KSP-OT-201611a: A Distant Population II Dwarf Nova Candidate Discovered by the KMTNet Supernova Program

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Abstract

We present a multicolor, high-cadence photometric study of a distant dwarf nova KSP-OT-201611a discovered by the Korea Microlensing Telescope Network Supernova Program. From 2016 October to 2017 May, two outbursts, which comprise a super/long outburst followed by a normal/short outburst separated by ~91 days, were detected in the BVI bands. The shapes and amplitudes of the outbursts reveal the nature of KSP-OT-201611a to be an SU UMa- or U Gem-type dwarf nova. Color variations of periodic humps in the super/long outburst possibly indicate that KSP-OT-201611a is an SU UMa-type dwarf nova. The super and normal outbursts show distinctively different color evolutions during the outbursts due most likely to the difference in time when the cooling wave is formed in the accretion disk. The outburst peak magnitudes and the orbital period of the dwarf nova indicate that it is at a large Galactocentric distance (~13.8 kpc) and height (~1.7 kpc) from the Galactic plane. KSP-OT-201611a, therefore, may provide a rare opportunity to study the accretion disk process of Population II dwarf novae.

Key words: stars: dwarf novae – surveys – techniques: photometric

1. Introduction

Dwarf novae as a subset of cataclysmic variables are known as close binary systems comprising a white dwarf primary with an accretion disk and a main-sequence secondary (Warner 1995). Dwarf novae, in general, have three major types: Z Cam, U Gem, and SU UMa (Osaki 1996) depending on unique characteristics of their light curves. Z Cam types have intervals of constant brightness called standstills, whereas U Gem types are featured by regular quasi-periodic outbursts. SU UMa types, which are more frequently found than the other types (Otulakowska-Hypka et al. 2016), show a combination of normal and superoutbursts. The superoutbursts of SU UMa types typically have longer outburst durations (~12–20 days) than normal outbursts (~8 days), and the former are usually brighter than the latter by ~0.8 mag in the V band (Patterson 2011; Otulakowska-Hypka et al. 2016). Their peak brightness is known to have a tight correlation with the orbital period (Warner 1987; Patterson 2011).

Studies of dwarf novae have been focused on the analysis of observed light curves since they can provide important information about the nature of the observed dwarf novae. For eclipsing dwarf novae, the origin of the accretion disk instability leading to outbursts can be investigated based on the shape of the light curves (Vogt 1983; Ioannou et al. 1999; Webb et al. 1999; Baptista et al. 2000). In this case, outside-in outbursts show symmetric light curves, whereas inside-out outbursts produce asymmetric light curves. Also, if dwarf novae show a delay between the ultraviolet (UV) and visible light, large and small UV delays mean outside-in and inside-out outbursts, respectively (Cannizzo et al. 1986; Cannizzo & Kenyon 1987). The accretion rate can also be investigated using the time interval between outbursts (Smak 1984; Schreiber et al. 2003). In addition, if multicolor information is available, more detailed analyses of the accretion process and related physical parameters can be conducted, including the size, temperature, surface density, and viscosity (Mayo et al. 1980; Cannizzo & Kenyon 1987). Unfortunately, however, multicolor observations have been very sparse in dwarf nova observations, limiting our understanding of their origin (Brown et al. 2018; Shugarov et al. 2018).

The typical V-band absolute magnitudes of dwarf novae are within a range of 7–9 mag (Warner 1987), and they have been mostly found in the solar neighborhood (~1 kpc; Downes et al. 2001; Özdonmez et al. 2015). These nearby dwarf novae are part of the thin disk of the Milky Way (Ak et al. 2013). Their mass donors, i.e., the main-sequence secondaries, have relatively high metallicities and low velocities (Ak et al. 2013; Harrison & Hamilton 2015; Harrison 2016). Most of the dwarf novae that have been studied so far, therefore, belong to Population I group. The properties of low-metallicity Population II dwarf novae have been poorly studied, mostly due to the lack of observed samples (Hawkins & Veron 1987; Howell & Skzody 1990; Edmonds et al. 2003). The handful of Population II dwarf novae that have been studied so far, to the best of our knowledge, are those in the globular cluster 47 Tucanae (Edmonds et al. 2003) at 4.5 kpc from the Sun (Zoccali et al. 2001) with [Fe/H] ~ −0.78 (Thygesen et al. 2014). Furthermore, few dwarf novae are spectroscopically classified as thick disk components (Ak et al. 2013). The only spectroscopically confirmed Population II dwarf nova is SDSS J1507+52 of [Fe/H] = −1.2 and d = 250 pc (Uthas et al. 2011). Due to the low metallicities, the accretion disk luminosities of Population II dwarf novae are expected to be higher than those of Population I (Stehle et al. 1997). Surprisingly, however, the dwarf novae in 47 Tucanae have been observed with much smaller accretion disk luminosities than theoretically expected (Edmonds et al. 2003). The origin of this discrepancy is not well understood, and it is imperative to obtain more observational samples of Population II dwarf novae.

