Keck/OSIRIS Pa$\beta$ high-contrast imaging and updated constraints on PDS 70b

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ABSTRACT

We present a high-contrast imaging search for Pa$\beta$ line emission from protoplanets in the PDS 70 system with Keck/OSIRIS integral field spectroscopy. We applied the high-resolution spectral differential imaging technique to the OSIRIS $J$-band data but did not detect the Pa$\beta$ line at the level predicted using the parameters of Hashimoto et al. (2020). This lack of Pa$\beta$ emission suggests the MUSE-based study may have overestimated the line width of H$\alpha$. We compared our Pa$\beta$ detection limits with the previous H$\alpha$ flux and H$\beta$ limits and estimated $A_V$ to be ~ 0.9 and 2.0 for PDS 70 b and c respectively. In particular, PDS 70 b’s $A_V$ is much smaller than implied by high-contrast near-infrared studies, which suggests the infrared-continuum photosphere and the hydrogen-emitting regions exist at different heights above the forming planet.

Keywords: Planet Formation, Exoplanet Astronomy

1. INTRODUCTION

A variety of theoretical and observational studies have investigated planet formation, yet the mechanisms are still poorly understood. High-contrast imaging at infrared (IR) wavelengths can detect the thermal emission of young exoplanets directly and thus provide key insights to distinguish between various planet formation mechanisms. Characterization of the physical and atmospheric parameters of protoplanets at specific ages helps in assessing the initial conditions of their formation (e.g. Bonnetoy et al. 2014). Furthermore, addressing such problems as reconciling the evolutionary cooling models (hot/warm/cold-start; Spiegel & Burrows 2012) with the relevant physical processes (e.g. core accretion and disk instability; Pollack et al. 1996; Boss 1997) are essential to improving our understanding of planet formation. One of the ways to probing planet formation is to observe hydrogen emission originating in active mass accretion onto protoplanets (Aoyama et al. 2018).
PDS 70 is one of the most intriguing young systems with high-contrast imaging, revealing two protoplanets located within a large cavity of the protoplanetary disk (PDS 70bc; Kepler et al. 2018; Haffert et al. 2019) and follow-up observations confirming active mass accretion onto them (e.g. Haffert et al. 2019). Previous studies have explored some of the hydrogen emission lines in the PDS 70 system: Hα (656.28 nm), Hβ (486.14 nm), Brα (4.050 µm), and Brγ (2.166 µm). Hα emission has been reported by MagAO (Wagner et al. 2018), VLT/MUSE (Haffert et al. 2019), and HST (Zhou et al. 2021). The measured Hα flux shows temporal variability on a 1–2-year timescale for reasons which are still controversial: either systematic instrumental calibration errors and/or an intrinsic time variability. The MUSE data include Hβ line but yielded only a null detection (Hashimoto et al. 2020) with 3σ upper limits of 2.3 and 1.6×10^{-16} erg s^{-1} cm^{-2} for PDS 70 b and c respectively. Christiaens et al. (2019) reported the K-band spectrum of PDS 70 b taken by VLT/SINFONI (R≈100) and Wang et al. (2021) presented the K-band spectra of PDS 70 bc taken by VLT/GRAVITY (MEDIUM resolution), but they did not detect significant Brγ emission. Wang et al. (2021) set 3σ upper limits of Brγ to 5.1 and 4.0×10^{-17} erg s^{-1} cm^{-2} for PDS 70 b and c respectively, which are limited by the K-band continua of PDS 70 bc. Stolker et al. (2020) reported the detection of PDS 70 bc with VLT/NACO NB4.05 filter (Brα filter; λcen=4.05 µm, Δλ=0.02 µm). However, they suggested that PDS 70 b’s spectrum is best fit by an atmospheric model without Brα and did not argue in favor of a line detection. In addition to the hydrogen emission lines, Zhou et al. (2021) reported ultraviolet (UV) emission from PDS 70 b with HST/WFC F336W filter and suggested that the hydrogen continuum emission dominates the UV flux. Aoyama et al. (2020) incorporated all these lines into a discussion of the emission mechanisms but were unable to determine fully the physical and accretion parameters of PDS 70 bc.

Here we report on a search for the previously unobserved line of Paβ (1.282 µm) around PDS 70 which is one of the brightest emission lines relative to Hα. We used Keck/OSIRIS mid-resolution integral field spectroscopy (IFS, R≈4000) to further investigate the accretion mechanisms of PDS 70 bc. The observations and preliminary result of the post-processing were originally reported in Uyama et al. (2021). In this paper we present the updated results with a detailed analysis of the data following Xie et al. (2020) (see Sections 2 and 3). Section 4 investigates constraints on the accreting parameters of PDS 70 bc by incorporating the OSIRIS results with the previous studies.

