Constraining Accretion Signatures of Exoplanets in the TW Hya Transitional Disk

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Abstract

We present a near-infrared direct imaging search for accretion signatures of possible protoplanets around the young stellar object (YSO) TW Hya, a multi-ring disk exhibiting evidence of planet formation. The Paβ line (1.282 μm) is an indication of accretion onto a protoplanet, and its intensity is much higher than that of blackbody radiation from the protoplanet. We focused on the Paβ line and performed Keck/OSIRIS spectroscopic observations. Although spectral differential imaging (SDI) reduction detected no accretion signatures, the results of the present study allowed us to set 5σ detection limits for Paβ emission of $5.8 \times 10^{-18}$ and $1.5 \times 10^{-18}$ erg$^{-1}$ s$^{-1}$ cm$^{-2}$ at 0".4 and 1"6, respectively. We considered the mass of potential planets using theoretical simulations of circumplanetary disks and hydrogen emission. The resulting masses were 1.45 ± 0.04 $M_J$ and 2.29$^{+0.03}_{-0.04}$ $M_J$ at 25 and 95 au, respectively, which agree with the detection limits obtained from previous broadband imaging. The detection limits should allow for the identification of protoplanets as small as ~1 $M_J$, which may assist in direct imaging searches around faint YSOs for which extreme adaptive optics instruments are unavailable.

Key words: infrared: planetary systems – planet–disk interactions – planetary systems – protoplanetary disks

1. Introduction

Young stellar objects (YSOs) often have protoplanetary disks in which planets are formed. If a protoplanet exists, it should be apparent by the effect it has on the disk. YSOs with protoplanetary disks have infrared (IR) excesses in their spectral energy distribution (SED). Some show far-infrared (FIR) excesses but little excess in the mid-infrared (MIR) region. Objects with such characteristic SEDs are called “transitional disks,” and may suggest inner gaps in the disk and ongoing planet formation (Marsh & Mahoney 1992, 1993). Protoplanetary disks with intriguing features, such as spiral arms, multiple rings, and large gaps, have been discovered based on IR and millimeter/sub-millimeter wavelength studies (e.g., Andrews et al. 2011; Hashimoto et al. 2011, 2012; Mayama et al. 2012; Muto et al. 2012; ALMA Partnership et al. 2015). Theoretical calculations can estimate the characteristics of potential protoplanets based on the derived parameters for these disks (Dong et al. 2015). Adaptive optics (AO)-based observations have detected substellar-mass companion candidates (e.g., HD 169142 and LkCa 15; Reggiani et al. 2014; Sallum et al. 2015) within gaps in protoplanetary disks. Compared to the number of gapped or asymmetric disk discoveries, however, few companion candidates have been detected around YSOs, which may be due to the contrast being too low to detect faint objects at small separations. The typical detection limits for previous YSO surveys are given in Uyama et al. (2017).

Extreme AO (ExAO) observations, such as VLT/SPHERE (Beuzit et al. 2006), Gemini/GPI (Macintosh et al. 2006), and Subaru/SCExAO (Guyon et al. 2010), enable us to overcome the difficulty due to low contrast. However, these instruments are limited to observations of brighter target ($R \leq 11-12$ mag) YSOs.

Here, we focus on the use of classical AO techniques to detect accretion signatures of protoplanets based on their hydrogen emission spectra. In the process of planet formation, accretion shocks excite the surrounding hydrogen. When the excited hydrogen returns to a lower energy state, emission lines such as Hα are produced (Calvet & Gullbring 1998). The intensity of hydrogen emission lines is much higher than that of blackbody radiation from the protoplanet (e.g., Bowler et al. 2014; Zhou et al. 2014). For an isolated stellar-mass object case, hydrogen emission is produced in shock-heated gas from the circumstellar disk to the stellar surface, whereas gas accretion onto a planetary-mass companion leads to another strong shock structure associated with flow from the circumstellar disk to the circumplanetary disk (e.g., Tanigawa et al. 2012). Considering this circumplanetary mechanism, the luminosity associated with hydrogen emission in the circumplanetary disk can be estimated as a function of the planetary mass and the gas density in the circumstellar disk (Y. Aoyama et al. 2017, in preparation).

