Dippers from TESS Full-frame Images. II. Spectroscopic Characterization of Four Young Dippers

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Received 2021 September 29; revised 2022 January 16; accepted 2022 January 23; published 2022 March 23

Abstract

Photometric monitoring by the Transiting Exoplanet Survey Satellite (TESS) has discovered not only periodic signals by transiting exoplanets but also episodic or quasiperiodic dimming around young stellar objects. The dimming mechanisms of these objects, the so-called “dippers,” are thought to be related to either the accretion property or the structure of protoplanetary disks especially in regions close to the host star. Recently, we have created a catalog of dippers from one year of TESS full-frame image data. In this paper, we report on the spectral features of four newly found dippers in that catalog and show that they potentially shed light on the dimming mechanisms. We found that all of the targets exhibit the Hα emission line, which is an indicator of ongoing accretion. Based on their line profiles and/or their variability, we characterized the properties of the disks of each source, which can support dimming mechanisms via a dusty disk wind or an accretion-driven inner-disk warp. Also, we found an interesting dipper (TIC 317873721), a “close-in binary dipper,” showing a complex variability of the line profile and a large radial velocity variation. Because the dimming intervals are similar to the orbital period of the binary, we suggest that the dips are caused by dust in the accretion warp from a circumbinary disk onto stars. Such a close-in (<0.1 au) binary dipper has been rarely reported thus far; further investigation will reveal new aspects of disk evolution and planetary formation.

Unified Astronomy Thesaurus concepts: Variable stars (1761); Protoplanetary disks (1300)

1. Introduction

Observations of young stellar objects (YSOs) provide an important clue for the study of planet formation processes (see Hillenbrand 2008). Some YSOs show episodic/quasiperiodic dimmings in their light curves with a duration of ~1 day. These irregularly dimming stars are called “dippers,” which are distinct from any stars showing regular variabilities. So far, the detailed mechanisms for such variability are not well understood. At first, it was thought that dippers were caused by their circumstellar environment, such as accretion from a warped inner disk (Bouvier et al. 1999). Also, various mechanisms have been considered thus far, including transiting circumstellar clumps (Ansdell et al. 2016a). In this scenario, the dippers are intriguing objects for understanding the dynamic process of disk evolution and planet formation. However, we need to reconsider such a classical view of dippers owing to recent long-term, high-cadence monitoring campaigns of young stars (e.g., Kepler, TESS).

Surveys of dippers have so far been limited mostly to star-forming regions due to the small fields of view (FOVs) of K2 and CoRoT and also due to constraints on the pointing for K2. TheTransiting Exoplanet Survey Satellite (TESS), launched in 2018, has dramatically changed the situation. TESS is an all-sky monitoring satellite with extremely precise photometry. It provides two types of data: short-cadence (2 minute) time-series of preselected targets and the full-frame images (FFIs) of 30 minute cadence. FFIs are close to raw data, providing us with a large discovery space for new types of stellar variability.

Recently, we have developed a pipeline to extract clean light curves from FFIs using recent machine-learning technologies, including the convolutional neural network (Tajiri et al. 2020, hereafter Paper I). We created 4 × 10⁶ light curves from TESS FFIs of Sectors 1–13, which correspond to the first year of the TESS mission that covers almost half of the hemisphere. The extensive investigation of TESS images led to the discovery of dipper-like phenomena for 35 stars across the sky, which is currently the largest homogeneous catalog of dippers with episodic/quasiperiodic dimming with infrared excess. This catalog includes TIC 284730577, which was identified as a star showing a dipper-like light curve by Gaidos et al. (2019) as well. This confirms...
that the newly developed pipeline indeed can identify dipper-like photometric variation.

Our catalog includes several interesting examples that do not fit the classical view of dippers. For example, in Paper I, we discussed in detail the properties of TIC 43488669, a “runaway” dipper that exhibits a large peculiar velocity (>30 km s\(^{-1}\)) and is not associated with any circumstellar material. Another example is an isolated YSO, which is isolated from molecular clouds and clusters but does not exhibit a large peculiar motion. Because these dippers are considered to have different origins or evolution processes from other dippers, they significantly expand the concept of a dipper. In this paper, we show the results of spectroscopic observations for some unexpected classes of dippers and some classical-type dippers in our catalog to characterize their disk properties and evolutionary phase.

In Section 2, we describe the spectroscopic observations for dippers and submillimeter observations for two dippers. In Section 3, we show the results of the spectral analysis. In Section 4, we explain the estimated cause of dimming for these dippers. The discussion and summary are in Section 5.

2. Observations and Data Reduction

2.1. Target

We observed four of the dippers in our catalog (Table 1 of Paper I); their TIC IDs are 457231768, 34397579, 434229695, and 317873721. We select them because they are bright enough to be observed with high-dispersion spectrographs on telescopes in the Northern Hemisphere. These dippers are located around Orion, as shown in Figure 1. Their properties are listed in Table 1.

The observations were performed several times from 2019 to 2021 with spectrometers on the Subaru telescope, the Calar Alto Observatory, the Okayama 188 cm reflector, and the submillimeter bolometer camera on the JCMT for each target. See Table 3 for the instruments used to observe each target.

2.2. Subaru/HDS

The observation by the High-Dispersion Spectrograph (HDS; Noguchi et al. 2002) installed on the Subaru telescope was performed on 16 September 2019 for all targets and on 6 September 2020 for TICs 434229695 and 317873721 with the nonstandard setup and a 2 \(\times\) 1 binning without the image rotator. We use image slicer (IS) #2 with a spectral resolution of about 80,000. The nonstandard setup of the wavelength range includes H\(\alpha\) and the lithium 6707 Å line as an indicator of YSOs and also Mg triplet lines (5165–5185 Å) for estimates of stellar temperature and radial velocity (RV).

The data were reduced by the standard procedure (the bias subtraction, flat-fielding, order tracing/extraction, and wavelength calibration) by using IRAF, which yields one-dimensional spectra with a signal-to-noise ratio (S/N) of 80–100 pixel\(^{-1}\) at 6563 Å.

