Revealing the Spectroscopic Variations of FU Orionis Object V960 Mon with High-resolution Spectroscopy

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Abstract
We present the results of the high-resolution spectroscopy of the FU Orionis-type star V960 Mon. The brightness of V960 Mon decreased continuously after the outburst was detected in 2014 November. During this dimming event, we carried out medium-resolution spectroscopic monitoring observations and found that the equivalent width of the absorption features showed variations. To further investigate the spectroscopic variations, we conducted a high-resolution spectroscopic observation of V960 Mon with the Subaru Telescope and the High Dispersion Spectrograph on 2018 January 8 and 2020 February 1. By comparing this spectrum with the archival data of the Keck Observatory and the High Resolution Echelle Spectrometer taken between 2014 and 2017, we found that the absorption profiles changed as V960 Mon faded. The line profile of absorption lines such as Fe I and Ca I can be explained by a sum of the spectra of the disk atmosphere and the central star. The model spectrum created to explain the variations of the line profiles suggests that the effective temperature of the central star is \( \sim 5500 \text{ K} \), which is comparable to that of the pre-outburst phase with a distance of 1.6 kpc with Gaia. The spectrum also shows that the effective temperature of the disk atmosphere decreased as V960 Mon faded. The variations of the H\( \alpha \) and Ca II lines (8498.0, 8542.1 \AA) also show that the V960 Mon spectrum became central-star dominant.

Unified Astronomy Thesaurus concepts: Pre-main sequence stars (1290); Protoplanetary disks (1300); Star formation (1569)

1. Introduction
An FU Orionis-type star (FUor) is a pre-main-sequence star that shows a sudden increase of brightness in optical wavelength. Understanding the mechanism of the FUor outbursts is crucial for revealing the star and planet formation processes. The optical spectra of FUors show similar features to those of F- to G-type supergiants, whereas the near-infrared spectra resemble those of K- to M-type supergiants (e.g., Hartmann & Kenyon 1996; Audard et al. 2014). The absorption profiles show a double-peak or a flat-bottom shape (e.g., Miller et al. 2011). The model of Hartmann & Kenyon (1985), which suggested that the outburst is triggered by an increase in the mass accretion rate (from \( 10^{-8} \rightarrow 10^{-7} \text{ M}_\odot \text{ yr}^{-1} \) to \( 10^{-6} \rightarrow 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \), Audard et al. 2014), reproduces these spectroscopic features. The disk wind also contributes to the formation of absorption features (Eisner & Hillenbrand 2011). V960 Mon (2MASS J06593158-0405277) is an FUor first identified in 2014 November (Maehara et al. 2014). The maximum magnitude was \( \sim 3 \) mag brighter in the optical wavelength compared to the quiescent phase. V960 Mon gradually faded by 0.5–1 mag between 2014 October and 2015 April (Hackstein et al. 2015), and it kept fading with a lower rate. Spectroscopic observations of V960 Mon in the early phase of the outburst demonstrated typical characteristics of FUors. The high-resolution optical spectrum (Hillenbrand 2014) showed blueshifted absorption components in Na D doublet, H\( \alpha \), and Ca II triplet lines, which is evidence of active outflow. Other absorption lines were similar to those of F-type giant stars.

We conducted medium-resolution optical spectroscopic monitoring of V960 Mon to investigate the evolution of FUor outbursts (Takagi et al. 2018). The Medium And Low-resolution Longslit Spectrograph (also known as MALLS; Ozaki & Tokimasa 2005) equipped on the 2.0 m Nayuta Telescope at the Nishi-Harima Astronomical Observatory was used for the monitoring. Spectra of V960 Mon were collected for 53 nights between 2015 January 27 and 2017 January 31. The wavelength coverage was 6280–6750 \( \text{ Å} \) with the resolving power of \( R \sim 10,000 \). During this observation period, we found variations in the strength of the absorption lines. While the equivalent width of Fe I and Ca I lines were nearly constant, the peak depth of Fe I and Ca I lines became deeper. Moreover, the equivalent width of the Fe II line (6456.4 \( \text{ Å} \)) decreased, and its peak became shallower. The comparison of the equivalent width of these lines and the synthetic spectra suggest that the variations of the absorption lines correspond to a decrease in effective temperature (\( T_{\text{eff}} \)) and an increase in surface gravity (g). These changes may indicate the variation of the protoplanetary disk during the FUor outburst, such as change of temperature distribution, mass accretion, and vertical structure.

