MULTI-EPOCH DETECTIONS OF WATER ICE ABSORPTION IN EDGE-ON DISKS AROUND HERBIG Ae STARS: PDS 144N AND PDS 453

HIROSHI TERADA and ALAN T. TOKUNAGA

1 Thirty-Meter Telescope Project, National Astronomical Observatory of Japan, 100 West Walnut, Suite 300, Pasadena, CA 91124, USA
2 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822, USA

Received 2016 March 30; revised 2016 November 26; accepted 2016 November 28; published 2017 January 9

ABSTRACT

We report the multi-epoch detections of water ice in 2.8–4.2 μm spectra of two Herbig Ae stars, PDS 144N (A2 IVe) and PDS 453 (F2 Ve), which have an edge-on circumstellar disk. The detected water ice absorption is found to originate from their protoplanetary disks. The spectra show a relatively shallow absorption of water ice of around 3.1 μm for both objects. The optical depths of the water ice absorption are ~0.1 and ~0.2 for PDS 144N and PDS 453, respectively. Compared to the water ice previously detected in low-mass young stellar objects with an edge-on disk with a similar inclination angle, these optical depths are significantly lower. It suggests that stronger UV radiation from the central stars effectively decreases the water ice abundance around the Herbig Ae stars through photodesorption. The water ice absorption in PDS 453 shows a possible variation of the feature among the six observing epochs. This variation could be due to a change of absorption materials passing through our line of sight to the central star. The overall profile of the water ice absorption in PDS 453 is quite similar to the absorption previously reported in the edge-on disk object d216-0939, and this unique profile may be seen only at a high inclination angle in the range of 76°–80°.

Key words: dust, extinction – evolution – infrared: ISM – protoplanetary disks – stars: individual (PDS 144N, PDS 453)

1. INTRODUCTION

Water is a crucial constituent for the formation of life; therefore, the way that water is delivered to a protoplanet is of great interest. Water ice from the natal cloud is thought to accrete onto a protoplanetary core forming icy planetesimals and comets as a possible carrier for water delivery. While the evolution of water ice in protoplanetary environments is important, astronomical detections for water ice in the protoplanetary disks are still too limited to develop a uniform view of water ice evolution in the disks (Pontoppidan et al. 2005; Terada et al. 2007; Honda et al. 2009, 2016; Terada & Tokunaga 2012a; Terada et al. 2012b).

Edge-on disks are suitable for investigating protoplanetary disks because the disk geometry is well defined, with the central star occulted by the circumstellar disk. Recent subarcsecond resolution imaging with Hubble Space Telescope and ground-based adaptive optics (AO) facilities enables us to spatially resolve disk formation sites, and the number of objects associated with circumstellar disk morphology has been increasing. Perrin et al. (2006) discovered an edge-on disk around an intermediate-mass yellow stellar object (YSO), the Herbig Ae star PDS 144N. The disk around PDS 144N exhibits an almost perfect edge-on morphology, and its inclination angle is estimated to be 83° (Perrin et al. 2006). PDS 144N has a widely separated companion object, PDS 144S, which is also a Herbig Ae star (Hornbeck et al. 2012). PDS 453 is another Herbig Ae object showing an edge-on disk morphology with a lesser inclination angle of 79° (Perrin et al. 2010). These two edge-on disks are unique objects to investigate protoplanetary disks around higher-mass YSOs since most of the detected edge-on disks are around low-mass YSOs.

Water ice shows a strong absorption at 3 μm with rich features to provide information about its grain size, crystallinity, and mixtures with other ices (Boogert et al. 2015).

Ground-based spectroscopy at 2.8–4.2 μm is a powerful tool to reveal water ice in protoplanetary disks. In particular, wavefront correction at μm is relatively easy, and AO-assisted spectroscopy is very beneficial not only for high spatial observation but also for obtaining stable and reliable spectra. In this wavelength region, the thermal emission from the ambient background is still acceptably low, which allows a high signal-to-noise ratio (S/N).