### 2. DATA

#### 2.1. Observations

| Table 1. OSIRIS observations using the Jn3 filter with the plate scale of 20 mas. |
|-----------------|-----------------|-----------------|
| Target          | t_{DIT} × n_{DIT} | On-source time (s) |
| PDS 70          | 40 × 120         | 4800(5)          |
| HD 143956       | 20 × 1           | 20              |
| HD 144609       | 2 × 1            | 2               |

Note—^a^ t_{DIT} is the exposure time per image frame in the unit of seconds and n_{DIT} is the number of image frames. ^b^ The last eight frames were excluded in the analysis due to the inferior observing conditions, resulting in a practical total integration time of 3840 s.

We observed PDS 70 with Keck/OSIRIS in the Jn3-band on 2020 May 31 UT (PI: Charles Beichman) to search for a Paβ emission line (1.282 µm) from accretion onto the protoplanets. We used the OSIRIS IFS spatial sampling of 0′′.02 spaxel^{-1} that covers a field of view of 0′′.96 × 1′′.28, where each spatial location has a spectrum from 1.275 µm to 1.339 µm (Jn3) with resolving power of ∼4000. The observations achieved a total exposure time of 4800 sec (120-sec single exposure × 40 frames) under good seeing conditions (0′′.4–0′′.6). The typical full width half maximum (FWHM) of the PDS 70′s point spread function (PSF) measured a diffraction-limited ∼60–70 mas, but the quality of the last sequence of the observations was poor because of high air-mass (≫2.2) and relatively bad seeing (∼ 0′′.7). Hence we excluded the last eight frames from this analysis. By taking the ratio of the flux within a 3-by-3-spaxel aperture and within the entire field-of-view (FoV), we estimated the Strehl ratio to be 9.88% at Paβ. Due to the relatively small FoV (0′′.96 × 1′′.28), we may overestimate the Strehl ratio. The low Strehl ratio (typically < 20%) can lead to flux loss and we took into account this effect in the data analysis. We also obtained unsaturated images of HD 143956 (spectral type: B9; Houk & Smith-Moore 1988) and HD 144609 (spectral type: K0; Houk & Smith-Moore 1988) for telluric correction and photometric reference, respectively. The details of the OSIRIS observations can be found in Table 1.

#### 2.2. Data Reduction

We used the OSIRIS Data Reduction Pipeline (reduction type: astronomical reduction pipeline; Lyke et al. 2017; Lockhart et al. 2019) with the corresponding rectification matrices\(^1\) to extract the data cube and calibrated for dark sub-

\(^1\) http://tkserver.keck.hawaii.edu/osiris/
traction, cosmic-ray removal, telluric correction, and wavelength solution. To search for faint companions with single emission lines, we need to first subtract the stellar light accurately. The preliminary data reduction presented in Uyama et al. (2021) applied the PCA-based SDI reduction that was originally used for the MUSE data (Hashimoto et al. 2020). However, this reduction technique left some instrumental residuals due to sensitivity differences between the OSIRIS spaxels. We therefore applied an advanced high-resolution spectral differential imaging (HRSDI) technique to remove the stellar emission (see, Haffert et al. (2019) and Xie et al. (2020) for the details). HRSDI is suitable for retrieving sharp emission lines while removing the stellar halo. However, before we applied the HRSDI to the final combined dataset, some residual bad pixels were removed from each exposure that passed through the OSIRIS Data Reduction Pipeline. To remove the bad pixels, we first applied HRSDI on each exposure, aiming for reducing the influence of stellar emission in the next step. Next, we applied a sigma clipping algorithm on the dithered exposures to make a bad pixel mask for each exposure. Then all the exposures were centered on the flux peak and mean combined after the removal of bad pixels.

The process of HRSDI consists of two steps, removing the stellar emission and removing the uncalibrated instrumental effects. The stellar emission was subtracted from all normalized spaxels with the normalized reference spectrum that was obtained after the continuum-normalization (Haffert et al. 2019). The uncalibrated instrumental residuals were removed using a principal component analysis (PCA) subtraction technique (Soummer et al. 2012; Amara & Quanz 2012). For example, the instrumental residual in Uyama et al. (2021) can be removed with the first few PCA components. The number of PCA components to subtract was determined by maximizing the signal-to-noise ratio (S/N) of injected fake planets at the location of PDS 70 b (see also, Section 2.3).