In order to explore potential line emission from accreting protoplanets, we first observed TW Hya, one of the nearest YSOs. The stellar parameters for this YSO are listed in Table 1. The SED for TW Hya indicates a transitional disk with active accretion (Calvet et al. 2002; Goto et al. 2012; Menu et al. 2014). Various observations have led to the conclusion that its disk contains multiple gaps and that the most likely locations for ongoing planet formation are at 0".4 and 1"6, where the disk’s surface and midplane have dents (Debes et al. 2013; Menu et al. 2014; Akiyama et al. 2015; Tsukagoshi et al. 2016; van Boekel et al. 2016). There have been no reports of companion candidates (e.g., van Boekel et al. 2016).

Section 2 describes the observations and results. In Section 3, we set detection limits for low-mass objects. This work mainly focuses on accretion signatures based on the emission line...
intensity. Conventionally, emission line intensity is converted into accretion luminosity. However, if there is only one observable, there is a degeneracy between mass and mass accretion rate. Therefore, we present an additional method for interpreting the obtained data and evaluating the mass of protoplanets. Finally, we summarize the results of this study in Section 4.

2. Observations and Results

2.1. Keck/OSIRIS

We performed Keck/OSIRIS observations in the Jn2-band (1.228–1.289 μm) with a 0"/0.35 plate scale, which corresponds to a 1".47 × 2".24 field of view (FOV) and a spectral resolution of R ~ 3800. Paβ (1.282 μm) and Brγ (2.166 μm) lines are available for OSIRIS. The AO performance at Brγ is better than that at Paβ (van Dam et al. 2004), while expected line intensity of Brγ is much smaller than that of Paβ. We compared the feasibility of detecting these lines with OSIRIS and finally selected a more favorable case of the Paβ line to search for accretion signatures. We set four FOVs around the central star to provide sufficient exposure time to avoid saturation of the stellar point-spread function (PSF), to perform a deep imaging survey. A schematic of the observation region is shown in Figure 1. We separated the FOVs 0"/25 from the central star and explored the disk from ~20 au to ~100 au.

The observation was conducted on 2016 April 27. The exposure time for each FOV was 15 minutes × 3 and the total observation time was 180 minutes. We also observed unsaturated frames of the central star for telluric correction, photometric standard, and PSF reference. We note that the OSIRIS enables to use the unsaturated frames as calibration references, regardless of their variability. Details are described in the following paragraph.

After the first reduction using the OSIRIS pipeline, which corrects dark flat distortion, wavelengths solution, and cosmic rays, we removed telluric contributions from the data cube. In the telluric correction process, the pipeline usually removes hydrogen, which means Paβ in our data cube is not affected by telluric correction. To achieve high contrast, we used a spectral differential imaging technique (SDI; Smith 1987). We selected seven channels around the Paβ wavelength as a science channel with a width of 1.05 nm and other 24 channels between 1.278 and 1.285 μm as continuum (reference) channels. We avoided the OH airglow region (Maihara et al. 1993) when selecting reference channels. The airglow sky lines remain in the data cube because they are used for wavelength references in the pipeline. We made reference PSFs for each FOV using linear combinations of the reference frames based on Equations (2)–(4) in Artigau et al. (2008) to determine the coefficients of the reference images. In this process, we divided the FOV into 12 annular regions in a similar manner to the locally optimized combination of images method (Lafrenière et al. 2007).

Following SDI data reduction, no point sources were detected in any of the FOVs. Figure 2 shows the Paβ image that was produced by combining the seven channels of the science frames, and Figure 3 shows the final SDI-reduced image for the first FOV. In the Paβ image, because of low AO performance, a stellar halo is evident near the central star where there is expected to be remnants of subtraction in the SDI-reduced image due to Poisson noise. We then normalized all of

![Figure 1. FOV arrangement for observations. Each rectangle represents a separate FOV. The red circle indicates the central star. The vertical and horizontal axes represent the angular distance from the central star. These settings avoid the central star together with an inner square of 0"/5 × 0"/5, which allows sufficient exposure time without saturation.](image1)