In Section 2, methods for observations and data analysis are described. Section 3 shows the results of the μm water ice absorption features for PDS 144N, PDS 144S, and PDS 453. Characteristics of the detected water ice absorption profile are discussed in Section 4, including its possible variability in time and similarity to the profile of the edge-on disk object d216-0939. The conclusion is summarized in Section 5.

2. OBSERVATION AND DATA REDUCTION

All the observations were performed using the Infrared Camera and Spectrograph (IRCS; Tokunaga et al. 1998; Kobayashi et al. 2000) mounted on the Nasmyth platform of the Subaru Telescope. The Subaru AO system (AO188; Hayano et al. 2010) was utilized only for the observations of PDS 453. The object itself served as a wavefront correction reference, since it is relatively bright in the optical (R ∼ 12.5). Imaging of PDS 453 at K′(λ = 2.12 μm) and L′(λ = 3.77 μm) was conducted with the 20 mas camera of the IRCS on a single epoch of 2009 June 3, and spectroscopy at 2.8–4.2 μm was carried out in two and six epochs from 2006 to 2014 for PDS 144N and PDS 453, respectively. The airmass mismatch between the spectroscopy of the object and the standard star was minimized to avoid any artificial features in the spectra due to a mismatch of the telluric absorption, and the resultant airmass difference was ∼0.01. In the second epoch of spectroscopy for PDS 144N, no standard star was observed, and PDS 144S acted as a spectral standard star for
the exact cancellation of the telluric absorption to obtain the PDS 144N spectrum. Sky conditions were excellent for all the observing epochs in terms of the sky extinction, seeing, and precipitable water level. The observation details are summarized in Table 1.

Five- and nine-point box-shaped dithering patterns were used for imaging of PDS 453 at $K^\prime$ and $L^\prime$ with a separation of 3", respectively. For spectroscopy of PDS 453, the slit was set with a position angle of 133° to align to the scattered light disk only for the first epoch observation on 2009 August 17. In the other observing epochs, the slit position angle was 0°. The slit position angle for PDS 144N was 119° in order to locate PDS 144S on the same slit. An A-BB-A nodding operation was performed for all the spectroscopy. Nodding separation for PDS 453 was 3" for the first epoch and 1"/5 for the other epochs. In case of PDS 144N, the nodding separations of 2"/5 and 3"/0 were chosen for the first and the second epochs respectively to avoid interference with PDS 144S, located with a separation of 5"/40. In the spectroscopy of PDS 144N under natural seeing conditions, the slit widths were selected to be 0"/6 (corresponding spectral resolving power, $R \sim 190$) in the first epoch and 0"/45 ($R \sim 260$) in the second epoch. For AO spectroscopy of PDS 453, the slit width was 0"/225 ($R \sim 510$) throughout all the epochs.

Data reduction was performed by IRAF software packages through a standard procedure that consists of flat fielding, sky subtraction, telluric correction, and wavelength calibration. HIP 79229 (A0V, $V = 6.64$ mag; Hog et al. 2000) was used with an assumption of $V - L^\prime = 0$ for a photometric estimate of PDS 453 at $L^\prime$. No $K^\prime$ photometric calibration was performed because the peak signal in the image of PDS 453 at $K^\prime$ was saturated. For spectroscopic reference, four A0 stars—HR 5197, HR 6061, HR 6354, and HR 6490—were observed for correction of the telluric absorption. The hydrogen absorption feature from the A0 stars was removed using the method of Vacca et al. (2003). The telluric absorption lines in the spectrum were used for the wavelength calibration.

3. RESULTS

We present the 2.8–4.2 μm spectra for two Herbig Ae stars (PDS 144N and PDS 453) with an edge-on morphology of the surrounding disks and extract the water ice absorption feature in the spectrum. For extraction of the feature, the continuum of the spectrum was estimated using a second-order polynomial fitting with wavelength regions of 2.875–2.89 μm and 3.7–4.0 μm. Since the water ice profile is known to continue in the wavelength region of <2.88 μm, it is noted that this continuum determination could cause an underestimate of the water ice absorption by ~25% at the peak.