2.3. Fake Planet Injection

To estimate the instrumental throughput, we performed the fake planet injection described in Xie et al. (2020). The instrumental throughput includes the flux loss due to the low Strehl ratio (see Section 2.1) and that made by the PSF subtraction. Unless we specifically mentioned, both effects were corrected throughout the paper. The fake planet was created based on a planet spectrum and a stellar PSF. We used a single Gaussian line as the planet spectrum because our observations did not utilize angular differential imaging and thus did not achieve sufficient contrast to detect the continua of PDS 70 bc. We adopted the line-of-sight redshift of 25 km s\(^{-1}\) (Haffert et al. 2019) and a FWHM of 70 km s\(^{-1}\) or 0.3 nm. The injected Gaussian line can be covered by two spectral channels. We measured the flux using the aperture photometry in spectral channels of 1281.75 nm and 1281.90 nm with a square aperture of 3 by 3 spaxels (60×60 mas). The noise was estimated at the same spatial location in the spectral direction after HRSDI, using 150 spectral channels (bandwidth: 22.5 nm) around Pa\(\beta\). After obtaining a 5 \(\sigma\) detection, we estimated the flux loss caused by the PSF subtraction by comparing the injected and recovered flux. The flux losses caused by the PSF subtraction are 28% and 14% at the location of PDS 70 b and c, respectively.

3. RESULTS

After the post-processing as mentioned in Section 2.2 we did not detect Pa\(\beta\) at the locations of PDS 70 b and c (see Figure 1). Figure 2 shows the residual spectra after the HRSDI reduction at the location of PDS 70bc. We then calculated the 5\(\sigma\) detection limits\(^2\) of \(1.4 \times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) and \(1.9 \times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\) for PDS 70b and c, respectively. The correction of the flux loss caused by the PSF subtraction and the low Strehl ratio has been taken into account. Figure 3 shows the radial profiles for 5\(\sigma\) detection limits at the two position angles (PAs) of the two planets. We note that the PSF of OSIRIS is not circularly symmetric. Although PDS 70 c is further away from the star, the noise at the location of PDS 70 c is higher, resulting in a higher detection limit.

Uyama et al. (2021) defined the noise as a standard deviation of a spectral channel at the location of PDS 70 b after the SDI reduction without taking into account the OSIRIS’ spectral resolution and flux loss by the post-processing. Their calculations also used the literature value of PDS 70 J-band flux (\(J=9.553\) mag; Skrutskie et al. 2006) to convert the contrast limit into a flux detection limit, but the central star is variable due to its activity and potentially also veiling by the circumstellar disk. In this study we used a field star of HD 144609 (\(J=5.459\) mag; Skrutskie et al. 2006) as a photometric reference and calculated a conversion factor from ADU to the apparent flux.

We also investigated the validity of the estimated limits by injecting fake sources. We used Aoyama & Ikoma (2019) to convert the MUSE-based H\(\alpha\) profiles into the Pa\(\beta\) profiles assuming the derived parameters of PDS 70 bc (the number density: \(n_0 = 3.8 \times 10^{12}\) cm\(^{-3}\), the gas velocity: \(v_0 = 144\) km s\(^{-1}\), and the extinction: \(A_{H\alpha} = 2.4\) mag) in Hashimoto et al. (2020). Our prediction for the Pa\(\beta\) flux from PDS 70 b is comparable to the actual OSIRIS detection limit. Since we did not detect Pa\(\beta\) emission our model may have overesti-

\(^2\) The 5\(\sigma\) detection limit is defined as the summation of the flux in the aperture on the residual image and 5 times of the corresponding noise. As mentioned in Section 2.3, the estimated noise (without throughput correction) at the locations of PDS 70 b and c are \(2.5 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) and \(2.7 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), respectively. The residual fluxes at the locations of PDS 70 b and c are \(-2.7 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) and \(2.5 \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\), respectively.
mated the Paβ flux. Alternatively, Hashimoto et al. (2020) may have overestimated the 10% and 50% widths of the Hα profiles and thus the parameters of \(n_0\) and/or \(v_0\), possibly because MUSE does not have sufficient spectral resolution \((R\sim2500)\). This latter interpretation can explain the difference between the mass measurements from the IR SED (e.g. Wang et al. 2020; Stolker et al. 2020) and the hydrogen emission lines (Hashimoto et al. 2020). The mass estimate in Hashimoto et al. (2020) using the Aoyama & Ikoma (2019) model is an upper limit on the dynamical mass of PDS 70 b.

