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Constraining PDS 70b's Formation Mechanism with Multi-hydrogen-emission Observations

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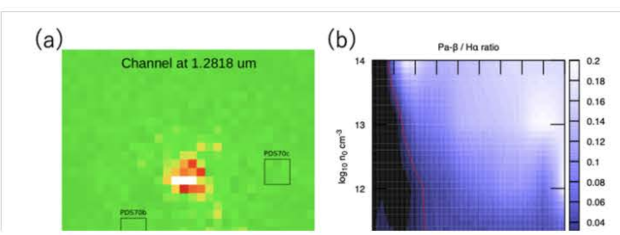
Abstract

We present our Keck/OSIRIS observations of the Paβ emission line (1.282 μm) to investigate accretion mechanisms of PDS 70 planetary system. Our spectral differential imaging reduction to remove the stellar PSF resulted in null detection of Paβ at the locations of PDS 70b and c. The 5σ detection limit of Paβ compared with the theoretical model of Aoyama & Ikoma (2019) indicates the gas velocity onto PDS 70b is smaller than 70 km s^{-1}, which suggests MUSE-based Hα studies overestimated the gas velocity and the mass of PDS 70b.

PDS 70 is one of the most intriguing young systems as previous high-contrast imaging observations reported the signatures of active mass accretion onto protoplanets (PDS 70bc; e.g., Haffert et al. 2019). PDS 70 offers the first glimpse of ongoing planet formation within a protoplanetary disk. Characterizing the physical parameters of the directly-imaged protoplanets and the disk can provide important information on the formation of Jovian planets. However, the masses estimated for PDS 70bc differ as measured by different techniques: broad-band observations at near-infrared combined with atmospheric models (e.g., Allard et al. 2012) suggest $\lesssim 4\,M_{\rm Jup}$ (Stolker et al. 2020; Wang et al. 2020) while VLT/MUSE-Hα observations combined with a hydrogen-emission model (Aoyama & Ikoma 2019) favor higher mass ($\sim 10\,M_{\rm Jup}$; Hashimoto et al. 2020).

To investigate the discrepancy between these two estimates we conducted Keck/OSIRIS observations (filter: Jn3, pixel scale: 20 mas) to search for Paβ line (1.282 μm). We observed PDS 70 on May 30 HST (PI: Charles Beichman) with a total exposure time of 4920 s (120 s single exposure × 41 frames). Seeing was good (0$''$4–0$''$6) and typical FWHM measures ~60–70 mas but the quality of the last sequence of the observations was poor because of high airmass (>2.2) and relatively bad seeing (~0$''$7). We used the OSIRIS Data Reduction Pipeline (reduction type: astronomical reduction pipeline; Lyke et al. 2017; Lockhart et al. 2019) with the corresponding rectification matrices to extract data cubes calibrated for dark subtraction, cosmic-ray removal, telluric correction, and wavelength calibration. The last 6 data cubes were ignored during the post-processing. The stellar halo was removed using the spectral differential imaging (SDI) technique as presented in the MUSE-Hα studies (Haffert et al. 2019; Hashimoto et al. 2020). Figure 1(a) shows the result of the SDI reduction at a channel that includes the Paβ line ($\lambda_{\rm cen}$ = 1.2818 μm and $\Delta\lambda$ = 0.15 nm). We did not detect Paβ at the locations of PDS 70b or c. We calculated the 5σ detection limit defined as the noise of the spectrum at each spaxel, which corresponds to 2.2 × 10^{-17} erg s^{-1} cm^{-2} for PDS 70b. We used the Hα flux and Hβ detection limit presented in Hashimoto et al. (2020) to constrain accretion mechanisms of PDS 70b. Hashimoto et al. (2020) suggested that the failure of MUSE to detect Hβ was due to large extinction. However, our Paβ detection limit suggests a lower gas velocity ($\lesssim$70 km s^{-1} assuming no extinction; Figure 1(b)), and provides a better constraint on the gas velocity than the Hβ detection limit (see Figure 1cd). Extinction alone does not provide a good explanation for this system since a large extinction would lead to brighter Paβ because of wavelength dependence (e.g., $A_\lambda \propto \lambda^{-1.75}$; Draine 1989) and this study provides the modest constraint on the gas velocity. This gas velocity is smaller than the estimated values from the MUSE observations ($\gtrsim$100 km s^{-1}; Haffert et al. 2019; Hashimoto et al. 2020). Combining our results with Hashimoto et al. 2020 suggests that these MUSE-based studies overestimated the gas velocity and thus the masses of PDS 70bc. Using Equation (3) of Hashimoto et al. (2020) with our constraint on v_0, preliminary upper limits to the mass of PDS 70b is $\lesssim 4 M_{\rm Jup}$, which is consistent with broad-band characterizations (Stolker et al. 2020; Wang et al. 2020).



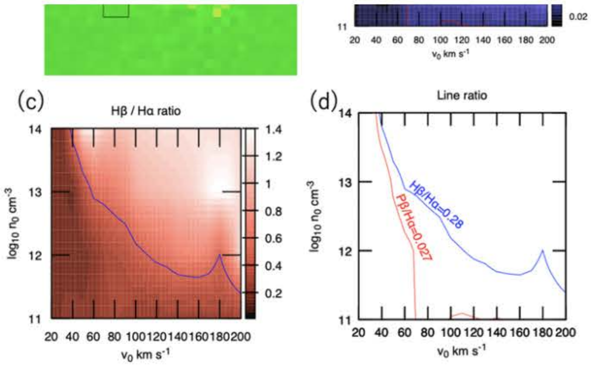


Figure 1. (a) Our SDI result of the Keck/OSIRIS observations centered at 1.2818 μm that includes Paβ line. We did not detect the counterparts of PDS 70bc. (b) The comparison plot of the Hα flux and the Paβ 5σ detection limit at the location of PDS 70b (red contour). Note that we do not take into account the extinction. The vertical and the horizontal axes indicate the number gas density (n_0) and the gas velocity (v_0) respectively (see also Aoyama & Ikoma 2019; Hashimoto et al. 2020). Note that the real combination of (n_0, v_0) is expected below the contour. (c) Same as Figure 1(b) for the comparison between the Hα flux and the Hβ 5σ detection limit (blue contour) as presented in Hashimoto et al. (2020). (d) The comparison of Hβ/Hα between Paβ/Hα contours suggesting that our OSIRIS observations could set more robust constraint on the gas velocity than the MUSE-Hα/Hβ studies.

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