3.1. PDS 144N

PDS 144N exhibits a clear edge-on morphology with a high spatial resolution imaging, while its binary companion, PDS 144S, shows no apparent disk structure (Perrin et al. 2006). Spectroscopies for PDS 144N and PDS 144S were simultaneously conducted with an appropriate position angle (119°) of the slit. The spectra of both objects are shown in Figure 1 for the first epoch (2006 February 07 UT) observation. The absolute flux is calibrated with $K^\prime$ and $L^\prime$ magnitudes derived by Perrin et al. (2006). The most prominent feature in the spectrum of PDS 144N is a polycyclic aromatic hydrocarbon (PAH) emission feature ranging from 3.2 to 3.6 μm, and the

---

**Table 1**

| Object      | Observing Date (UT) | Mode       | Exposure Time (s) | Spectral Resolution ($\lambda/\Delta\lambda$) | Average Airmass | Standard Star | ΔAirmass Obj.–Std. |
|-------------|---------------------|------------|-------------------|----------------------------------------------|-----------------|---------------|-------------------|
| PDS 144S & N | 2006 Feb 7          | L Spectroscopy | 1080             | 190                                          | 1.497           | HR 5197       | −0.025            |
| PDS 144N    | 2008 Feb 18         | L Spectroscopy | 840              | 260                                          | 1.470           | ...           | ...               |
| PDS 453     | 2009 Jun 3          | K' Imaging   | 75               | ...                                          | 1.495           | HIP 79229     | −0.007            |
|             | 2009 Aug 17         | L Spectroscopy | 480              | 510                                          | 1.467           | HR 6061       | +0.001            |
|             | 2011 Aug 14         | L Spectroscopy | 360              | 510                                          | 1.531           | HR 6490       | −0.010            |
|             | 2011 Aug 19         | L Spectroscopy | 480              | 510                                          | 1.572           | HR 6490       | −0.014            |
|             | 2012 Sep 17         | L Spectroscopy | 480              | 510                                          | 1.594           | HR 6354       | +0.0002           |
|             | 2014 Mar 20         | L Spectroscopy | 720              | 510                                          | 1.440           | HR 6490       | +0.008            |
|             | 2014 Mar 21         | L Spectroscopy | 720              | 510                                          | 1.439           | HR 6490       | −0.001            |

---

**Figure 1.** Spectra of PDS 144N and PDS 144S. The inset shows a spectrum of PDS 144N simply divided by PDS 144S, which is normalized at 4.1 μm. The estimated continuum is shown by the gray solid lines. While PDS 144S exhibits no absorption feature, a shallow absorption around 3.1 μm is seen in the spectrum of PDS 144N.
shallow water ice absorption feature is seen in the wavelength region of 2.9–3.2 μm. On the other hand, the spectrum of PDS 144S is featureless (τ_{ice} ≤ 0.002) and flat in this low-resolution spectrum except for the hydrogen recombination lines at 2.873, 3.039, 3.297, 3.741, and 4.052 μm, which means that PDS 144S can act as an atmospheric calibrator to obtain nearly perfect cancellation of the telluric absorption.

After extraction of the water ice absorption from the spectrum of PDS 144N in the first and second (2008 February 18 UT) epochs using PDS 144S for the telluric absorption cancellation, their optical depths are plotted in Figure 2. There is no significant change of the optical depth (τ_{ice} = 0.09 ± 0.01) and the wavelength of maximum optical depth (∼3.09 μm) in the two epochs.