![Figure 2. Paβ image of the first FOV. The image is aligned with that in Figure 1. The black square near the upper-right vertex is a badpixel cluster.](image2)
to distinguish between the mass and mass accretion rate. Section 3.2 proposes a new method for interpreting the detection limit by considering circumplanetary disk mechanisms. We focus on the two notable gaps at 0\'04 and 1\'6. We assume that these locations represent ∼25 au and ∼95 au using the distance data (59 ± 1 pc) published by Gaia Collaboration et al. (2016), whereas previous studies have assumed that the gaps are at ∼20 au and ∼80 au based on data published by van Leeuwen (2007). We assume that extinction of the Paβ line by the circumstellar disk is negligible. TW Hya’s disk is almost face-on (Qi et al. 2004, 2008). The vertical direction from the Jovian-mass protoplanet can be estimated locally clear for Paβ (Tanigawa et al. 2012; Y. Aoyama et al. 2017, in preparation).

3.1. Using the Empirical Relationship

The Paβ luminosity of YSOs has been reported to have an empirical correlation with the accretion luminosity (Natta et al. 2004, 2006) for objects down to ∼10 $M_J$ (e.g., GSC 06214−00210 b and FW Tau b; Bowler et al. 2011, 2014). The relationship is given by

$$\log \left( \frac{L_{\text{acc}}}{L_\odot} \right) = 1.36 \times \log \left( \frac{L_{\text{Pa}\beta}}{L_\odot} \right) + 4,$$

(1)

where $L_{\text{acc}}$ is the accretion luminosity and $L_{\text{Pa}\beta}$ is the Paβ luminosity. In this discussion, we assume that the empirical relationship is valid for objects as small as ∼1 $M_J$.

As we did not detect any accretion signals, constraining the mass of planets requires other assumptions for the accretion rate and radius. We assume an excess radius and modest accretion rate because the accretion luminosity ($L_{\text{acc}} = GMM/R$, where $R$, $M$, and $M$ are the radius, mass, and accretion rate, respectively) increases in proportion to the accretion rate and in inverse proportion to the radius. We define an upper limit of $R_p = 10 R_J$, Ayliffe & Bate (2009) and Szulágyi et al. (2016) suggested with nominal simulations that an object with $R_p = 10 R_J$ has a peak temperature of ∼10^4 K, which causes spectral emission from hydrogen. The accretion rate for TW Hya is 9.0 × 10^{-10} M_\odot/yr, which causes spectral emission from hydrogen. The accretion rate for TW Hya is 9.0 × 10^{-10} M_\odot/yr (Dupree et al. 2012). Considering ongoing planet formation, the accretion rate for protoplanets should be close to that for the star (Tanigawa & Tanaka 2016). We define a lower limit of $M_p = 10^{-11} M_J$ yr^{-1}, which is smaller than the theoretical accretion rate of $M_p \sim 10^{-10} M_J$ yr^{-1} for a $M_p \sim 1 M_J$ object (Lissauer et al. 2009). With these assumptions and the stellar parameters in Table 1, the calculation results give 5σ detection limits of 1.1 × 10^{-2} and 1.7 × 10^{-3} M_\odot at each gap. We do not think that these values can really constrain the mass of the protoplanets. The detection limits are calculated by extrapolation of Equation (1) and thus less than the lower limit of the relationship in Natta et al. (2004). These values correspond to an Earth-mass object, which should have, qualitatively, a mass too low to accrete hydrogen and to emit Paβ. Therefore, the mass of possible protoplanets is not actually constrained if we use Equation (1) with only Paβ detection limits.

3.2. Based on a Recent Theoretical Study

A recent study of one-dimensional shock dynamics with detailed radiative transfer, including line emissions and chemical reactions, has yielded values for the Paβ flux, as a result of integrating the flux over a circumplanetary disk. Assuming the circumstellar disk structure, total Paβ

Figure 3. SDI-reduced image of the first FOV. The alignment is the same as in Figure 2.
luminosity from the circumplanetary disk can also be estimated (Y. Aoyama et al. 2017, in preparation).