To further study these spectroscopic variations of V960 Mon, we conducted high-resolution spectroscopy to investigate the changes in the line profile of the absorption lines. In our previous mid-resolution spectroscopic study of V960 Mon, we assumed that the absorption lines have a single Gaussian profile. Because of the insufficient resolution power, it was difficult to investigate the variation of the line profiles. The detailed evolution of V960 Mon outburst can be revealed by the line-profile investigations. Time series high-resolution spectra of FUors produce crucial information to understand the evolution of the wind and the disk during the outburst (e.g., Lee et al. 2015). In Section 2, we describe the details of the...
observed data and the archival data. The brightness information of V960 Mon is summarized in Section 3. We discuss the change in both absorption lines and the emission lines and the cause of these variations in Section 4.

2. Observations and Data Reductions

2.1. Subaru HDS

The high-resolution spectrum of V960 Mon was obtained with the High-Dispersion Spectrograph (HDS; Noguchi et al. 2002) mounted on the optical Nasmyth focus of the Subaru Telescope. Observations were conducted on 2018 January 8 (UT) and 2020 February 1 (UT) with averaged seeing sizes of \(\sim1.5^\prime\) and \(\sim0.6^\prime\), respectively. To resolve the components of the absorption features, a spectrum with high resolution and high signal-to-noise ratio (S/N) was needed. An image slicer with a slice pattern of \(0.45 \times 3\) (Tajitsu et al. 2012) was used to achieve high S/N with high spectral resolution (\(R \sim 80,000\)). The exposure times were \(6000 \text{s} (1500 \text{s} \times 4)\) and \(2400 \text{s} (1200 \text{s} \times 2)\), respectively. The nearby early-type star HR 2901 (B9V; Houk & Swift 1999) was also observed with an exposure time of 20 s before or after the observation of V960 Mon for the telluric line correction. The angles of the echelle grating and the cross-disperser were set to observe the lines at \(6510\) – \(6512.5\), \(6505\) – \(6507.5\), \(6510\) – \(6512.5\) Å simultaneously. Dispersed light was collected with two \(2K \times 4K\) CCDs with a pixel scale of 13.5 μm.

The Image Reduction and Analysis Facility (IRAF) software package\(^3\) was used for reducing the data in the standard manner such as overscan subtraction, scattered light subtraction, flat-fielding, and spectrum extract. The comparison spectrum of Th-Ar was used for the wavelength calibration. Before the telluric line corrections, the Hα line and Ca II absorption features were removed from the HR 2901 spectrum. To derive the line profiles of these broad lines, we corrected the blaze function of the aperture of which these lines are included, by using the information of the blaze function of nearby echelle orders. The telluric lines were then corrected with the spectrum of HR 2901 with no Hα and Ca II lines. The S/N of all V960 Mon spectra were calculated using the continuum regions (6505–6507.5, 6510–6512.5 Å). The observation details are shown in Table 1.

2.2. Keck HIRES Archive

We used the archival data obtained with High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) of the Keck Observatory to investigate the time variations of the spectroscopic features (Table 1). Spectra were taken on seven nights between 2014 December and 2017 January (PI: L. Hillenbrand). The wavelength range was from 4800 to 9200 Å. The slit width was set to 0.574 or 0.861, corresponding to the resolution power of 72,000 and 48,000, respectively. Three \(2K \times 4K\) CCDs (blue, green, and red) with a pixel scale of 15 μm were used to collect the dispersed light. We focused on the spectral features within 5850–8550 Å to discuss the spectral variations from 2014 December to 2020 February, which is the range overlapping with the Subaru HDS data.

We used the extracted data published on the website of the Keck Observatory Archive. To investigate the uniformity of the data between the HDS data and HIRES data, and because the spectrum obtained with the green detector (6250–7750 Å) was lacking in public data of 2014 December 9 and 2016 February 2, we conducted the data reduction for data taken on these two nights. The data of all three detectors were reduced in the same manner as HDS. The spectra extracted from the blue and red CCDs with our reductions were comparable with the public data. Therefore, we decided that the quality of the public data would be sufficient for our discussion. The S/N of the spectra were calculated using the same continuum regions (6505–6507.5, 6510–6512.5 Å) as the HDS data (Table 1).