In this paper, we present the discovery and high-cadence, multicolor monitoring of a new dwarf nova, KSP-OT-201611a,
that most likely belongs to Population II group at the distance of \( \sim 13.8 \) kpc from the Galactic center and at the height of \( \sim 1.7 \) kpc from the Galactic plane. Sections 2 and 3 provide our discovery and photometry of the source and an analysis of its light curves and colors, respectively. We determine the nature of KSP-OT-201611a to be an SU UMa-type dwarf nova and measure the orbital period and related parameters in Section 4. We discuss the properties of KSP-OT-201611a in Section 5 and provide a summary and conclusion in Section 6.

2. KSP-OT-201611a: Discovery and Photometry

As a part of the Korea Microlensing Telescope Network (KMTNet; Kim et al. 2016) Supernova Program (KSP; Moon et al. 2016), we monitored a 4-deg\(^2\) area toward the lenticular galaxy NGC 2292 since 2016 October. In the program, we obtained 60 s exposure of \( BVI \) bands with typical \( \sim 8 \) hr cadences. We discovered a new transient source, which we name KSP-OT-201611a, at \( (\alpha, \delta)_2000 = (06^h42^m02^s1, -26^\circ00'21.6'') \) or \( (l, b) = (235.51135, -13.45849) \) on 2016 November 29 (MJD = 57721.17 day) at a \( V \)-band magnitude of 19.19 \( \pm \) 0.02 mag (see below for the photometric calibration).

Figure 1 compares \( V \)-band images centered on KSP-OT-201611a obtained before the first detection and when the source is at its peak brightness. It also shows a deep image made by stacking 170 individual exposures of 60 s obtained when the source was fainter than the detection limit in each image. As seen in the right panel of Figure 1, KSP-OT-201611a appears as a very faint source of \( V = 23.45 \pm 0.11 \) mag on the deep stack image (see Section 3.2).

We conducted point-spread function (PSF) photometry using the Dominion Astrophysical Observatory Photometry (DAOPHOT II; Stetson 1987) and used the AAVSO Photometric All-Sky Survey database (APASS)\(^5\) \( BVI \) standard stars for photometric calibration. We used about 300 stars near the source to obtain the Penny function based the PSF of each image. The typical limiting magnitude of the 60 s exposure image obtained in this way is \( \sim 21.5 \) mag at a signal-to-noise ratio \( (S/N) = 5 \) under 1/\( \sqrt{2} \) seeing in the \( V \) band. Given the discrepancy between our \( I \)-band observations and \( i' \)-band standard photometric system used in APASS, we adopt the relation of \( I = i' - 0.4 \) that is known between the KMTNet \( I \) band and the APASS \( i' \) band (Park et al. 2017; H. S. Park et al. 2019, in preparation). We use the extinction of \( A_B = 0.41 \) mag, \( A_V = 0.32 \) mag, and \( A_I = 0.20 \) mag using the extinction \( E(B - V) = 0.101 \) mag obtained toward KSP-OT-201611a in the Galactic extinction model of Schlegel et al. (1998) with \( R_V = 3.1 \). The extinction-corrected photometric results are shown in Table 1. In this paper, we use extinction-corrected magnitudes and colors unless otherwise specified.

3. Light Curves and Color Analysis

3.1. Two Outbursts

Figure 2 shows the \( V \)-band light curve of KSP-OT-201611a obtained during a period of 192 days. We detected two outbursts separated by \( \sim 91 \) days: the first, which is brighter, one at MJD \( \sim 57723 \) day and the second one at MJD \( \sim 57814 \) day. Figure 3 shows \( BVI \) light curves and color evolutions of the first outburst. As in the figure, the outburst lasts about 18 days, reaching its peak brightness \( (V = 18.94 \) mag; see below) about 2 days after the first detection. The light curves, overall, are an asymmetric shape. After reaching the peak brightness, they appear to enter a relatively flat plateau phase and gradually decay for 10 days, followed by a decline phase below the detection limit.