2.3. CAHA/CAFÉ

We performed additional observations for TICs 434229695 and 317873721 with the Calar Alto Fiber-fed Échelle spectrograph (CAFÉ; Aceituno et al. 2013) attached on the 2.2 m telescope of the Calar Alto Observatory (CAHA). We observed them on 2019 October 2 and 16, November 13, and December 18, and on 2019 November 8, but only for TIC 434229695. The spectral range is 407–925 nm with a spectral resolution of about 62,000.

The data were reduced using the CAFExtractor pipeline (Lillo-Box et al. 2020), partly based on the CERES algorithms (Brahm et al. 2017).

2.4. Okayama/HIDES

We also performed additional observation for TIC 317873721 on 2021 January 20 and 25 and February 2, 4, 19, 22, and 28 by using the High Dispersion Échelle Spectrograph (HIDES; Izumiura 1999) at Okayama Astrophysical Observatory (OAO). The observing wavelength of HIDES is 360–1000 nm, and the resolution is 52,000 by using the HE mode.

The data were reduced by the standard procedure (the bias subtraction, flat-fielding, order tracing/extraction, and wavelength calibration) by using IRAF.

2.5. JCMT/SCUBA-2

We performed submillimeter photometric observations for TIC 434229695 and TIC 317873721 with the Submillimeter Common-User Bolometer Array 2 (SCUBA-2; Dempsey et al. 2013) on the James Clerk Maxwell Telescope (JCMT) at Maunakea, Hawai. The observations of TIC 434229695 were conducted on 2020 September 8 UT using the Pointsource Daisy Map Mode with an observing time of 26 minutes. The observations of TIC 317873721 were conducted on 2020 August 3, September 8, and September 21 using the Pointsource Daisy Map Mode with an observing time of 26 minutes.

The data were reduced using the pipeline in the Starlink software (Currie et al. 2014). The recipe REDUCE_SCAN_FAINTE_POINT_SOURCES is used for point-source detection.
Notes.
- TESS Input Catalog ID.
- Gaia Source ID.
- R.A., decl. (J2015.5), effective temperature, and stellar radius listed in TICv8 (ExoFOP 2019).

3. Results

3.1. Classification of TESS Light Curves

We reviewed the periodicity of the light curve for each target from the first-year data of the TESS mission and classified them according to the morphologies. A set of statistical metrics was introduced to classify YSO light-curve shapes into different categories by Cody et al. (2014), which were the flux asymmetry, $M$, and the stochasticity, $Q$. If the amplitude of a light-curve variation is symmetric, $M \in [-\infty, \infty]$ will be equal to zero, while $M > 0$ means that the dimming time is relatively short. $Q \in [0, 1]$ will be equal to zero for a perfectly periodic light curve and will be close to 1 for a stochastic one. We followed the classification from Cody & Hillenbrand (2018), which classified variable stars into several classes such as bursters ($M < -0.25$), quasiaperiodic dippers ($0.15 < Q < 0.85$ and $M > 0.25$), and aperiodic dippers ($Q > 0.85$ and $M > 0.25$).

Figure 2 shows the light curves of the TESS FFI and the result of folding it by the period most related to the dip. We searched for these periods using the Lomb–Scargle periodogram. Figure 3 shows the variability types according to $M$ and $Q$ statistics. We found that TICs 317873721 and 434229695 are quasiaperiodic dippers with periods of 2.67 days and 1.59 days, respectively, and TIC 457231768 is an aperiodic dipper with a period of roughly 2.56 days, while we cannot measure the periodicity for TIC 34397579 because the dip appears only once in the light curve.

3.2. Spectral Energy Distributions

We also revisited the spectral energy distributions (SEDs) of dippers we observed. From one of our definitions of the dipper described in Paper I, they show an infrared excess in the SEDs (Figure 4). We built the SEDs by using Virtual Observatory (VOSA; Bayo et al. 2008) and calculated the spectral index $\alpha = -\Delta \log (\lambda F_\lambda) / \Delta \log (\lambda)$ between 3.4 $\mu m$ and 22 $\mu m$. The results are between $-1.28$ and $-0.014$ (listed in Table 5), which implies that they are in the phase of Classes II–III according to the discussion of the classification of disks (Lada 1987).

To characterize their disks in more detail, we performed submillimeter observations on JCMT for two dippers whose memberships were not identified in Paper I (TIC 4343229695 and TIC 317873721). Unlike the other two objects, which are young and are thought to have disks, the nature of the disks of these objects is unknown.

TIC 434229695 was detected with 25 mJy at 850 $\mu m$ with an S/N of 17 and with 156 mJy at 450 $\mu m$ with an S/N of 6.9. The detection of submillimeter emission indicates that the star is in a dusty environment. The $F_\nu = 25$ mJy of the 850 $\mu m$ emission corresponds to the total dust mass $M_d$ of $\sim 0.1 M_\odot$ as calculated using the formula in Hildebrand (1983): $M_d = d^2 F_\nu / \kappa \rho \nu (T)$, where $T$ is the temperature, $d$ is the distance, $\kappa$ is the opacity per unit dust mass, and $\rho \nu (T)$ is the Planck function. Here, we have assumed $T = 20 K$ and $\kappa = 8.5$ g cm$^{-2}$ as in other submillimeter photometry studies (e.g., Ansdell et al. 2016b).

TIC 317873721 was not detected with JCMT. The 3$\sigma$ upper limit for TIC 317873721 is 67 mJy for 450 $\mu m$ and 7.8 mJy for 850 $\mu m$. However, the SCUBA-2 pipeline tentatively identified four weak point-like emission at $\sim 1'$ ($\sim 0.2$ pc) away from the object at 850 $\mu m$ (Figure 5 and Table 2). Among the four, the source S1 is located 3$\sigma$ away from 2MASS J05574918–1406080 and S2 is located 6$\sigma$ away from 2MASS J05574947–1405356, both within the beam size ($\sim 13''$) of JCMT. The two 2MASS sources are both identified as YSOs. Moreover, IRAS 05555–1405 is located close to the sources. The two 2MASS and one IRAS sources are considered to be associated with the cloud called VdB 64 (Lee & Chen 2009). We confirmed that the Gaia DR2 proper motions (pm) in R.A. and decl. and parallaxes of the two 2MASS sources are close to those of TIC 317873721 (pm(R.A.), pm(decl.)) $\sim (−2, 1.8)$ mas yr$^{-1}$ and parallax $\sim 1.5$ mas and therefore we consider TIC 317873721 to be a member of VdB 64.