3. Brightness Variation

The information of brightness variation of V960 Mon during the period when the high-resolution spectra were observed is vital for understanding its spectroscopic variations. The brightness of V960 Mon in the \(r\)- and \(i\)-bands in 2014 October were 2.9 mag brighter than those in the quiescent phase (Hackstein et al. 2015). The light curve of V960 Mon during the period when the spectra were collected was created with data of the American Association of Variable Star Observers (AAVSO). According to the light curve (Figure 1), the

\begin{table}[ht]
\centering
\caption{Summary of the High-resolution Spectroscopic Observations of V960 Mon}
\begin{tabular}{|c|c|c|c|c|}
\hline
Observation Date & Instruments & Exp & \(R\) & S/N \\
(UT) & & (s) & & \\
\hline
2014 Dec 9–10 & Keck HIRES & 915 & 72000 & 131 \\
2015 Feb 9 & Keck HIRES & 731 & 72000 & 130 \\
2015 Oct 27 & Keck HIRES & 300 & 48000 & 89 \\
2016 Feb 2 & Keck HIRES & 600 & 72000 & 142 \\
2016 Oct 14 & Keck HIRES & 180 & 48000 & 80 \\
2017 Jan 13 & Keck HIRES & 180 & 72000 & 67 \\
2018 Jan 8 & Subaru HDS & 6000 & 80000 & 202 \\
2020 Feb 1 & Subaru HDS & 2400 & 80000 & 125 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{light_curve.png}
\caption{Light curve of V960 Mon with the data of AAVSO. The vertical dashed lines show the date when high-resolution spectra were obtained.}
\end{figure}

\(^3\) IRAF is distributed by the National Optical Astronomy Observatory.
Table 2  Line Data

| Line | Wavelength (Å) | L.E.P. (eV) | log gf | References¹ |
|------|----------------|------------|--------|-------------|
| Ba II 5853.7 | 0.604 | −0.908 | 1 |
| Fe I 5934.7 | 3.929 | −1.12 | 1 |
| Fe II 5991.4 | 3.153 | −3.6 | 1 |
| Fe I 6003.0 | 3.882 | −1.120 | 2 |
| Ca I 6122.2 | 1.886 | −0.315 | 1 |
| Fe I 6265.1 | 2.176 | −2.550 | 1 |
| Si II 6347.1 | 8.121 | 0.149 | 1 |
| Fe I 6393.6 | 2.433 | −1.576 | 1 |
| Fe I 6411.6 | 3.654 | −0.718 | 1 |
| Ca I 6439.1 | 2.526 | 0.47 | 1 |
| Ca I 6471.7 | 2.526 | −0.59 | 1 |
| Fe I 6546.2 | 2.759 | −1.536 | 1 |
| Ni I 7555.6 | 3.847 | −0.046 | 2 |
| Fe I 7568.9 | 4.283 | −0.882 | 2 |
| Ni I 7727.6 | 3.678 | −0.16 | 1 |
| Fe I 7937.1 | 4.312 | 0.152 | 2 |

Note. ¹ References. (1) Kramida et al. (2018); (2) Kurucz (1993).

Absorption lines that are mainly seen in high $T_{\text{eff}}$ stars such as Fe II and Si II did not show profile variations. The depths of these lines became shallower as V960 Mon faded. In addition, no peak appeared at the line center. The depth of Si II (6347.1 Å) showed a significant decrease in the spectrum between 2015 February and 2015 October, while that of Fe II (5991.4 Å) decreased especially from 2017 and 2018 January. The depth variation of Fe I, Ca I, and Fe II lines were comparable with the result of Takagi et al. (2018). The wavelength shift was not detected in the absorption features listed in Table 2.

To investigate the line width variation of the broad component, the full width of the line at the region close to the continuum level was measured (e.g., Jayawardhana et al. 2003). In Jayawardhana et al. (2003), the width at the 10% depth was employed. But because the 10% widths of the observation data of V960 Mon were contaminated by the poor S/N and adjacent lines, we measured the width of the lines at the 15% depth of the line center (FW15D; horizontal dashed lines in Figure 2). Fe II (5991.4 Å) and Si II (6347.1 Å) lines were used to estimate the line width variations of the broad component (Figure 3). The width of Si II (6347.1 Å) showed a decrease during the observation period, from ∼140 to ∼80 km s$^{-1}$. The slope of the regression line calculated with the plots of Si II (6347.1 Å) was −0.034 ± 0.007, which indicates the decreasing trend. Meanwhile, that of Fe II (5991.4 Å) was nearly constant or showed a slight decrease, of which the slope of the regression line was 0.014 ± 0.008. This result indicates that the broad component, especially of Si II, became narrower as V960 Mon faded.