In order to characterize the light curve, we conduct fourth-order polynomial fits to the light curves as shown by dashed lines in Figure 3. Based on the fits, we obtain the epochs and magnitudes of the peak as well as the rising rate, decay rate of the plateau, and decline rate. The \( V \)-band peak magnitude and epoch at the peak brightness are \( 18.94 \pm 0.06 \) mag and MJD = 57723.01 day, respectively. Table 2 contains vital physical parameters of the first outburst obtained from the polynomial fits, including the epoch and magnitude of the peak brightness, rising rate, decay rate of the plateau, and decline rate. It also includes the amplitude and duration of the outburst measured from quiescence magnitude (see Section 3.2).

The bottom panel of Figure 3 shows color evolutions of the first outburst in \( B - V \) and \( V - I \). The mean colors during the outburst are \( 0.13 \) mag \((B - V)\) and \(-0.07 \) \((V - I)\), respectively, and show no apparent variation as the outburst brightness changes. Although the colors, overall, stay mostly constant during the outburst, we do note that notable scatter in colors exists even for very similar epochs next to each other as indicated by arrows. This scatter in colors is probably related to the periodic humps of dwarf novae (see more details in Section 4.2).

Figure 4 shows the light curves and color evolutions of the second outburst detected about 91 days after the first outburst. The second outburst is distinctively different from the first outburst in its shape, duration, and color evolution. While the first outburst lasts about 18 days with multiple phases (such as rise, plateau, and decline), the second outburst lasts for a much shorter duration of time with much simpler but sharp variation

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5 https://www.aavso.org/apass
in light curves. The lack of the number of observed epochs, which is three separate epochs with eight pointings for each $BVI$ band, makes it difficult to analyze the observed light curves from the second outburst. We, therefore, simply adopted a linear fit to characterize the light curves. We conduct first-order polynomial fits (dashed lines shown in the top panel of Figure 4) to the rising and decline parts, separately. Based on the fits, the peak epochs ($57814.03 \pm 0.06$ day) and magnitudes ($19.40 \pm 0.14$ mag in the $V$ band) are calculated from a crossing point between the best-fit models of the rising and decline parts. Inverse slopes of the best-fit models give rising and decline rates. The faster rising rate (0.32 day mag$^{-1}$ in the

Note. Measured magnitudes are extinction-corrected.
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V band outburst. Arrows indicate the locations of notable scatter in colors. Figure 2. V-band light curve of KSP-OT-201611a. Small vertical bars at the bottom of the panel present the V-band epochs when observations are made.

Figure 3. (Top) BVJ light curves of the first outburst. Dashed lines are fourth-order polynomials for each light curve. (Bottom) Color evolutions of the first outburst. Arrows indicate the locations of notable scatter in colors.

V band than the declining rate (1.22 day mag⁻¹ in the V band) means that the second outburst is an asymmetric shape. The calculated parameters are shown in Table 3, which also includes the amplitude and duration of the second outburst from quiescence (see Section 3.2). When comparing the first and second outbursts, we conclude that the peak magnitude and duration of the second outburst are 0.46 mag fainter and ~3 times shorter than those of the first outburst, respectively.

In the bottom panel of Figure 4, while the B − V color becomes bluer as the outburst progress, the V − I color becomes redder. These are clearly different from the color evolution of the first outburst (Figure 3) where no apparent color evolution is identified. Based on the light-curve properties and color evolution pattern, the two outbursts appear to have a different origin (see Section 5.1).

3.2. Quiescent Phase

As we already showed above in Figure 1, we stack 170 individual images taken when the source is outside the outbursts to obtain a deep image with a much deeper detection limit. The source appears at 23.51 ± 0.11 mag (B), 23.45 ± 0.11 (V) mag, and 22.68 ± 0.09 mag (I) on these stack images. In order to see if there is any variation in the source magnitude outside the outbursts, we obtain four stack images at different time intervals: one before the first outburst, two between the outbursts, and one after the second outburst. We use about 40–70 images, on average, to create each of these deep stack images. The source brightness remains constant in all these four stack images as in Figure 5. Mean magnitudes of the source in these four stack images are consistent with the magnitudes of the source in the 170 stacked images. We, therefore, adopt the magnitude from the 170 stacked images as the quiescent magnitude of the source.