In Figure 4, we show the SEDs and the fitted model for each target. For the stellar component ($\lambda < 3.4 \mu m$) of the fitted model, we use the best-fit theoretical spectra by Coelho (2014) obtained from VOSA, then for residual data, fit the blackbody radiation from multiple point sources by using the least-squares method. Some points with bad quality for whatever reason were not used for the fitting. The model of TIC 317873721 is not built in this way because the infrared excess is thought to be related not only to the disk component but also to the companion star (Section 4.2.2). Therefore, we set the theoretical model with $T_{\text{eff}} = 8250 K$ as the primary star’s component instead of the best-fit model selected by VOSA. Similarly, we considered that the points that were not used for the fit of TIC 457231768 were the variability due to the companion in this binary system (SB2), as reported in Doering & Meixner (2009) (see also Alecian et al. 2013). The temperatures of the primary and secondary are 9000 K and 5000 K, respectively, which roughly match the temperatures of the fitted blackbody radiations.

All fitted models were composed of three components. For TICs 34397579 and 434229695, we can see the flux in the 10–100 $\mu m$ region does not decrease with a simple power law, but increases slightly with wavelength and decreases with a steep slope in the submillimeter region. Although these are not unique models to explain this feature, the flared disk model (Chiang & Goldreich 1997) or the “puffed-up” inner rim (Isella et al. 2006)}
are candidate models to explain it. The former is a two-layered disk with different temperatures on the surface and inside the disk. Only half of the photon energy from the star absorbed by the disk surface is reradiated, while the other half heats up the inside of the disk. As a result, in addition to the light from the star and the reflected light from the disk surface, longer-wavelength light from inside the disk is also observed. In the latter model, there is a region in the center of the disk where dust sublimates, and the entire edge of the inner disk expands due to the radiation from the star.

3.3. Estimation of the Stellar Age from the Li Absorption Line

In the spectra except for TIC 317873721, we confirmed the Li absorption line (6707 Å), which indicates they are in the pre–main sequence because lithium depletion occurs rapidly after the core temperature becomes high enough (∼3 × 10⁷ K) to start burning lithium. The fact that the Li absorption line was not detected in the spectrum of TIC 317873721 can be interpreted that the high temperature of the star has already fused all lithium.

We measured the Li equivalent widths (EWs) in the spectra observed with HDS/Subaru in 2019 and 2020 by fitting the absorption line with the Gaussian function. Results are listed in Table 3. Following Figure 13 in Gaidos et al. (2019), we plotted the Li EWs measured from the spectra of the dippers taken in 2019 with those of nearby young moving groups in Figure 6. The effective temperatures are set to the values in the TESS Input Catalog version 8 (TICv8; Stassun et al. 2019).

From Figure 6, we roughly estimate their ages to be <125 Myr according to the location in that parameter space, in the same way as Éric Mamajek, who fitted polynomials to the data of clusters in this type of diagram. Note that the ages estimated from Li EWs may have a large uncertainty and should only be seen as a rough estimate. One of the reasons for this is that we did not take into consideration the veiling, which causes lines

13 http://www.pas.rochester.edu/~emamajek/images/li.jpg
to appear shallower due to excess emission from an accretion shock. Because correcting this effect increases the EW, the age should not be higher than the estimated ages. Another reason is that the data compared from each moving group itself show a large scatter, for example, due to the different achievable S/Ns and stellar properties such as rotational speed. It means that a clear age boundary in this figure is difficult to determine.

Indeed, other results estimate ages that are much younger than this upper limit, for example, Figure 4 of Paper I, which shows the Hertzsprung–Russell diagram of dippers constructed from the Gaia DR2 data and compares it with MESA isochrones; both dippers are plotted between lines of the ages of 1 Myr and 10 Myr. Also, the age of TIC 34397579 reported in Arun et al. (2019) is $\sim 7$ Myr.

### 3.4. Hα Emission Lines

The Hα emission line is one of the features of classical T Tauri stars or weak-line T Tauri stars. The observed line profiles of the emission lines of classical T Tauri stars are well explained by the accretion model along the stellar magnetic field as follows: In young stars, gas is accreted from the edge of the inner disk to the stellar surface. When the gas reaches both poles at a freefall speed along the magnetic field, X-rays and EUV are emitted by its shock. Because the gas is optically thick, this short-wavelength radiation is immediately absorbed and visible and UV radiation are reemitted (Calvet & Gullbring 1998; Gullbring et al. 2000). The redshifted or blueshifted absorptions are often seen in these emission lines, which is considered to be caused by disk wind or accretion flow (Kurosawa et al. 2006).

All of our targets show the Hα emission line, and we found that, from the broad feature of the emission line, they are considered to be young stars with accretion. According to White & Basri (2003), stars with Hα broader than 270 km s$^{-1}$ at 10% maximum intensity are classified as accreting, and all the targets exceed this threshold (Figure 7). TICs 457231768 and 34397579 are known to show this emission line from previous observations. In this observation, a double-peaked line profile and a blueshifted absorption line are observed in the spectrum of TICs 457231768 and 34397579, respectively. They will be described in Sections 4.1.1 and 4.1.2.

We checked the line-profile variations from additional observations for TICs 434229695 and 317873721. The line profiles of TIC 434229695 vary and sometimes even disappear, but basically, their peak on the redshift side is less than half of that on the blueshift side. The variation of the line profile for TIC 317873721 is more complicated, as shown in Figure 7. The interpretation of each emission-line profile will be dealt with in Section 4.