Assuming a sufficiently strong shock, the gas velocity, density, and composition govern post-shock characteristics such as the energy of hydrogen emission lines (e.g., Landau & Lifshitz 1959). Gas accretion in a circumstellar disk is governed by viscous dissipation with turbulence (e.g., Alexander & Armitage 2006). On the other hand, gas transfer from the gravity field of a star to that of a planet is driven by shock (Tanigawa & Watanabe 2002). Hydrodynamic simulations show that a protoplanet actively grows by capturing the circumstellar disk gas (e.g., D’Angelo et al. 2003; Ayliffe & Bate 2009). The accreting gas moving toward the planet forms shock surfaces at the top of the circumplanetary disk (Tanigawa et al. 2012; Szulagyi et al. 2014). In the thin layer of the post-shock region, the gas can be very dense (10^7 cm^-3), which gives rise to hydrogen emission lines due to electron transitions (Szulagyi & Mordasini 2017). We can convert the accretion rate to the number density of the circumstellar disk with these assumptions, and thus the line luminosity can be written as a function of the planetary mass and the gas density in the circumstellar disk (Y. Aoyama et al. 2017, in preparation). By performing this simulation using a disk model and a formula for TW Hya (Gorti et al. 2011), we can estimate the luminosity of a possible protoplanet down to 0.5 M_J. Note that the planetary radius and gas viscosity, which would be important factors for determining the line luminosity in the traditional models, hardly affect the luminosity in our shock model. Detailed concepts of the simulations are explained in the Appendix.

We found that the luminosity of the circumplanetary disk around a 1 M_J planet at 25 au from the central star can be as high as 4.1^{+0.6}_{-0.4} \times 10^{23} \text{ erg}, which corresponds to 9 \pm 1 \times 10^{−19} \text{ erg cm}^{-2}. Considering the detection limits (5.8 \times 10^{−18} \text{ erg cm}^{-2} at 25 \text{ au}, 1.5 \times 10^{−18} \text{ erg cm}^{-2}), the upper limit for the observation is 1.45 \pm 0.04 \ M_J at 25 \text{ au} for an actively growing protoplanet, and 2.29^{+0.03}_{-0.04} \ M_J at 95 \text{ au}. Although the detection limit for the inner gap is larger than that for the outer gap, the simulations can constrain the mass of a potential planet more strictly in the inner region because the gas density decreases with increasing radial distance from the central star.

3.3. Comparison with Previous Imaging Studies

The present study was based on a search for signatures of accretion by protoplanets, whereas previous studies have explored protoplanets themselves or disk structures indicative of planet formation. Direct imaging observations combined with classical AO instruments gave typical \pm 5\sigma detection limits of \sim 16 \ M_J and \sim 3 \ M_J at 0''4 and 1''6 (Subaru/HiCIAO; Uyama et al. 2017). L''-band observation with Keck/NIRC2, whose AO performance can be close to those of ExAO instruments, achieved 1−2.5 \ M_J (Ruane et al. 2017). We also compared the detection limits of VLT/SPHERE observation (van Boekel et al. 2016) to evolutionary models of low-mass objects (e.g., COND03 model, BT-Settl model; Baraffe et al. 2003; Allard et al. 2011), which suggests that potential planets are expected to be smaller than 0.5 \ M_J in each gap. Despite uncertainties due to the assumptions made in the present study, the derived mass is comparable to that obtained from angular differential imaging (ADI; Marois et al. 2006) studies. Our observations show that classical AO instruments combined with SDI can feasibly set constraints on the mass of potential planets up to \sim 1 \ M_J around faint YSOs, for which ExAO instruments cannot be used. Although we assumed zero extinction from the circumstellar disk in our study, we note that direct imaging studies have not overcome an issue of this extinction, which means we allow the uncertainty of the extinction from the circumstellar disk.

Disk observations, using both the Atacama Large Millimeter/ sub-millimeter Array (ALMA) and polarization differential imaging (PDI) with AO instruments, together with simulation results, showed that ongoing planet formation can carve gaps in the disk. The predicted mass of a potential planet in the TW Hya gaps is 0.03−0.5 \ M_J (e.g., Akiyama et al. 2015; Dong & Fung 2017; Teague et al. 2017). We note that our discussions assume that the circumplanetary disk is around an object more massive than 0.5 \ M_J, and so our discussions are independent from disk morphology. The simulation results in Section 3.2 are based on the number density of hydrogen atoms in the disk determined by radio wavelength observations, and are independent of the disk morphology.

Our estimated detection limits agree with the results of previous exoplanet and disk explorations in TW Hya, which suggests that protoplanets, if at all present, are so small that hydrogen emission spectra are not produced.