Figure 5 shows the light curves of the two outbursts (open circles) together with their quiescent magnitudes obtained during the four different time intervals (square symbols) and from the 170 stacked images (triangle symbols). Using the quiescent magnitudes and the polynomial fits obtained in the first and second outbursts, we estimate the duration of the two outbursts to be 18.43 ± 0.72 and 6.23 ± 0.90 days, respectively (Tables 2 and 3). The differences of the quiescent magnitude and the peak magnitudes in the V band provide amplitudes (4.51 mag for the first outburst and 4.05 mag for the second outburst). In the bottom panel of Figure 5, the quiescent colors of KSP-OT-201611a are ~0.07 ± 0.16 mag (B − V) and 0.76 ± 0.15 mag (V − I). The B − V color is similar to the mean B − V color of both outbursts, while its V − I color is redder than the mean V − I colors of both the outbursts.

3.3. Color–Magnitude and Color–Color Diagrams

Figure 6 shows the first/second (open cyan/red circles) outbursts and the quiescent phase (black triangle) in the color–magnitude diagrams. We compare the outbursts and the quiescence with stars in these color–magnitude diagrams. For the stars, we adopt stellar evolutionary tracks from the main-sequence to red giant stars (Yi et al. 2001) and white dwarf cooling tracks (Liu et al. 2012). In order to convert the absolute magnitudes of models to apparent magnitudes, we use a distance modulus of 14.33 mag (see Section 4.3). The outbursts and quiescence are located between the main sequence (gray shade) and white dwarf cooling sequence (blue lines). This seems to mean that KSP-OT-201611a is not a single star like as a white dwarf or a main-sequence star.

The two outbursts and the quiescent phase are investigated in a color–color diagram (Figure 7). The first/second (open cyan/red circles) outbursts present blue colors in both of B − V and V − I colors and cross the white dwarf cooling tracks with an effective temperature of ~13,000 K. As seen in the dashed box in the left panel of Figure 7, the B − V color ranges of the two outbursts are similar and the V − I color ranges are also similar except the reddest V − I color (0.34 mag) for the second outburst. The right two panels focus on the dashed box to show evolutions of color–color changes for the two outbursts. In the two right panels, blue circles are colors around the outburst peak and black diamonds present their mean color. Green circles show colors after the outburst peak and black pentagons are their mean color. For the first outburst (right top panel), the mean colors between around and after the outburst peak are similar within uncertainties, which means that there are no color variations in the first outburst. The mean colors for the second outburst (right bottom panel), however, are clearly different. During the second outburst, the B − V and V − I colors become bluer and redder, respectively.

The quiescent phase in the color–color diagram (left panel of Figure 7) deviates from the outbursts, especially in the V − I color. Since the V − I color depends on the emission of cool components, it seems that the processes from the quiescence to
The properties of KSP-OT-201611a and the three types of dwarf novae obtained from Otulakowska-Hypka et al. (2017; Shugarov et al. 2018) are consistent with prediction by this mechanism, which suggests that KSP-OT-201611a is an SU UMa- or U Gem-type dwarf nova. Therefore, we expect KSP-OT-201611a to have periodic humps in the super/long outbursts.

### 4. Periodic Humps

In order to investigate periodic humps in the super/long outburst of KSP-OT-201611a, we calculate $\Delta$mag (observation–best-polynomial fit) between 2 days before and 12 days after the superoutburst peak and combine $BVI$-band data to increase the sample points. Then we conduct a Lomb–Scargle analysis. The resultant power spectrum is shown in Figure 9. There are possibly two local peaks. The local maximum powers are at frequencies of 7.18 and 13.72 cycle day$^{-1}$ (orange arrows). Uncertainties of these frequencies are roughly 0.01 cycle day$^{-1}$ (Patterson et al. 2003) and the false alarm probabilities of the powers are $9.187 \times 10^{-8}$ and $1.107 \times 10^{-17}$. Based on the maximum frequency (13.72 cycle day$^{-1}$), we show a phase diagram in the top panel of Figure 10. The periodic variations of $\Delta$mag are clearly shown. The existence of the periodicity is also shown in each band (blue circles for $B$, green circles for $V$, and red circles for $I$), which strengthens the fact that the periodicity is real and the existence of periodic humps. In the case of the second local maximum frequency, it shows a similar phase diagram to that of the maximum frequency.