Emission in the Hα line can also arise from chromospherically active stars instead of accretion onto the surface of a star from a disk. Objects can be distinguished as either nonaccreting or magnetospherically accreting by their line widths and line profiles. The large-velocity magnetospheric accretion columns produce broad (>200 km s$^{-1}$) and asymmetric line profiles (Natta et al. 2004). We measured the width at 10% of the line peak ($W_{10}$) in Subaru/HDS spectra, which are listed in Table 3. Then, we estimated the accretion rates of their disk according to the empirical relation obtained by Natta et al. (2004),

$$
\log(M_{\text{acc}}(M_\odot \text{yr}^{-1})) = -12.89(\pm 0.3) + 9.7(\pm 0.7) 
\times 10^{-3}\Delta V(\text{km s}^{-1}).
$$

The results of the mass accretion rate $\sim 10^{-6}M_\odot$ yr$^{-1}$ are consistent with the model prediction of the observed line profiles by Kurosawa et al. (2006).

#### 3.5. Radial Velocity Variation of TIC 317873721

We found that TIC 317873721 shows a large RV variation, which indicates there is a close-in object. These RVs were derived by cross-correlating the observed spectra with the template spectrum around the Mg triplet (5150–5200 Å). We used the high-resolution synthetic spectra of $T_{\text{eff}}=8200$ K calculated by PHOENIX (Husser et al. 2013) as the template spectrum. For the spectra with low S/N, we removed outliers by sigma-clipping and smoothed them by convolving a Gaussian function. Errors were estimated by Monte Carlo simulation with the mock spectrum for each observation, resulting in about 1–3 km s$^{-1}$.

The RV, $V(t)$, of the primary star in a binary system is given by

$$
V(t) = \gamma + K_1 \{ \cos(\theta(t) + \omega) + e \cos \omega \},
$$

where $\gamma$ is the long-term mean or systemic velocity of the binary, $\theta(t)$ is the true anomaly as a function of time $t$, $\omega$ is the argument of periastron, and $e$ is the eccentricity. $K_1$ is the RV semiamplitude of the primary star, which is given by

$$
K_1 = \frac{na_1 \sin i}{\sqrt{1 - e^2}},
$$

where $n = 2\pi/P_{\text{orb}}$ is the mean motion, $P_{\text{orb}}$ is the orbital period, and $a_1$ is the semimajor axis of the primary star’s orbit. The velocity semiamplitude of the secondary star in the binary, $K_2$, is defined in an analogous manner using $a_2$. $\theta(t)$ in the Equation (2) is related to time via the following two equations, as introduced in Robin & Green (1985): first, an expression between the true anomaly and the eccentric anomaly, $E$, and
second, between the eccentric anomaly and time (the latter is known as Kepler’s equation, where \( \tau \) is the time of perihelion passage):

\[
\tan \frac{\theta}{2} = \sqrt{1 + e} \tan \frac{E}{2},
\]

\[
t = \frac{E - e \sin E}{n} + \tau.
\]

We searched the orbital parameters of the primary star by using Markov Chain Monte Carlo (MCMC) sampling. The choice of prior distributions for each parameters is given in Table 4. In the MCMC fitting, we assume that the measurement errors for RVs to be

\[
\sigma = \sqrt{\sigma_i^2 + \sigma_{\text{jitter}}^2},
\]

where \( \sigma_i \) is an internal error of the \( i \)th data point and \( \sigma_{\text{jitter}} \) is any other excess scatter that is not included in \( \sigma_i \) (see Masuda & Hirano 2021). Figure 8 shows the result of this sampling, and the folded RVs and the mean of the
fitted models are shown in Figure 9. Because the data are sparse in terms of the phase, the parameters of $\tau$ and $\omega$ were not well determined as shown in the near-linear relationship in Figure 8. If we collect more data with various phases from further observations, all the parameters should be well determined.

Then, we estimated the mass of the companion. The binary mass function $f$ is given by

$$f = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P_{\text{orb}}K^3}{2\pi G}(1 - e^2)^{3/2},$$

where $M_1$ and $M_2$ are the stellar masses and $G$ is the gravitational constant. Given the mass of TIC 317873721 is $M_1 = 2.01 M_\odot$ from TICv8, the minimum mass of the unseen object is $M_2 = 0.65 M_\odot$, which is calculated by setting $i = 90^\circ$. In addition, the semimajor axis of this binary system can be estimated from Kepler’s third law,

$$\frac{a^3}{P_{\text{orb}}^2} = \frac{G}{4\pi^2}(M_1 + M_2),$$

and is $a \sim 0.036$ au $= 7.9 R_\odot$.

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**Figure 7.** Observed spectrum around the Hα emission line. The vertical dashed line is at the rest wavelength (6562.8 Å). To show the line profiles clearly, observed spectra of TICs 434229695 and 317873721 are smoothed by convolving a Gaussian function. See Table 3 for observational instruments.

**Table 3**

| TIC ID     | $W_10$ (km s$^{-1}$) | $M_{\text{acc}}$ ($M_\odot$ yr$^{-1}$) | $\text{EW}$ (m Å) | Instruments                  |
|------------|-----------------------|----------------------------------------|-------------------|------------------------------|
| 457231768  | 507                   | $1.07 \times 10^{-8}$                 | 27 ± 6            | HDS                          |
| 34397579   | 549                   | $2.78 \times 10^{-8}$                 | 150 ± 7           | HDS                          |
| 434229695  | 360/555               | $4.08 \times 10^{-10}/3.18 \times 10^{-8}$ | 254 ± 9/247 ± 9   | HDS, CAFÉ, SCUBA-2           |
| 317873721  | –/526                 | –/1.65 $\times 10^{-8}$               | –/…              | HDS, CAFÉ, SCUBA-2, HIDES    |

**Note.** Results for the Hα and Li of TICs 434229695 and 317873721 are derived from the spectra observed in 2019/2020. All other results are from spectra observed in 2019.