4. DISCUSSION

We use our detection limits of Paβ to further constrain the physical parameters of PDS 70 bc with a theoretical model (Aoyama et al. 2018; Aoyama & Ikoma 2019). For a comparison with our Paβ detection limits, we refer to: 1) the MUSE results (Hashimoto et al. 2020) which is most similar to the OSIRIS data rather than MagAO or HST because of the similarity of the data format and post-processing techniques; and 2) the HST results (Zhou et al. 2021) which were obtained in 2020 May close to when we observed PDS 70 with OSIRIS, thereby mitigating any effects of the year-timescale intrinsic variability.

We assume magnetospheric accretion (filling factor of the hydrogen emission - the coverage fraction of the shock on the planetary surface: \(f_t \lesssim 0.1\)) for the accretion mechanism of PDS 70 bc (e.g. Thanathibodee et al. 2019), from which we can set a lower limit in the \((n_0, v_0)\) parameter space (see also Figure 3 in Hashimoto et al. 2020, for the modeled Hα luminosity with different filling factor values). With this assumption, Hβ and Paβ line strengths are expected to be close to the MUSE and OSIRIS detection limits, respectively. Detailed explanations about the relationship between filling factor, other accretion parameters, and hydrogen emission luminosity are given in Aoyama et al. (2020). If the filling factor is much larger than the above assumption we cannot simply compare the Paβ limits with the theoretical model. For example, when the shock comes from the circumplanetary disk surface flow rather than the magnetospheric accretion, the filling factor is a few tens of percent (Takasao et al. 2021).

4.1. Comparison between the OSIRIS and MUSE results

Instrumental differences in the comparison of the visible and IR data should be small since the MUSE and OSIRIS IFSS have similar properties and the two datasets were treated in a similar fashion, using HRSDI to remove the stellar halo and searching for emission lines at small angular separations. We compare our Paβ detection limits with the MUSE-based Hα fluxes. However, we note that we have the uncertainty of time variability due to the difference of the epochs.

We used our 3σ Paβ detection limits \((6.6 \times 10^{-17}\ erg\ s^{-1}\ cm^{-2}\ and\ 1.3 \times 10^{-16}\ erg\ s^{-1}\ cm^{-2}\ for\ PDS\ 70\ b\ and\ c\ respectively)\) and the MUSE-based Hα fluxes and 3σ Hβ limits (Hashimoto et al. 2020) to constrain the PDS 70 bc’s parameters. Combining the hydrogen line data from these two AO-fed integral field units provides better constraints on the effects of extinction. The difference of extinction effect between Hβ/Hα and Paβ/Hα ratios enables us to estimate the \(A_V\) value. Figure 4 shows the contours of line flux ratio as a function of \(n_0\) and \(v_0\), with a variety of \(A_V\) values for PDS 70 b (left) and c (right) respectively. Although our final detection limit is higher than the preliminary result presented in Uyama et al. (2021), the comparison between the Paβ and Hβ limits suggests that \(A_V\) for the line emitting region of PDS 70 b is consistent with \(\sim 0.9\) \((A_{H\alpha} \sim 0.69\ mag\ assuming\ the\ extinction\ law\ in\ Wang\ &\ Chen\ 2019)\).

Our extinction estimates are lower than other estimates. Hashimoto et al. (2020) attributed the failure of MUSE to detect Hβ to large extinction \((A_{H\alpha} > 2.0\ mag)\) but this may be due to the overestimation of \((n_0, v_0)\) and due to the insufficient spectral resolution of MUSE as mentioned in Section 3. Our derived \(A_V\) value is also inconsistent with the Spectral Energy Distribution (SED)-fitting argument with the GRAVITY observations \((A_V \sim 4 - 10\ mag\ assuming\ ISM\ extinction\ and\ the\ best-fit\ extended\ models;\ Wang\ et\ al.\ 2021)\) that used the shape of the continuum and the molecular-mapping argument from SINFONI observations \((A_V \sim 16 - 17\ mag)\).
; Cugno et al. 2021), which used the depths of the lines. However, this discrepancy might suggest a vertical difference between the location of the photosphere responsible for the IR continuum and the hydrogen-emitting regions. The evaporated materials at the shock can sublimate beneath the hydrogen-emitting regions to create an additional extinction source for the PDS 70 b’s atmosphere. This assumption does not conflict with the physical assumption of Aoyama et al. (2018). In that sense, IR-continuum observations and hydrogen-emission observations of protoplanets should be careful to identify each extinction effect independently. The large difference between \((n_0, v_0)\) estimated in Hashimoto et al. (2020) and the \((n_0, v_0)\) contour with \(A_V = 0.9\) mag suggests that the filling factor may be larger than a lower limit of Hashimoto et al. (2020) \((f_1 \sim 0.01)\) by about an order of magnitude. To test the hypothesis about the filling factor, observing the hydrogen emission line with higher spectral resolution is required. We note that the discussion in this section ignores the time variability as mentioned above. Section 4.2 takes into account the variability effect.