In the middle and bottom panels of Figure 10, $B - V$ and $V - I$ colors of the periodic humps change as a function of the orbital phase. Both colors have red peaks around 0.5 and 1.5 orbital phases, showing the brightest peak of periodic humps. When periodic humps have the faintest peak (orbital phase $\sim$1.0), the colors are blue. Two different mechanisms have been proposed to explain periodic color variations in dwarf nova humps. The first one is the color change caused by changing visibility of a hot spot on the accretion disk to explain the color changes observed from short orbital period ($<2$ hr) SU UMa types or long orbital period ($>3$ hr) U Gem types (Patterson et al. 1981; Smak 2005). This mechanism predicts a bluer color at the maximum brightness of periodic humps than that at the minimum brightness, which appears to be inconsistent with our observations of KSP-OT-201611a (see Figure 10). The other mechanism, on the other hand, is based on a color change caused by the expansion of low-temperature regions, which predicts red colors at the maximum brightness of superhumps (Warner 1995; Matsui et al. 2009; Neustroev et al. 2017; Shugarov et al. 2018). The color variations observed from KSP-OT-201611a are consistent with prediction by this mechanism, which suggests that KSP-OT-201611a is an SU UMa- or U Gem-type dwarf nova.

4.2. Periodic Humps

The properties of a light curve are used to classify the nature of a transient, which include the amplitude, duration, rising rate, decline rate, and so on. The $V$-band multiple outbursts with the amplitudes of 4.51 and 4.05 mag and durations of 18.43 days and 6.23 days in KSP-OT-201611a are consistent with typical properties of dwarf novae (Osaki 1996; Otulakowska-Hypka et al. 2016). Since there are three types of dwarf novae (SU UMa, Z Cam, and U Gem), we compare the properties of KSP-OT-201611a and the three types of dwarf novae obtained from Otulakowska-Hypka et al. (2016) in Figure 8. Because the first outburst has a larger amplitude and a longer duration than the second outburst, we assume that the first and the second outbursts of KSP-OT-201611a are the super/long outburst and normal/short outburst, respectively. In all panels of Figure 8, the properties of KSP-OT-201611a are well matched with those of SU UMa and U Gem types. This suggests that KSP-OT-201611a is a SU UMa- or U Gem-type dwarf nova. Therefore, we expect KSP-OT-201611a to have periodic humps in the super/long outbursts.

### Table 2

| Parameter | Values |
|-----------|--------|
| $B$ | $19.05 \pm 0.06$ |
| $V$ | $18.94 \pm 0.06$ |
| $I$ | $19.02 \pm 0.06$ |

**Note.** All uncertainties are measured from the bootstrap resampling method, but uncertainties of amplitudes are propagated from the peak and quiescence errors.

4.1. The Nature of KSP-OT-201611a

The nature and parameters of KSP-OT-201611a are used to classify the nature of a transient. We classify the nature of a transient with the following parameters:

- Amplitude: The peak magnitude $\Delta$mag.
- Duration: The outburst duration.
- Rise rate: The rising rate of the outburst.
- Decay rate: The decay rate of the outburst.
- Plateau duration: The duration of the plateau.
- Quiescence: The quiescence magnitude.

These parameters are used to distinguish between different types of dwarf novae. The properties of KSP-OT-201611a are consistent with properties of SU UMa types or long orbital period dwarf novae. Therefore, we expect KSP-OT-201611a to have periodic humps in the super/long outbursts.

**Figure 4.** (Top) $BVI$ light curves of the second outburst. Dashed lines are first-order polynomials for each light curve at rising and decline phases. (Bottom) Color evolutions of the second outburst.
SU UMa-type dwarf nova. We note, however, since a significant uncertainty still exists in our understanding of the color variation in period humps, we cannot rule out the first mechanism (Matsui et al. 2009).

When we divide the data into two groups around 0.5 days (between −2 and 3 days) and 5.5 days (between 4 and 12 days) after the super/long outburst peak in the middle panel of Figure 3, a 0.5 day region (open circles) has a systematically blue color in $B − V$ than the 5.5 day region (filled circles) in the middle panel of Figure 10. This implies that we observed the red colors of the periodic hump variations by chance in the 5.5 day region.

### 4.3. Distance and Parameters of KSP-OT-201611a

In SU UMa-type dwarf novae, the superhump period ($P_s = 1/f_s$) tightly correlates with an orbital period ($P_o$), where $f_s$ is a superhump frequency (Mennickent et al. 1999). In U Gem-type dwarf novae, the hump period is considered as an orbital period (Rutten et al. 1992; Webb et al. 1999; Baptista et al. 2000). Orbital periods of the maximum and the second local maximum power are 0.0705 days (1.69 hr), as calculated by the Equation (7) of Mennickent et al. (1999), and 0.1393 days (3.34 hr), respectively. Parameters of dwarf novae, including the masses of the primary and secondary, the effective temperature and absolute magnitude of the secondary, and the absolute magnitude of the super/long outburst peak, can be derived from the orbital period (Beuermann et al. 1998; Mennickent et al. 1999; Knigge et al. 2011; Harrison 2016; Szkody 1976; Matsui et al. 2009). To derive the absolute magnitude of the super/long outburst and the other parameters, we use Equation (4) of Patterson (2011) and tables from Knigge et al. (2011). The derived parameters of KSP-OT-201611a are shown in Table 4.