**Table 4**

| Parameter | Prior | Min. | Max. |
|-----------|-------|------|------|
| log $K$   | Uniform | −2   | 2    |
| $\varepsilon$ | Uniform | 0    | 1    |
| $\cos \omega$ | Uniform | −1   | 1    |
| $\sin \omega$ | Uniform | −1   | 1    |
| $P_{\text{orb}}$ | Uniform | 1.56 $\times$ 0.99 | 1.56 $\times$ 1.01 |
| ln $i$    | Uniform | −5   | 5    |

**The Assumed Prior Distribution of Orbital Parameters**
The spectral feature from the unseen companion in high-resolution spectra could not be found. If the Li absorption line was in the spectra, it could signal the existence of a cooler companion, but it was not detected. We also tried to derive the RVs of the secondary by cross-correlation of the HDS spectra after removing the feature of the primary star. We searched for signs of the secondary in the spectrum as follows: We first smoothed the raw spectrum by taking the median filter with the rotation speed of the primary star, $v \sin i \sim 40$ km s$^{-1}$. This rotation speed was roughly estimated by cross-correlating with the template spectrum of a similar-temperature star. Then, we divided the raw spectra by the smoothed ones, and because the smoothed spectrum can be regarded as the spectrum of the primary star, the features from the companion should remain. Finally, we took the cross-correlation of the remaining spectrum and the stellar template spectrum, but no signals could be detected. It might be because the contrast ratio of the primary star to the companion star is not enough to be detected at such noise level. For example, when we set the effective temperature and the radius of the companion to be $T_{\text{eff}} = 4100$ K and $R = 0.7R_\odot$, the contrast ratio at 5200 Å becomes $\sim 6 \times 10^{-3}$.

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**Figure 8.** Posterior distribution of the RV model ($\tau$ [day], $P_{\text{orb}}$ [day], $K$ [km s$^{-1}$], $e$, $\omega$ [radians], $\gamma$ [km s$^{-1}$], ln jitter). The parameter of “ln jitter” is the natural log of the $\sigma_{\text{jitter}}$—see the text for more information.
4. Plausible Scenarios for the Four Dippers

The plausible scenarios for the dimming mechanisms for the four dippers are summarized in Figure 10 and Table 5.

4.1. Dippers around the Orion Complex

In this section, we discuss the dimming mechanisms for TIC 457231768 (HD 29409) and TIC 34397579 (V 1650 Ori). The Orion molecular cloud complex (or, simply, the Orion complex) is one of the largest star-forming regions near the Sun. These targets belong to Orion C and D, respectively, which are older parts of the Orion complex with little molecular gas (Kounkel et al. 2018). The most likely cause of the aperiodic and quasiperiodic dimming of these dippers is “dusty disk wind.” It is a scenario in which the dust is lifted by the disk wind generated by the XUV radiation from the star and the magnetic field, and the dust blocks the light in the line of sight, resulting in dimming. The absorption line seen in Hα emissions of these targets indicates the outflow from the disk. The detailed properties of each object are described in the following subsections.

4.1.1. TIC 457231768

The age of TIC 457231768 was previously estimated to be about ∼4.8 Myr in Paper I from the catalog of Kounkel & Covey (2019), but Arun et al. (2019) reported that it to be a Herbig Be star with the age of ∼7 Myr. Also, Alecian et al. (2013) found that it is a spectroscopic binary (SB2).

We confirmed that a Hα emission line with a slightly redshifted absorption was seen in the spectrum (Figure 7). Compared to past observations, the line profile is likely to show variability. In Torres et al. (1995), it is reported that the emission has a slightly stronger blueshifted peak compared to the redshifted one. But in Vieira et al. (2003), it is reported to be a double-peaked shape just like our observation. These line profiles suggest that this system is viewed from a high inclination angle (i ∼ 80°) (Kurosawa et al. 2006).

Although the observed redshifted absorption suggests mass accretion, we considered that the cause of the dips was dust lifted above the disk midplane by the disk winds. Because this star is hot, dust would not be expected to survive in an accretion-driven inner-disk warp close to the star. The inclination angle is high enough to observe the disk wind, which is known to be generated in the region ≥30° (Blandford & Payne 1982). For example, in HD 163296, one of the Herbig Ae star dippers, Ellerbroek et al. (2014) reported that dust clouds in its disk caused the variations in the brightness in the visible and near-infrared. Similar to TIC 457231768, the double-peaked Hα emission line of HD 163296 was observed in the spectrum (Acke et al. 2005), and the age was determined to be 6.52 Myr. Therefore, we concluded that the more likely scenario to explain the dips for this star is the dusty disk wind scenario (Figure 10(a)).

We calculated the size of the dust clouds in the disk from the duration of the dimming. In the calculation, we set the location of the dust for TIC 457231768 to be about 0.4 au from the star, adopting the estimate of the dust location causing the dipper phenomenon in HD 163296 made by Rich et al. (2020). This is a reasonable value in that the sublimation radius of dust, which is related to the dust sublimation temperature as $R_{\text{sub}} = R_* \left( \frac{T_{\text{sub}}}{T_*} \right)^{2.085}$, is $R_{\text{sub}} \approx 78R_\odot = 0.36$ au for TIC 457231768 when $T_{\text{sub}} = 1500$ K. With the dimming duration of ≈5 days, we estimated that the source of the dipper event has the azimuthal extent of 0.2 au.

4.1.2. TIC 34397579

TIC 34397579 is a variable star of Orion type with a spectral type of F7. In Paper I, it was classified as a member of Orion south-1 (∼3.0 Myr) according to the catalog of Kounkel & Covey (2019). In the TESS FFI light curve, there is a single large dip that lasts for about 4 days. Aside from TESS FFI, quasiperiodic dimming was observed from the observation of ASAS-SN (Pojmanski 2002) and KELT (Oelkers et al. 2018).