4.2. Equivalent Width of Absorption Lines

The equivalent width (EW) variations of the absorption lines reflect the physical parameters of the V960 Mon spectrum. The EWs of absorption lines were estimated with the "e" command of the splot task in IRAF, by summing up the EWs of absorption lines were estimated with the absorption features. Because these two colors were equal through the observation period, the brightness can be estimated as 2.1 mag, 1.7 mag, and 1.4 mag brighter on 2016 February, 2018 January, and 2020 February, respectively. Since the brightness of V960 Mon between 2014 October and 2017 December was nearly equal, the increment of brightness was estimated as 2.1 mag, 1.7 mag, and 1.4 mag brighter on 2016 February, 2018 January, and 2020 February, respectively, compared to the quiescent phase.

4. Spectroscopic Variations

4.1. Line Profiles of Absorption Features

In order to investigate the spectroscopic variation, we selected absorption lines within the observation range of the Subaru/HDS data, which were not blended with adjacent absorption features (Table 2). The line variation patterns of these lines were not uniform (Figure 2). Most of the lines such as the Fe I and Ca I lines show a broad line profile with a flat bottom in the spectrum of 2014 December–2015 February. This is one of the typical characteristics seen in FUors (Petrov & Herbig 2008). As V960 Mon faded, Fe I and Ca I lines showed a peak around the line center (0 km s$^{-1}$). This narrow component became deeper as V960 Mon got fainter, whereas the broad component declined.
decreased rapidly compared to Fe II (5991.4 Å). Then the EW of Si II became constant after 2016 February. The residual of the plots may imply the short-term variability of the EWs, similar to the periodic variation observed in FU Orionis (Powell et al. 2012). The discrepancy in decline rates (Figure 5 bottom) indicates that these decreases of EWs were not caused by the “filling-in” effect due to the variation of the continuum excess, so-called veiling.

4.3. Cause of the Variations in Absorption Lines

As described in Sections 4.1 and 4.2, the line profile, width, and EW were not uniform along the lines. Based on the steady-disk model (Hartmann & Kenyon 1985), a FUor spectrum is mainly composed of radiation from the accretion disk. The absorption profiles seen in FUors such as a boxy shape or a double peak correspond to the radiation from a rotating disk. The characteristics of the V960 Mon spectrum observed at the beginning of the observation period were similar to those of typical FUors. However, the absorption peak at around 0 km s\(^{-1}\) seen in the latter-phase spectrum is an unusual feature for FUors.

Because the brightness of V960 Mon decreased during the observation period, it can be considered that the fraction of the central-star spectrum gradually increased in the observed spectrum. In 2014 December, V960 Mon was 2.9 mag \((2.5^{2.9} = 14.3 \text{ times})\) brighter in the \(R\) band compared to the quiescent phase. In this phase, the fraction of the central-star spectrum...
The line width variations of Fe II (5991.4 Å) and Si II (6347.1 Å) lines. The green long-dashed line shows the regression line of the Fe II (5991.4 Å) with a slope of $-0.014 \pm 0.008$. The regression line of the Si II (6347.1 Å) is represented with a blue short-dashed line with a slope of $-0.034 \pm 0.007$.

Figure 4. Equivalent widths of absorption lines. The offset EW values shown with the label for line name are added to each EW.

The spectrum in the observed spectrum was 0.07 (1/14.3), and thus the disk spectrum was dominant. In 2020 February, the brightness increment of V960 Mon was 1.4 mag in $R$ band (2.5$^{1/4} = 3.6$ times). Therefore, because of the fractional increase of the central star in the observed spectrum, the absorption peak at 0 km s$^{-1}$ can be considered as the line of the central star, which was unveiled as the disk spectrum faded.