3.2. PDS 453

Figure 3 shows the AO images taken at K′ and L′. Aperture photometry is applied to the L′ image with a radius of 1′′5 to find L′ = 8.10 mag. The photometric error is ∼0.1 mag. After subtracting the object images from the normalized images of the nearby star (Two-Micron All Sky Survey [2MASS] J17205612-2603307), the residual images are displayed at the bottom panel. Scattered light disks around the object can be seen in the point-spread function (PSF) subtracted image at K′, which is consistent with the discovery result of Perrin et al. (2010). At L′, no significant structure is found in the PSF subtracted image. The normalization factor for L′ is determined taking into account its brightness at L′. For the K′ image, the factor is searched to obtain the best subtraction of a speckle pattern around the object. Since the nearby star is fainter than the object, the S/N of the PSF is limited by the nearby star.

The 2.8–4.2 μm spectra are presented in Figure 4 for six epochs from 2009 August 17 UT to 2014 March 21 UT, after being normalized for the observed L′ magnitude of 8.10. The slope of the continuum changes with time, and a shallow water ice absorption is clearly detected in all the spectra. In all the epochs, the water ice absorption has a depth of 0.19 ± 0.01 with a wide absorption band ranging from 3.10 to 3.23 μm.

Regarding the water ice profile, its normalized optical depth in the six epochs is presented in Figure 5. The normalization is applied to the averaged optical depth in the wavelength range of 3.15–3.18 μm, where it is almost free from the telluric absorption. While the overall profile is quite consistent throughout the six epochs, an apparent change of the water ice absorption profile can be seen at 3.20–3.25 μm. More specifically, data on 2009 August 17 UT and 2012 September 17 UT show deviations from the other spectra. This change of the water ice absorption profile is discussed in Section 4.

4. DISCUSSION

Physical parameters for PDS 144N, PDS 144S, and PDS 453 are summarized in Table 2. Although the distance to PDS 144N was originally suggested to be around 1000 pc (Perrin et al. 2006), more recent investigation favors the smaller value of 145 pc (Hornbeck et al. 2012). The distance to PDS 453 is more uncertain, but the value of 140 pc assumed by Perrin et al. (2010) is adopted here.

4.1. Location of Detected Water Ice

Water ice absorption toward young stellar objects is often attributed to foreground cloud materials residing in front of the targets, and that possibility is investigated here.

While PDS 144S shows no water ice absorption, its binary Herbig Ae star, PDS 144N, exhibits a shallow water ice absorption around 3.1 μm. Therefore, the detected water ice toward PDS 144N is confirmed to be localized around PDS 144N with a radius of less than 5′′40 (783 au) and is most likely attributed to the circumstellar protoplanetary disk of PDS 144N.

Regarding PDS 453, there is no bright nearby star around the object to use as a comparison. To see the surrounding environment around PDS 453 within 71′′4 × 71′′4 (corresponding to 10,000 au × 10,000 au), Figure 6 shows a two-color diagram using J, H, and Ks photometry from the 2MASS catalog. In this figure, PDS 453 is separated significantly in these J–H and H–Ks colors, and therefore the absorbing material is localized around PDS 453.

According to Hornbeck et al. (2012), the inclination angle of the circumstellar disk around PDS 144S is very high (73° ± 7°). However, no signature for the scattered light morphology of the disk is seen in the infrared image of PDS 144S, which implies a small inclination angle for the circumstellar disk. Terada et al. (2012b) found a threshold of the inclination angle of 65°–75° for protoplanetary disks that exhibit water ice absorption in low-mass YSOs in the Orion nebula cluster and M43 regions. Analogous to the result for low-mass YSOs, no detection of water ice absorption toward PDS 144S suggests a critical inclination angle of more than 73° for the detection of water ice absorption on the assumption that PDS 144S has an abundance of water ice in the circumstellar disk similar to that of PDS 144N and PDS 453. Figure 7 shows the optical depth of the water ice detected for PDS 144S, PDS 144N, and PDS 453 together with data from Terada et al. (2012b). Here, the critical inclination angle for showing the water ice absorption appears to be 73°–79° for the disks around the intermediate-mass YSOs.
4.2. Effect of UV Radiation from the Herbig Ae Stars on Water Ice in the Disks

Water ice in the circumstellar disk can be depleted through photodesorption by far-UV (FUV) radiation (e.g., Oka et al. 2012). Since FUV radiation from the central stars is supposed to be harsher in the Herbig Ae star system than in the low-mass YSO system, the water ice distribution especially at the disk surface could be completely different between these two systems.