In the observed spectrum, we confirmed the Hα emission line with blueshifted absorption (Figure 7). This absorption is caused by materials moving toward the observer, and the line profile is observed in a star with a fast wind observed at moderate inclination and with a high accretion rate from the simulation by Kurosawa et al. (2006). Compared to past observations, it is not clear whether there is an apparent change in the line profile. In Rojas et al. (2008) only, they reported it as “complex emission profiles.” In any case, the observed Hα line profile may suggest the “dusty disk wind” scenario for the dipper phenomenon of TIC 34397579. Also, crystalline silicate features have been confirmed in the spectrum by Chen et al. (2016) from the observation with the Spitzer Infrared Spectrograph. Protoplanetary disks contain crystalline dust grains where the dust temperatures are lower than the threshold value for their formation through the thermal annealing of amorphous interstellar silicates. The “dusty disk wind” scenario could explain emission from silicates even in the low-dust-temperature region due to the transport of particles by the disk wind (Giacalone et al. 2019).

4.2. Dippers Showing Hα Emission Variability

We discuss the dimming mechanisms from our spectroscopic observations for TICs 434229695 and 317873721 in this section. They are far from nearby molecular clouds and do not belong to any young moving groups and associations as shown in Paper I. There are fewer spectroscopic observations for these targets, so this is the first time they have been characterized in detail. We observed them several times and found the
variability of the Hα emission line, which indicates accretion flow or interaction with an unseen object, as described below.

4.2.1. TIC 434229695

We found that the Hα emission line of this target varies as shown in Figure 7. These line profiles, which have a double-peaked shape with a low peak on the redshift side overall, correspond to the model of Kurosawa et al. (2006) when viewing the accretion flow onto the star from a high inclination angle. In the model of Kurosawa et al. (2006), it is also shown that the larger the inclination, the deeper the absorption feature.

To confirm the location of the source that causes the dips, we calculated the Keplerian rotation radius $R_K = \left(\frac{GM_*}{P^2}\right)^{1/3}$ that corresponds to the period of dips in the light curve. Because $P_{\text{dip}} = 2.56$ days (from Section 3.1) and $M_* = 0.915M_{\odot}$ (from TICv8) for this target, then $R_K$ is 0.037 au. This is consistent with the typical truncation radius $R_t$ of a T Tauri star (3R$_c$–5R$_c$, Shu et al. 1994), about 0.027–0.045 au for TIC 434229695, at which the magnetic field truncates the inner disk and drives accretion flow through funnel flows.

Therefore, we concluded that the more likely scenario for the dipper phenomenon of this star is the accretion flow generated along the axis of the magnetic field, which is inclined to the axis of rotation, and that the viewing angle of the accretion flow changes with rotation, causing the quasiperiodic dimming and the variation of the line profile (Figure 10(b)). This dimming mechanism is also applied to AA Tau, one of the typical dippers, and is considered to be the typical scenario (Bouvier et al. 1999, 2014). If simultaneous spectroscopy and photometry are performed in the future, we will be able to confirm this scenario by connecting each line profile of the Hα with the dimming phase. On the other hand, a unique point about this dipper is that it is located far from star-forming regions. The estimated formation process for such objects is that they are formed in a small region with high-density gas and dust like the “Bok globule,” or they experienced the rapid dissipation of a surrounding molecular cloud. It is known that dippers represent ~20% of YSOs (and up to about 30%–40%; Alencar et al. 2010; Cody et al. 2014; McGinnis et al. 2015; Bodman et al. 2017; Cody & Hillenbrand 2018), and TIC 434229695 suggests that there are many YSOs outside star-forming regions.

4.2.2. TIC 317873721

Although this star is located far from the Orion molecular cloud, it is considered to be a member of the star-forming region called VdB 64 (see Section 3.2).

From our observational results, we found that TIC 317873721 is a single-lined spectroscopic binary (SB1) with a circumstellar disk. Interestingly, the estimated orbital period of this binary system ($P_{\text{orb}} = 1.56$ days) is close to the period of

![Figure 10](image)

Figure 10. Sketches based on the plausible scenarios for dippers introduced in this paper. The key properties of each target corresponding to the dimming mechanism are summarized in Table 5. (c) Because TIC 317873721 is in a close-in binary system, the circumstellar dust structures may coalesce around both stars.

| TIC ID     | Spectral Index | Disk Type$^a$ | Hα Line Profile$^b$ | Hα Variability | RV Variation | Plausible Dimming Scenario |
|------------|----------------|---------------|---------------------|----------------|--------------|---------------------------|
| 457231768  | $\alpha = -0.014$; Class II | F             | double peak;         | ✓ (?)$^e$       | ✓            | (a) disk wind             |
| 34397579   | $\alpha = -0.418$; Class II | F             | Disk winds & High inclination | ✓$^c$          | ✓            | (a) disk wind             |
| 434229695  | $\alpha = -0.111$; Class II | F             | Blueshifted absorption due to disk wind | ✓$^c$          | ✓            | (b) accretion warp        |
| 317873721  | $\alpha = -1.284$; Class II | F             | Redshifted absorption due to accretion | ✓$^c$          | ✓            | (c) binary and accretion warp |

Notes.
$^a$ Disk type determined from Figure 3 in Paper I: F = full.
$^b$ Observed line profiles and their estimated cause.
$^c$ The classification of Hα emission-line profiles defined by Reipurth et al. (1996).
$^d$ In Torres et al. (1995), the emission has a slightly stronger blueshifted peak than the redshifted one.
$^e$ Rojas et al. (2008) reported as “complex emission profiles.”
the dips seen in the TESS light curve \((P = 1.59\) days), so the dipper phenomenon seems to be strongly related to the binary motion. Another intriguing feature of this star is the variability of the H\(\alpha\) emission line (Figure 7), indicating ongoing accretion. The circumbinary accretion onto the binary is caused by complex accretion streams; the two circumstellar disks surrounding each star and the circumbinary disk are connected and all exchange mass via accretion streams launched at the inner edge of the circumbinary disk, as shown in numerical simulations (e.g., Günther & Kley 2002; Kaigorodov et al. 2010; Muñoz & Lai 2016).