4.3.1. Line-Profile Variations

The spectrum of V960 Mon can be considered as a sum of central-star and disk-atmospheric spectra. The physical parameter of the central star can be estimated by extracting the central-star component from the observed spectrum taken in the latter phase. To estimate the $T_{\text{eff}}$ and the log $g$ of the central star, we established a simple model spectrum to reproduce the spectra of 2016 February, 2018 January, and 2020 February. The observed spectrum $I$ can be expressed as

$$I = I_{\text{star}} + kI_{\text{disk}},$$

(1)

where $I_{\text{star}}$ is the central-star spectrum, $I_{\text{disk}}$ is the disk-atmospheric spectrum, and $k$ is the coefficient. For $I_{\text{star}}$, we used the software SPTOOL developed by Yoichi Takeda, which is based on Kurucz’s ATLAS9/WIDTH9 atmospheric model.
The synthetic spectra of the central star with \( T_{\text{eff}} \) of 4500, 5000, 5500, 6000, 6500, and 7000 K were created. The log \( g \), the rotational velocity \((v \sin i)\), and the microturbulence were fixed to typical values for a pre-main-sequence star, which are 3.7, 10.0 km s\(^{-1}\), and 1.6 km s\(^{-1}\) (Padgett 1996), respectively. The metal abundance was set to the solar value. For \( I_{\text{disk}} \), we used the observed spectrum of 2014 December (Hillenbrand 2014) for simplicity. The coefficient \( k \) was calculated based on the brightness. The brightness increments of V960 Mon in 2016 February, 2018 January, and 2020 February were 2.1 mag, 1.7 mag, and 1.4 mag, respectively, in the \( R \) band (see Section 3). Based on the brightness, the adopted \( k \) values were 5.8 for 2016 February, 3.7 for 2018 January, and 2.6 for 2020 February.

We compared the profile of absorption lines with negligibly small or no blending with other lines (Table 2) between the model spectra and the observed spectra (Figure 6). The sum of the squared residual (SSR) was calculated in each absorption line (Table 3). The sum of SSR for all lines \((\Sigma\text{SSR})\) became minimum when the effective temperature of the central star was set to 5000–6000 K. We also created a model spectrum that leads to the change in the brightness ratio of the disk and...
central star. The brightness variability of the quiescent phase was assumed as \pm 0.3 mag based on the pre-outburst brightness (Kóspál et al. 2015). The model spectrum including the brightness uncertainty was compared with the observed spectrum on 2018 February. Even including this brightness uncertainty, the \Sigma SSR became minimum when the $T_{\text{eff}}$ was 5500–6000 K.

The $T_{\text{eff}}$ estimated from the observed spectrum conflicts with that of pre-outburst spectral energy distribution (SED; 4000 K, Kóspál et al. 2015), which was calculated on the assumption that there is no extinction and the distance is 450 pc. On the other hand, the distance estimated by Gaia is 1.6 \pm 0.2 kpc (Gaia Collaboration et al. 2016, 2018), which implies that the absolute magnitude of V960 Mon is brighter, and therefore the $T_{\text{eff}}$ can be higher. However, the V960 Mon should be reddened to explain the pre-outburst SED with $T_{\text{eff}}$ higher than 4000 K.

We investigated whether the progenitor photosphere of 5500 K is compatible with the pre-outburst brightness and the
To estimate the extinction, we compared the pre-outburst color with the typical color of a star with a $T_{\text{eff}}$ of 5500 K. The color of $I - J$ was used since the $I$-band brightness is likely to be less affected by the veiling (Cieza et al. 2005). The averaged $I$- and $J$-band magnitudes of Kóspál et al. (2015) were used for calculations, which were $I = 12.17 \pm 0.35$ mag and $J = 11.03 \pm 0.02$ mag, and then the pre-outburst $I - J$ is calculated as $1.14 \pm 0.35$ mag. By comparing this color with the typical color of the 5500 K photosphere (0.47 mag; Kenyon & Hartmann 1995) and the reddening law (Mathis 1990), the extinction in $I$-band was estimated as $1.26 \pm 0.66$ mag. The pre-outburst SED can be explained well with a central star of $T_{\text{eff}} = 5500$ K and the extinction of 1.26 mag with a near-infrared excess typically seen in young stars. The absolute magnitude of V960 Mon in $I$-band can be calculated as $-0.11 \pm 0.45$ mag, taking into account the distance estimated by Gaia and assuming the extinction in $I$-band to be 1.26 mag. This magnitude is comparable to the absolute magnitude of a pre-main-sequence star with $T_{\text{eff}}$ of 5500 K and the age of $\sim$0.7 Myr (Siess et al. 2000). Therefore, the photosphere with the $T_{\text{eff}}$ of 5500 K is comparable with the pre-outburst brightness and the distance of Gaia. However, when the extinction is near the lower or upper limit, the SED cannot be explained with a 5500 K central star. To discuss the central-star nature, further observations and discussions of the post-outburst phase are necessary.