For the case of PDS 70 c, we could not explore as deep parameter space as PDS 70 b because the Pa\(\beta\) detection limit is higher than that of PDS 70 b as mentioned in Section 3 and the H\(\alpha\) flux is smaller (Haffert et al. 2019; Hashimoto et al. 2020). The comparison with the Pa\(\beta\) and H\(\beta\) detection limits suggests \(A_V \sim 2.0\) mag \((A_{H\alpha} \sim 1.5\) mag). Compared with Hashimoto et al. (2020), who set a lower limit of \(A_{H\alpha}\) and \(f_1\) to 1.1 mag and \(v_0 \sim 0.003\) respectively, our estimated \(A_V\) value is consistent with their argument. We note that this argument relies on the assumption that the H\(\alpha\) profile of PDS 70 c was sufficiently resolved by MUSE. If \(n_0\) and \(v_0\) of PDS 70 c given in Hashimoto et al. (2020) are overestimated as well as those of PDS 70 b, higher contrast levels at H\(\beta\) and Pa\(\beta\) are required to constrain these parameters. As mentioned above, PDS 70 c’s photospheric continuum may also be extincted by additional material compared with the hydrogen-emitting regions. Resolving the H\(\alpha\) line profile with higher resolution and/or deeper searches for H\(\beta\) and Pa\(\beta\) will improve the constraints on the accretion parameters of PDS 70 c.

4.2. Comparison between the OSIRIS and HST results

As mentioned above, the OSIRIS and MUSE observations were not conducted in the same epoch and thus simply comparing these observational results leaves the uncertainty of the temporal variability. Zhou et al. (2021) monitored PDS 70 b’s H\(\alpha\) line with HST between 2020 February and 2020 July, which covers the OSIRIS observation on 2020 May 31 UT, and did not find larger variability in the line flux than 30% \((\sim 2.4\sigma)\). They also suggested the hydrogen line emission was variable on a year-timescale by incorporating MagAO and MUSE results obtained in 2018 (Wagner et al. 2018; Hashimoto et al. 2020). In this section we compare our Pa\(\beta\) detection limit of PDS 70 b with the time-averaged H\(\alpha\) flux estimated from the HST observations \((1.62 \pm 0.23 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2};\ Zhou et al. 2021)\). Although the HST data format and post-processing technique are different from OSIRIS, we used injection testing to account for differences in instrumental parameters and data analysis techniques. Figure 5 shows the same contours of PDS 70 b as Figure 4 assuming our Pa\(\beta\) limit and the HST-based H\(\alpha\) flux. Note that we do not include the H\(\beta\) limits because the H\(\beta\) observations were not conducted at the same epoch. The higher H\(\alpha\) flux value than the MUSE result helps us to explore a deeper parameter space. Assuming that the extinction effect is stable at \(A_V = 0.9\) mag, our \(3\sigma\) detection limit can set an upper limit of \(v_0\) at \(\sim 70\) km s\(^{-1}\). Using Equation (3) in Hashimoto et al. (2020), this upper limit corresponds to \(\sim 3-4\) \(M_{\text{Jup}}\) for the upper limit of PDS 70 b’s mass and is consistent with the mass estimation by the IR high-contrast studies (Wang et al. 2020; Stolker et al. 2020, 2021).
Figure 4. Contours of the $3\sigma$ H$\beta$ detection limits (blue; Hashimoto et al. 2020) and the $3\sigma$ Pa$\beta$ detection limits (red, this work) in comparison with the MUSE-based H$\alpha$ flux of PDS 70 b (left) and PDS 70 c (right). The estimated $n_0$ and $v_0$ of PDS 70bc in Hashimoto et al. (2020) are indicated as black crosses respectively. We take into account the extinction effect ($A_V$) and the wavelength dependency (see Equations (9) and (10) in Wang & Chen 2019). As H$\beta$ is bluer and Pa$\beta$ is redder than H$\alpha$, using these detection limits enables us to set upper and lower limits for $A_V$, from which we estimate $A_V$.

e.g.). To better determine/constrain the (variable) accreting parameters simultaneous observations of H$\alpha$, H$\beta$, and Pa$\beta$ are more helpful.