4. Summary

Previous direct imaging explorations of YSOs have focused on thermal emission from exoplanets themselves. We focus on emission signatures of accretion by protoplanets within the circumstellar disk, which are expected to be more luminous than blackbody radiation associated with an exoplanet.

We used Keck/OSIRIS to observe TW Hya, one of the most well known YSOs, which has a multi-gapped disk, in order to explore Paβ emissions. Using several FOVs, we developed an unconventional method for avoiding saturation while still allowing for a sufficient exposure time. Although no signals associated with accretion were identified, Paβ detection limits of 5.8 \times 10^{−18} and 1.5 \times 10^{−18} \text{ erg s}^{-1} \text{ cm}^{-2} at 0''4 and 1''6 were determined, thus providing the first constraints on the mass of potential protoplanets. We estimated the mass of protoplanets using both an empirical relationship and a disk simulation, each based on different assumptions. The first method is conventional and is based on the empirical relationship between the accretion luminosity and the Paβ flux, and cannot separately determine the mass and the mass accretion rate. The simulation assumes an active circumplanetary disk and thus avoids this problem. Based on the results, we determined detection limits for protoplanetary mass of 1.45 \pm 0.04 \ M_J and 2.29^{+0.03}_{-0.04} \ M_J for the gaps at 25 and 95 au, respectively, in the TW Hya disk. These limits agree with the results of previous exoplanet explorations, though modeling of disk observations points to significantly lower upper limits of the order of 0.1 \ M_J. The latest ExAO instruments have a magnitude limit of R \leq 12, but many YSOs are fainter than this. Our results indicate that searching for very young exoplanets with classical AO instruments can be an option.

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Table 2
Adopted Model Parameters of TW Hya

| Parameters                     | Value |
|-------------------------------|-------|
| Pre-shock gas temperature (K) | 100   |
| Pre-shock gas density (g cm⁻³) | ρ_CSD (a) |
| Planet Radius (Rₚ)             | 2     |
| Dust/gas ratio                | 0.0   |
| Magnetic field (G)            | 0.0   |
| Metal line optical depth (cm⁻¹) | 0.0 |

Note, ρ_CSD is the gas density of circumstellar disk where a is the planet’s semimajor axis.

Hydrogen lines are strongly emitted when the pre-shock velocity v₀ ≥ 30 km s⁻¹. In a slower case, post-shock hydrogen cannot be excited enough to emit the strong hydrogen lines. This lower limit of the velocity corresponds to the free fall velocity on the planet surface of ~0.5 Mₒ. The planet radius affects the surface integral of 1D numerical simulation results especially near the lower limit mass (Y. Aoyama et al. 2017, in preparation). However, this hardly affects the hydrogen-line luminosity, because the outer region in the circumplanetary disk (with a larger area) contributes more to the luminosity than does the planet surface or inner region in the circumplanetary disk (with a smaller area).

We also assume dust, magnetic field, and metal line cooling are negligible in the hydrogen-line emitting region around protoplanets. Because the dust settling to midplane and the gas accreting near the planet originate from high altitudes of the circumstellar disk, hydrogen-line-emitting gas flow hardly contains dust. When the pre-shock gas is ionized, the magnetic field changes the shock structure and lowers the post-shock temperature (e.g., Draine 1980). In the post-shock region, magnetic pressure can affect the post-shock structure (Hollenbach & McKee 1979). When the optical depth of the hydrogen lines becomes thick enough not to cool the gas effectively, the metal line cooling becomes important (Hollenbach & McKee 1989).

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Appendix
Theoretical Simulation of Hydrogen Emissions within the Circumstellar Disk

Model parameters for mass constraint are listed in Table 2. We assume that the gas temperature before the shock surface is 100 K. Before the strong shock, the gas temperature depends on the primary star emission and bow shock, which hardly makes the gas thermal energy larger than the shock energy of the strong shock (e.g., Tanigawa et al. 2012). However, this parameter hardly affects structures of flow and radiation field after the shock unless it becomes over thousands of K, because shock energy is at least ~3 × 10⁸ K in hydrogen-line-emitting region (Y. Aoyama et al. 2017, in preparation).

The gas density of the pre-shock region is assumed to be the same as that of the circumstellar disk, based on the 3D hydrodynamic simulation of Tanigawa et al. (2012). Planet disturbance on a global disk structure, e.g., global gap structure, is not included.

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