In addition, there were several discrepancies between the observed spectrum and the model spectrum (Figure 7). The absorption lines in the wavelength of $>7000$ Å showed a slight mismatch between the observation and the model, especially in the spectrum of 2018 January 8. The broad component of the model spectrum is deeper than that compared to the observed spectrum. The coefficient $k$ used in the model calculation is determined from the $R$-band magnitude. Because the decrease rate of the brightness $I$-band was lower compared to the $R$ band (Figure 1), the fraction of the disk spectrum in the observed spectrum is...
4.3.2. Fe II and Si II Lines and the Disk Spectrum

While most of the absorption lines show a change in line profile, Fe II (5991.4 Å) and Si II (6347.1 Å) did not show profile variations during the observation period. This indicates that the central-star spectrum does not have strong Fe II and Si II lines. In fact, these lines are weak in the star with a $T_{\text{eff}}$ of 5500 K. Therefore, the EW variations of these two lines reflect the change in the physical parameters of the disk atmosphere.

Because the observed spectrum of V960 Mon can be assumed to be a sum of the disk spectrum and central-star spectrum, the EW of an absorption line includes the information of both the disk and the central-star atmosphere. The EWs of the Fe II and Si II lines can be considered to be veiled by the stellar continuum of the central star. For this reason, it is difficult to derive the disk property from the EW itself.

The EW ratio of nearby absorption lines is a valid tool for estimating the physical parameters of the spectrum with continuum veiling (Takagi et al. 2010, 2011). The “filling-in” effect of absorption lines caused by the veiling can be removed by using the EW ratio of nearby absorption lines by assuming that the veiling is nearly uniform among absorption lines in a limited wavelength range. We used the EW ratio of Fe II and Si II lines to estimate the variations of $T_{\text{eff}}$, log g, and the EW ratio by using the synthetic spectrum. The synthetic spectra were created by changing the $T_{\text{eff}}$ from 4500 to 7500 K, and log g from 1.0 to 4.0, by using the software SPTOOL. The metal abundance was set to the solar value. Microturbulence was set to a value based on the empirical relations (Gray et al. 2001; Takagi et al. 2018).

A comparison of the EW ratio of the observed spectrum (Figure 5 bottom) and the derived EW–$T_{\text{eff}}$–log g relationship showed that the physical parameters of the disk spectrum changed during the observation period (Figure 8). The EW ratio of Fe II and Si II increased by a factor of 2 from 2014 December to 2016 February. This EW ratio variation indicates that $T_{\text{eff}}$ decreased by ~1000 K during this period. Meanwhile, it is difficult to estimate the variation in log g. The variation from 2016 to 2020 February was uncertain since the EW ratio of Fe II and Si II was nearly stable during this period (Figure 5).

We also used other absorption lines such as Fe I and Ca I to discuss the variations in the disk atmosphere. The spectrum of the disk atmosphere can be extracted from the observation spectrum by subtracting the central-star component. The disk components of 2016 and 2020 February were obtained by subtracting the synthetic spectrum that reproduces the central star. The $T_{\text{eff}}$ of this synthetic spectrum was set to 5500 K, based on the model fitting (Section 4.3.1). Other parameters such as log g, $v \sin i$, metallicity, and microturbulence velocity were the same as described in Section 4.3.1. The fractions of the central-star spectrum and the disk spectrum were calculated based on the brightness of V960 Mon (Section 3). We used relatively strong absorption lines for the EW ratio, which were Ba II (5853.7 Å), Fe I (5934.7 Å), Fe II (5991.4 Å), Fe I (6003.0 Å), Ca I (6122.2 Å), Si II (6347.1 Å), Fe I (6393.6 Å), and Fe I (6411.6 Å). The EW ratios were calculated by combining Fe II (5991.4 Å) and Si II (6347.1 Å) with other lines. Absorption lines within a limited wavelength range (∼200 Å) were used for EW ratios.

All six pairs of EW ratios (Figure 9) showed that the physical parameters of the disk atmosphere changed during the dimming event. By taking into account the variation of the EW ratio of Fe II and Si II, it can be assumed that the changes of these EW ratios were caused by the decrease in $T_{\text{eff}}$. This indicates that the accretion rate decreased (Kenyon et al. 1988; Kenyon & Hartmann 1991), which is consistent with the decline in the brightness. The change in the V960 Mon color is also consistent with this cooling. According to the photometric observations (Figure 1), $B - V$, $V - R$, and $R - I$ on 2014 December 19 were 1.0 mag, 0.8 mag, and 0.7 mag, respectively. These colors then changed to 1.5, 0.9, and 1.0 mag on 2020 February 1.