Zhou et al. (2021) estimated the continuum flux at the wavelength $\lambda = 336$ nm to be $(1.4 \pm 0.3) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ $\AA^{-1}$. This wavelength is located in the hydrogen Balmer continuum. Using the model of Aoyama et al. (2018), we can estimate the fluxes of the hydrogen recombination continua from the shock-heated gas, as a byproduct of the hydrogen line fluxes. The model prediction can reproduce both the continuum and H$\alpha$ fluxes observed for PDS 70 b, with some parameter sets. However, our calculation with $(v_0, n_0)=(144$ km s$^{-1}$, $3.8 \times 10^{12}$ cm$^{-3}$), which is estimated in Hashimoto et al. (2020), resulted in $F_{\lambda,336}/F_{H\alpha} = 5.2 \times 10^{-3}$ $\AA^{-1}$, where $F_{\lambda,336}$ is the flux per unit wavelength at $\lambda = 336$ nm and $F_{H\alpha}$ is the H$\alpha$ flux, while its observed value is $(8.6 \pm 2.2) \times 10^{-4}$ $\AA^{-1}$ when the flux in the F656N filter of HST represents the H$\alpha$ flux (Zhou et al. 2021). This comparison shows inconsistency with the results of Hashimoto et al. (2020). This implies that the spectral profile given by MUSE can be overestimated, which is consistent with our interpretation about the null detection of Pa$\beta$ in the OSIRIS observations. Note that the above estimate of $(v_0, n_0)$ comes from the MUSE-based spectral profile. However, the continuum flux for higher values of $v_0$ is less reliable due to a lack of coolants effective for hot gases in the Aoyama et al. (2018) model. Also, a part of photosphere that is heated by the accretion should emit continuum (e.g., Hartmann et al. 2016). Further theoretical studies on planetary recombination continua are essential.

Figure 5. $3\sigma$ Pa$\beta$ detection limit (red) in comparison with the HST-based H$\alpha$ flux of PDS 70 b. The contours assume $A_V=0$, 0.5, 1.0, and 1.5 (from top to bottom) and the same wavelength dependency as Figure 4.

5. SUMMARY

We present high-contrast spectral imaging for the unexplored emission line of Pa$\beta$ from PDS 70 bc with Keck/OSIRIS integral field spectroscopy. After removing stellar halo utilizing the same HRSDI technique that was ap-
plied to VLT/MUSE observations, we did not detect Paβ despite the predicted Paβ flux of PDS 70 b from the estimated accretion parameters in Hashimoto et al. (2020) being comparable to the detection limit of our dataset. The null detection suggests that our model overestimated the Paβ flux, probably because MUSE does not have sufficient spectral resolution and Hashimoto et al. (2020) overestimated $n_0$ and $v_0$ from the Hα profile.

We then compared our detection limits with previous Hα and Hβ observations to set further constraints on the accretion parameters. We adopted two Hα observations from MUSE and HST - comparing OSIRIS with MUSE can assume the smallest systematic difference in terms of the data format and post-processing techniques, whereas HST covers 2020 May when we observed PDS 70 thereby minimizing the effect of time variability on our conclusions. The MUSE-based comparison between Paβ/Hα and Hβ/Hα ratios enables us to estimate $A_V$ assuming the extinction law. We estimated $A_V \sim 0.9$ and 2.0 for PDS 70 bc respectively. Particularly the derived $A_V$ of PDS 70 b is inconsistent with the previous NIR studies, but this might suggest an additional extinction source of PDS 70 b’s IR-continuum photosphere that is located beneath the hydrogen emitting regions. The HST-based Paβ/Hα ratio suggested that the year-timescale variation does not significantly affect the $A_V$ estimate. We also incorporated the Balmer continuum detected by HST/WFC F336W observations in the Aoyama et al. (2018) framework. The comparison between the Balmer continuum with Hα flux suggests that the Hα spectral profile may be overestimated. This interpretation is consistent with the null detection of Paβ in our OSIRIS observations.

Higher spectral resolution will resolve the hydrogen emission line profiles and a deeper search could detect multiple hydrogen emissions, which helps to better estimate the accreting parameters and understand the accretion mechanisms of protoplanets.

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