We estimate the distance to KSP-OT-201611a by comparing the observed $I$-band magnitude in quiescence with the known absolute magnitudes of the secondary in dwarf novae (Knigge et al. 2011). Considering that the observed $I$-band magnitude also has contributions from the accretion disk and hot spot (Szkody 1976; Matsui et al. 2009), this estimation gives only a lower limit of the distance. For the two cases of the orbital periods of 1.69 and 3.34 hr, we obtain the distance of 1.7 and 4.7 kpc, respectively. Since the absolute magnitudes of the secondary in Knigge et al. (2011) are for those with solar metallicities, the distance of KSP-OT-201611a can be increased to 2.7 and 7.4 kpc if it has a lower metallicity. For
low metallicities, we consider that the K- or M-type secondaries with low metallicities \((Z \approx 0.001)\) may have about 1 mag brighter than those with solar metallicities (Yi et al. 2001; Herczeg & Hillenbrand 2015).

In addition to quiescent magnitudes, in order to derive a distance to KSP-OT-201611a, we use the super/long outburst peak magnitude. The derived absolute magnitude combined with the observed apparent magnitude of the super/long outburst peak provides the distance \((d_S)\) of \(7.3^{+1.5}_{-1.3}/8.5^{+1.5}_{-1.5}\) kpc from the Sun.

Using the Galactic coordinates \((l, b)\) of KSP-OT-201611a and assuming the distance of the Sun from the galactic center to be \(R_0 = 8.3\) kpc (Reid et al. 2014), with the orbital period of 1.69 hr, we derived a Galactocentric distance \((\sqrt{d_S^2 + R_0^2} - 2R_0d_S \cos(l) \cos(b) = 13.8^{+1.3}_{-1.1}\) kpc) and a height \((d_S \sin(b) = -1.7^{+0.3}_{-0.4}\) kpc) from the Galactic plane. In the case of the orbital period of 3.34 hr, the Galactocentric distance is \(14.9^{+1.5}_{-1.3}\) kpc and the height from the Galactic plane is \(-2.0^{+0.3}_{-0.4}\) kpc.

5. Discussion

5.1. Outbursts

For the outbursts of dwarf novae, two types of outburst mechanisms have been suggested (Smak 1984; Cannizzo et al. 1986; Osaki 1996; Frank et al. 2002; Schreiber & Lasota 2007).
Table 4
Parameters of KSP-OT-201611a

| Parameter | Values (for Max. Freq./Local Second Max. Freq.) |
|-----------|-----------------------------------------------|
| Expected type of dwarf nova | SU UMa/U Gem |
| Frequency of humps ($f_s$) | 13.72 ± 0.01/7.18 ± 0.01 cycle day$^{-1}$ |
| Period of humps ($P_s$) | 1.750 ± 0.001/3.343 ± 0.004 hr |
| Orbital period of primary star ($P_\ast$) | 1.69 ± 0.01/3.343b ± 0.004 hr |
| Mass of primary star ($M_\ast$) | 0.75 M$_\odot$ |
| Mass of secondary star ($M_2$) | 0.11 ± 0.01/0.21 ± 0.01 M$_\odot$ |
| I-band absolute magnitude of secondary ($M_I$) | 11.56 ± 0.01/9.33 ± 0.01 mag |
| Effective temperature of secondary star ($T_{\text{eff}2}$) | 2976 ± 10/3319 ± 10 K |
| Absolute magnitude of superoutburst peak ($M_v$) | 4.61 ± 0.41/4.29 ± 0.41 mag |
| Distance modulus ($m - M$) | 14.33 ± 0.41/14.66 ± 0.41 mag |
| Distance from the Sun ($d_S$) | 7.3$^{+1.7}_{-1.5}$/8.5$^{+1.3}_{-1.5}$ kpc |
| Distance from the Galactic center ($d_{GC}$) | 13.8$^{+1.5}_{-1.3}$/14.9$^{+1.6}_{-1.5}$ kpc |
| Scale height from the Galactic plane ($Z$) | −1.7$^{+0.4}_{-0.3}$/−2.0$^{+0.1}_{-0.1}$ kpc |

Notes.

a Equation (7) of Mennickent et al. (1999).
b In the case of U Gem types, $P_\nu$ is the same as the period of humps.
c Table 8 of Knigge et al. (2011) only provides $M_\ast = 0.75 M_\odot$.
d Table 6 of Knigge et al. (2011); uncertainties are propagated from that of $P_\nu$.
e Equation (4) of Patterson (2011).
f For the super/long outburst.
g Noted that the study of Knigge et al. (2011) stemmed from dwarf novae with solar metallicities.