The change in the physical parameter of the disk can be considered as one of the causes of the discrepancy in the model spectrum and the observed spectrum, especially seen in the Ba II (5853.7 Å) and Ca I (6122.2 Å) lines (Figure 7). Meanwhile, even using the disk component spectrum, the actual $T_{\text{eff}}$ and log g values of the disk atmosphere are difficult to estimate. One of the causes of this difficulty may be the uncertainty of the physical parameter estimations of the central star. Another reason is the variations in the local disk atmosphere cannot be revealed with the EW ratio investigations. The disk spectrum is considered to be composed of the disk atmosphere that extends from the hot inner region to the cold outer part of the disk (Hartmann & Kenyon 1996). The observed disk spectrum is the sum of the spectra arising from different regions with various $T_{\text{eff}}$. Therefore, the region where an absorption line arises dominantly may depend on each line. In fact, the line widths of Fe II and Si II has decreased as V960 Mon faded, and the decreasing rate was not equal between these two lines (Figure 3). Investigations of EW ratios can
reveal the averaged parameters of the whole disk atmosphere, which allows a qualitative study of the physical parameter variations.

4.4. Hα and Ca II Lines

Strong lines such as Hα and Ca II lines also showed significant variations during the observation period (Figure 10). Both Hα and Ca II lines had absorption components, especially in the early phase of the observation. It can be considered that the absorption component at the line center arises from the disk atmosphere. The blueshifted absorption component is evidence of an active outflow. As V960 Mon faded, emission features became dominant instead of the absorption features. The increase of the emission features suggests that the typical emission lines of a pre-main-sequence star reappear, because the fraction of the disk atmosphere has decreased.

Ca II lines (8498.0, 8542.1 Å) were blended with the Paschen lines (8502.5, 8545.4 Å). Other Paschen lines (8438.0,
8467.3 Å) were also detected, which were blended with the nearby Fe I lines. The Paschen absorption lines are seen in other FU Ori-type stars (Connelley & Reipurth 2018). It was difficult to investigate the variation of the Paschen lines due to the blend, but they became shallow in the latter phase of the observation. These lines are seen in stars with high $T_{\text{eff}}$ (<F-type star) and small gravity such as giants. Therefore, the depth decrease of these lines is consistent with the change of EW ratios (Section 4.3.2), which indicates the $T_{\text{eff}}$ decrease of the disk atmosphere. In addition, these lines are also veiled by the central-star spectrum mainly in the early phase of the observation period.

The absorption peak of Ca II lines showed a shift (Figure 11). The averaged peak velocity was $\sim -25$ km s$^{-1}$ from 2014 to 2016, and then it decreased to $-8$ km s$^{-1}$ in 2020 February. This result indicates that the blueshifted absorption component from the outflow became weak. The shift of the absorption peak is also consistent with the trend that the spectrum of the central star became dominant in the latter phase.

5. Summary

We conducted a study of spectroscopic variations of the FU Ori-type star V960 Mon. We used high-resolution optical spectra from 2014 December to 2020 February, including both observed and archival data during the phase in which the brightness of V960 Mon decreased by 1.5 mag in the $R$ band. The depths of the neutral and ionized absorption lines showed different variations; most of the lines became deep while the ionized lines such as Fe II (5991.4 Å) and Si II (6347.1 Å) became shallow. In addition, the profile of the absorption lines such as Fe I and Ca I changed. The absorption profile shown in the former phase was mainly composed of the disk atmosphere. As V960 Mon faded, the component of the central star became dominant in the absorption line profile. Our model spectrum showed that the observed spectrum can be described by a sum of the spectrum from the disk atmosphere and that from the central star, where the $T_{\text{eff}}$ of the central star can be estimated as 5500 K. The disk spectrum also indicated variation in the $T_{\text{eff}}$. The EW ratios of the absorption lines presumed that the averaged $T_{\text{eff}}$ decreased by 1000 K. The H$\alpha$ and Ca II lines also showed variations due to the change in the fractions of two components, the disk atmosphere and the central star.

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