Past observations of the T Tauri spectroscopic binary have revealed that some binaries show quasi-periodic photometric oscillations occurring at the binary orbital period, known as “pulsed accretion” (Jensen et al. 2007; Muzerolle et al. 2013; Bary & Petersen 2014). In addition, they can show periodic variations in spectral veiling and emission-line intensities with orbital phase. Such brightening is thought to be caused by complex accretion streams as the material flowing from the circumbinary disk is shocked when it collides with the circumstellar disk(s) or accretes onto the stellar surface(s) with the changing accretion rate (Muñoz & Lai 2016).

The light curve of TIC 317873721 is not “brightening” periodically like pulsed accretion, but the depth of dimming is changing. But we simply assumed that this system has the same geometry as a binary system with pulsed accretion and that in this system, dust in the accretion stream, which rotates with the binary, hides the starlight and is observed as such a dip when it is observed from a high inclination angle (Figure 10(c)). From our observation results, no clear periodicity of either the line profile or EWs of the H\(\alpha\) emission with respect to the orbital phase of the binary was observed, partially due to the low-S/N data taken by CAHA/CAFÉ and Okayama/HIDES for this target. Further high-S/N spectroscopic observations will be able to reveal the accretion in more detail. Also, we plan to perform photometric observation in the near-infrared. If the dip is due to interstellar dust, the effect of dust fading in the \(K\) band becomes smaller than that in the \(V\) band (e.g., Grinin et al. 2018). Therefore, the fading due to an eclipsing binary (if any) may be observed in the \(K\)-band observation, and it will be able to confirm relations between the binary motion and the accretion stream.

5. Discussion and Summary

The dipper phenomenon, or the episodic/quasi-periodic dimming seen in the light curves, is considered to be related to the dust in the protoplanetary disk, which is lifted above the disk midplane by the disk wind or by the accretion flow along the stellar magnetic field from the disk to the stellar surface. Therefore, observations of dippers can reveal the region close to the star in protoplanetary disks. While it is difficult to spatially resolve that region, high-dispersion spectroscopic observations can give a clue to understanding such detailed properties of dippers.

In this paper, we characterized four newly found dippers by performing follow-up observations. These targets are selected from our catalog that contains a sizable, unbiased, and homogeneous sample of dippers. The observed spectra provide information on the presence of Li absorption lines (for TICs 457231768, 34397579, and 434229695), an indicator of stellar youth, and H\(\alpha\) emission lines (for all targets), suggesting accretion onto the star, as well as RV variation caused by a close-in binary (for TIC 317873721). From these results, the dipper phenomena of our targets were considered to be caused by various mechanisms such as “dusty disk wind” (TICs 457231768 and 34397579) or dust in an accretion-driven disk warp (TIC 434229695). An accretion-driven disk warp may also exist around TIC 317873721, a binary dipper, and rotate with the binary based on the fact that the dimming period and the orbital period of the binary are almost the same.

From the detection of the H\(\alpha\) emission line, our observed dippers are still accreting, as one of them (TIC 434229695) is located far from nearby molecular clouds. By considering that dippers are common among YSOs (\(\sim 20\%–40\%\); Alencar et al. 2010; Cody et al. 2014; McGinnis et al. 2015; Bodman et al. 2017; Cody & Hillenbrand 2018), there could be many YSOs in star-forming regions. At the point where they are less affected by interstellar medium, our targets are suitable for researching the evolutionary processes of pre-main-sequence stars in further follow-up observations. Also, the measurements of RVs revealed a new aspect of dippers with a circumbinary disk. Dippers in binary systems have rarely been investigated to date, and TIC 317873721 is an important sample in the understanding of dipper mechanisms.

We thank the anonymous reviewer for the helpful comments and suggestions. We also thank Masayuki Tanaka, Ryo taroh Ishikawa, Takaharu Shishido, Raiga Kashiwagi, Suzuka Nakano, and Takahoko Masai for their help in preparing and carrying out the observation on 2019 September 16. These data were acquired as part of practical observation training with the Subaru telescope by SOKENDAI.

This study was supported by JSPS KAKENHI grant nos. JP18H04577, JP18H01247 (H.K.), JP20H00170, 21H04998 (T.K. and H.K.), 17H01103, 18H05441 (T.M. and M.M.), 19K03932 (T.M.), JP21K13965, and JP21H00053 (K.H.). In addition, this study was also supported by the JSPS Core-to-Core Program Planet2, SATELLITE Research from the Astrobiology center (AB022006), and JST SPRING, grant No. JP21J02104.

This research is based [in part] on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. We are honored and grateful for the opportunity of observing the universe from Mauna Kea, which has cultural, historical, and natural significance in Hawaii.

The JCMT SCUBA-2 data are collected under program ID M20BP004. The James Clerk Maxwell Telescope is operated by the East Asian Observatory on behalf of The National Astronomical Observatory of Japan, Academia Sinica Institute of Astronomy and Astrophysics, the Korea Astronomy and Space Science Institute, and Center for Astronomical Mega-Science (as well as the National Key R&D Program of China with No. 2017YFA0402700). Additional funding support is provided by the Science and Technology Facilities Council of the United Kingdom and participating universities and organizations in the United Kingdom and Canada. Additional funds for the construction of SCUBA-2 were provided by the Canada Foundation for Innovation.

Facilities: TESS, Subaru (HDS), CAHA (CAFÉ), Okayama; 1.88 m (HIDES), JCMT (SCUBA-2).