The first one is an inside-out outburst where matter is accreted from the secondary and thermal instability starts at the inner disk. Then, the thermal instability propagates to the outer disk. In contrast to the inside-out outburst, in the outside-in outburst, thermal instability is triggered at outer disk first and the instability propagates inward. In KSP-OT-201611a, the asymmetric shape of the super/long outburst suggests outside-in accretion disk instability (Smak 1984; Cannizzo et al. 1986; Cannizzo & Kenyon 1987), although we cannot completely rule out the possibility of an inside-out origin if the accretion disk is affected by stream impact from the secondary and tidal torque dissipation (Buat-Ménard et al. 2001). Although the light curves of the normal/short outburst (Figure 4) also indicate that they are asymmetric, the incomplete sampling makes it difficult to reach a firm conclusion of whether or not it is indeed asymmetric.

The two outbursts show distinctively different color evolution; while the super/long outburst shows no color variation in $B - V$ and $V - I$ during the outburst, the normal/short outburst shows blue and red evolution in the $B - V$ and $V - I$ colors, respectively, during the outburst. The invariant colors are consistent with expectation of the constant viscosity model in the accretion disk during the outburst, suggesting that there is a constant mass flow rate throughout the accretion disk (Cannizzo & Kenyon 1987). It is difficult, on the other hand, to explain the observed color evolution during the normal outburst where the $B - V$ and $V - I$ colors evolve in opposite directions: the former becomes bluer, while the latter become redder (Figures 3 and 4). Similar patterns have been observed in $B - V$ and $V - R$ of RZ LMi (Shugarov et al. 2018).

However, the origin of the color evolution is unknown. We also note that such color evolution is observed in the classical nova, where Antoniadis et al. (2017) suggest that the formation of a dust shell may have an additional thermal emission component, although how a dust shell can be formed is not explained. Here, for KSP-OT-201611a, the color evolution during the normal outburst may be explained if there is new cold material accreted from the secondary at the outer part of the accretion disk, increasing the flux in the I band while the overall temperature of the accretion disk increases during the outburst (Osaki 1989). More detailed analyses are required to investigate this possibility more thoroughly.

5.2. Halo or Thick Disk Dwarf Novae

In the Milky Way, Population I, which shows a young age, high metallicity, and cold kinematics, is located in the thin disk, whereas Population II, which is characterized by an old age, low metallicity, and hot kinematics, is classified as a halo or a thick disk component (Lee et al. 2011; Li et al. 2018). Population I is generally concentrated in the Galactic disk (a height of $\lesssim 0.6$ kpc) and Population II is populated at a further distance (a height of $\geq 1$ kpc; Lee et al. 2011; Mateu & Vivas 2018). In the same situation, dwarf novae follow the same trend. That is, Population I dwarf novae are more concentrated in the Galactic disk than Population II dwarf novae (Howell & Szkody 1990; Uthas et al. 2011; Ak et al. 2013; Özdnömez et al. 2015). Since Population I dwarf novae are located near the Sun, they have been found and well studied (Coppejans et al. 2016; Otałakowska-Hypka et al. 2016). In the case of Population II, although there have been attempts to find distant dwarf novae (possible Population II) in the halo or thick disk (Hawkins & Veron 1987; Howell & Szkody 1990; Shara et al. 2003), few candidates have been found because they reside at large distances from the Sun. Notably, no distance ($>5$ kpc from the Sun) Population II dwarf nova has been observed with light curves other than the nearby (250 pc) source SDSS J1507+52 (Uthas et al. 2011).

KSP-OT-201611a is a possible candidate Population II dwarf nova with $BVI$ light curves and the faintest quiescent magnitudes that have ever been observed (see Coppejans et al. 2016). KSP-OT-201611a has a Galactocentric distance of 13.8 kpc and a height of $\sim 1.7$ kpc. The large height of KSP-OT-201611a safely rejects the possibility that KSP-OT-201611a is a thin disk component. Considering the Galactic position of KSP-OT-201611a, it is located near the Perseus arm, which is warped toward the direction of KSP-OT-201611a (Koo et al. 2017). However, the warped disk reaches a height of about $\sim 1$ kpc (Koo et al. 2017; Skowron et al. 2018). This fact implies that KSP-OT-201611a is well separated from the warped disk and may be a halo or thick disk populations (Özdönmez et al. 2015; Mateu & Vivas 2018).

