. S. 2015, ATel, 6862, 1
Sato, S., Okia, K., Yamashita, T., et al. 1992, ApJ, 398, 273
Senkov, E. 2015, ATel, 8019, 1
Takagi, Y., Itoh, Y., Arai, A., Sai, S., & Oasa, Y. 2015, PASJ, 67, 87
Takagi, Y., Itoh, Y., & Oasa, Y. 2014, PASJ, 66, 88
Tody, D. 1986, Proc. SPIE, 627, 733
Tody, D. 1993, in ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II, ed. R. J. Hanisch, R. J. V. Brissenden, & J. Barnes (San Francisco, CA: ASP), 173

The Astronomical Journal, 155:101 (8pp), 2018 February

Takagi et al.