Software: Astropy (Astropy Collaboration et al. 2013, 2018), astroquery (Ginsburg et al. 2019), matplotlib (Hunter 2007), numpy (Harris et al. 2020), scipy (Virtanen et al. 2020), pandas
References

Aceituno, J., Sánchez, S. F., Grupp, F., et al. 2013, A&A, 552, A31
Acek, B., van den Ancker, M. E., & Dulmund, C. P. 2005, A&A, 436, 209
Alecián, E., Wade, G. A., Catala, C., et al. 2013, MNRAS, 429, 1001
Alencar, S. H. P., Teixeira, P. S., Guimarães, M. M., et al. 2010, A&A, 519, A88
Ansdell, M., Gaidos, E., Rappaport, S. A., et al. 2016, ApJ, 818, 69
Ansdell, M., Williams, J. P., van der Marel, N., et al. 2016b, ApJ, 828, 46
Arun, R., Mathew, B., Manoj, P., et al. 2019, AJ, 157, 159
Astropy Collaboration, Robin, M., & Green, R. M. G. 1985, Spherical Astronomy

Bradbury, J., Frostig, R., Hawkins, P., et al. 2018, JAX: composable transformations of Python+Numpy programs, v0.2.5, GitHub, http://github.com/google/jax

Brahm, R., Jordán, A., & Espinoza, N. 2017, PASP, 129, 034002
Calvet, N., & Gullbring, E. 1998, ApJ, 509, 802
Chen, R., Luo, A., Liu, J., & Jiang, B. 2016, AJ, 151, 146
Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368

Currie, M. J., Berry, D. S., Jenness, T., et al. 2014, in ASP Conf. Ser. 485, Astronomical Data Analysis Software and Systems XXIII, ed. N. Manset & P. Forsay (San Francisco, CA: ASP), 391

Dempsey, J. T., Friberg, P., Jenness, T., et al. 2013, MNRAS, 430, 2534

Doering, R. L., & Meixner, M. 2009, AJ, 138, 780

Ellerbroek, L. E., Podio, L., Dougados, C., et al. 2014, A&A, 563, A87

ExoFOP 2019, Exoplanet Follow-up Observing Program—TESS (IPAC), doi:10.26134/EXOFOP3
Foreman-Mackey, D. 2016, JOSS, 1, 24
Gaidos, E., Jacobs, T., LaCourse, D., et al. 2019, MNRAS, 488, 4465

Giacalone, S., Teitler, S., Königl, A., & Krijt, S., & Ciesla, F. J. 2019, ApJ, 882, 33
Ginsburg, A., Sipőcz, B. M., Brasseur, C. E., et al. 2019, AJ, 157, 98
Grinin, V. P., Barsunova, O. Y., Sergeev, S. G., et al. 2018, ArXiv, 62, 677
Güntner, R., & Kley, W. 2002, A&A, 387, 550
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Natur, 585, 357
Hildebrand, R. H. 1983, QJRAS, 24, 267

Hillenbrand, L. A. 2008, PIST, 130, 04024
Hunter, J. D. 2007, CSE, 9, 90
Husser, T. O., Wende-von Berg, S., Dreizler, S., et al. 2013, A&A, 553, A6
Isella, A., Testi, L., & Natta, A. 2006, A&A, 451, 951
Izumiura, H. 1999, Proc. 4th East Asian Meeting on Astronomy, Observational Astrophysics in Asia and its Future, ed. P. S. Chen, (Kunming: Yunnan Observatory), 77
Jensen, E. L. N., Dhlal, S., Stassun, K. G., et al. 2007, AJ, 134, 241
Kaigorodov, P. V., Biskalo, D. V., Kateeva, A. M., & Sytov, A. Y. 2010, ARep, 54, 1078

Kanodia, S., & Wright, J. 2018, RNAAS, 2, 4
Kounkel, M., & Covey, K. 2019, yCat., 1/158/122
Kounkel, M., Covey, K., Suárez, G., et al. 2018, AJ, 156, 84
Kurosawa, R., Harries, T. J., & Symington, N. H. 2006, MNRAS, 370, 580

Lada, C. J. 1987, in IAU Symp. 115, Star Forming Regions, ed. M. Peimbert & J. Jugaku (Dordrecht: D. Reidel), 1
Lee, H.-T., & Chen, W. P. 2009, ApJ, 694, 1423
Lillo-Box, J., Aceituno, J., Pedraza, S., et al. 2020, MNRAS, 491, 4496
Masatake Aizawa

Mandeville, S., & Kharchenko, N. 2016, AJ, 152, 116
Mayer, R., & Bovy, J. 2014, MNRAS, 439, 1590
McGinnis, P. T., Alencar, S. H. P., Guimarães, M. M., et al. 2015, A&A, 577, A11
Mauroz, D. J., & Lai, D. 2016, ApJ, 827, 43
Muzerolle, J., Furlan E., Flaherty, K., Bolzog, L., & Gutermuth, R. 2013, Natur, 493, 378

Natta, A., Testi, L., Muzerolle, J., et al. 2004, A&A, 424, 603
Noguchi, K., Aoki, W., Kawanomoto, S., et al. 2002, PASJ, 54, 855
Oelkers, R. J., Rodríguez, J. E., Stassun, K. G., et al. 2018, AJ, 155, 39
pandas development team 2020, pandas-dev/pandas: Pandas, Zenodo, doi:10.5281/zenodo.3509134
Phan, D., Pradhan, N., & Jankowiak, M. 2019, arXiv:1912.11554
Pojmanski, G. 2002, A&A, 52, 397
Reipurth, B., Pedrosa, A., & Lago, M. T. V. T. 1996, A&AS, 120, 229
Rich, E. A., Wisniewski, J. P., Sitko, M. L., et al. 2020, ApJ, 902, 4
Roblin, M., & Green, R. M. G. 1983, Spherical Astronomy (Cambridge: Cambridge Univ. Press)

Rojas, G., Gregorio-Hetem, J., & Hetem, A. 2008, MNRAS, 387, 1335
Shu, F., Najita, J., Ostriker, E., et al. 1994, ApJ, 429, 781
Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, AJ, 158, 138

Tajiri, T., Kawahara, H., Aizawa, M., et al. 2020, ApJS, 251, 18
Takita, S., Doi, Y., Ootsubo, T., et al. 2015, PASJ, 67, 51
Torres, C. A. O., Quast, G., de La Reza, R., Gregorio-Hetem, J., & Lillo-Box, J. 1998, AJ, 156, 123

Virtanen, P., Gommers, R., Peurho, M., et al. 2020, Nature, 585, 137

White, R. J., & Basri, G. 2003, ApJ, 582, 1109

(2022 April 25 12:29 UTC)