Theoretically, dwarf novae with the low-metallicity secondary expect to have a brighter accretion disk, owing to larger accretion rates, than dwarf novae with the solar-metallicity secondary (Stehle et al. 1997). In observations, eight dwarf novae in a globular cluster, 47 Tucanae, have fainter accretion disk luminosities than those of field dwarf novae with solar metallicities (Edmonds et al. 2003). This inconsistency between theory and observation may stem from a poor understanding of the emission mechanism of the accretion
disk related to metallicity. It is worth comparing dwarf novae with low- and high-metallicity secondaries to tune the emission mechanisms.

In Figure 11, we compare the V-band absolute magnitudes in quiescence ($M_V$; red circle) of KSP-OT-201611a with those of solar-metallicity secondaries (solid line; Warner 1995) and those of low-metallicity secondaries (dashed line; $Z \lesssim 0.001$) that are 1 mag brighter than the solid line. At a given orbital period, $M_V$ of KSP-OT-201611a is $\sim$4 mag and $\sim$5 mag brighter than the brightness of the secondaries with solar and low metallicities, respectively. This means that KSP-OT-201611a has brighter accretion disk than the secondaries with solar and low metallicities. At a given orbital period, SU UMa types of field dwarf novae (Population I; black circles Verbunt et al. 1997) also have brighter accretion disks and have similar $M_V$ of KSP-OT-201611a. Although solar-metallicity dwarf novae have fainter accretion disks than low-metallicity dwarf novae in the theoretical model, our results show that solar-metallicity dwarf novae and KSP-OT-201611a have similar accretion disks. It may be interpreted that metallicity effects on accretion disk luminosities are not strong (Belloni et al. 2018).

Discovering more Population II dwarf novae at a large distance (Galactic height of $\gtrsim$1 kpc) gives a chance to modify the emission mechanisms in the accretion disk. Although this rare distant dwarf nova is difficult detect, KSP is an optimal field dwarf nova observed during 2016 October–2017 May. Below, we provide a summary of our study and conclusions.

1. We detect two outbursts of possible SU UMa-type dwarf nova separated by $\sim$91 days. The first outburst (super-outburst) lasts about 18 days with the peak outburst amplitude of $\sim$4.51 mag in the V band, while the second one (normal outburst) remains only 6 days with a slightly smaller outburst amplitude of $\sim$4.05 mag in the V band. Both outbursts show an asymmetric shape in light-curve evolution with a rapid pre-peak ascent followed by a slow post-peak decline.

2. The two outbursts show a clear difference in their colors; while the superoutburst shows no color evolution during the outburst in $B - V$ and $V - I$, the normal outburst shows that $B - V$ moves in the blue direction and $V - I$ is reddened during the outburst. This may result from the difference in time when the cooling wave is formed in the accretion disk.

3. The observed light curves of the superoutburst are consistent with the presence of superhumps of a 1.69 hr period superimposed on the outburst. The superhumps become redder as they become brighter, showing that dwarf novae reach the superhump maximum by the expansion of a low-temperature region in the accretion disk.

4. The observed magnitude of the source during its quiescent phase is $V \approx 23.45$ mag with the $B - V$ and $V - I$ colors of 0.07 and 0.76 mag, which cannot be explained by a typical binary system for a dwarf nova composed of a white dwarf and a main-sequence star. This strongly indicates the presence of substantial emission from the accretion disk during the quiescent phase.

5. The estimated Galactocentric distance of KSP-OT-201611a is 13.8 kpc, making it one of the most distant dwarf novae ever observed. This also gives 1.7 kpc as a height of the source from the Galactic plane. It is, therefore, highly likely that the source is a rare Population II dwarf nova in the halo or thick disk of the Galaxy. More detailed observations and studies of the source may provide a new clue to understanding how the metallicity is related to the accretion disk process.

This research has made use of the KMTNet system operated by the Korea Astronomy and Space Science Institute (KASI) and the data were obtained at three host sites of CTIO in Chile, SAAO in South Africa, and SSO in Australia.

Facility: KMTNet.

Software: DAOPHOT (Stetson 1987), astropy (Astropy Collaboration et al. 2013, 2018).

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