Due to the high-quality spectra with an S/N of \( \geq 100 \), very shallow water ice absorption can be detected with \( \tau \sim 0.1 \) and 0.2 for PDS 144N and PDS 453, respectively. These values are significantly smaller compared with those of the low-mass YSOs associated with edge-on disks (\( \tau = 0.7-1.7 \)), HK Tau B, HV Tau C, and d216-0939 (Terada et al. 2007, 2012b). This can be qualitatively explained by the stronger photodesorption process.

In addition, photodesorption due to the stronger FUV radiation may be the primary cause of the possible larger critical angle (73°–79°) of the disk inclination for producing water ice absorption. The stronger FUV radiation pushes the snow line at the disk surface farther into the disk midplane, and as a result the opening angle of the ice region in the disk will be smaller.

4.3. Water Ice Absorption Profile and Similarity between PDS 453 and d216-0939

The strong PAH emission features seen in PDS 144N prevents an accurate evaluation for the entire absorption profile of the water ice. However, PAH emission features are typically exhibited from 3.2 to 3.6 \( \mu \)m (e.g., Tokunaga et al. 1991; van Diedenhoven et al. 2004; Tielens 2008), and we assume a negligible contribution of the PAH emission to the optical depth of the water ice at wavelengths of \( \leq 3.2 \mu \)m. The water ice profile of PDS 144N presented in Figure 2 shows a water ice absorption at a peak wavelength of \( \sim 3.08 \mu \)m, which is similar to that in the edge-on disks of the low-mass YSOs (Terada et al. 2007).

Regarding PDS 453, the overall profile of the detected water ice absorption exhibits an enhanced optical depth of around...
3.2 μm (see Figure 5). It resembles the features reported for the silhouette disk object d219-0939 in the M43 region (Terada & Tokunaga 2012a), in which the feature is interpreted as a large-particle-size (∼0.8 μm) crystallized water ice absorption. The same procedure for extracting the water ice feature was applied to the PDS 453 and d219-0939 data. The two optical depths are plotted in Figure 8 for the best-quality spectra of PDS 453 (2014 March 21 UT) and d216-0939 (center position on 2009 October 02 UT), with a normalization of around 3.15–3.18 μm. The figure clearly shows a very similar water ice absorption in these objects. This absorption feature is unique among the water ice absorption profiles detected so far in various kinds of astronomical targets (Boogert et al. 2015). Taking into account that both PDS 453 and d216-0939 have similar inclination angles of their disks of around 78° ± 2° with a line of sight to the disk surface (see Figure 7), this suggests that a unique phenomenon for grain growth and crystallization process occurs at the icy disk surface to produce this peculiar feature.

4.4. Possible Time Variability of Water Ice Absorption

As described in Section 3, the absorption profile of the water ice detected for PDS 453 at multiple epochs exhibits variability in the wavelength region of 3.2–3.25 μm, whereas the absorption feature of PDS 144N is found to be the same for the achieved S/N. In this wavelength region, strong telluric water vapor features exist, and there is a possibility that this apparent variability is due to inappropriate estimates of the telluric absorption.

Even given that difficulty in identification of the variation source, it is still very interesting here to note the large photometric variation (ΔV ∼ 1 mag) of PDS 453 in the optical found in the ASAS3 survey (Pojmansky 2002), which may suggest a variable extinction due to the absorbing material change in the sightline to the disk (Perrin et al. 2010). In fact, signals in the optical obtained by an avalanche photodiode
on the AO 188 system for wavefront sensing with PDS 453 show a variation through these observation epochs. In addition, a continuum slope change is seen in the 3\textmu{}m spectra. We define the L continuum slope index as $\alpha = (\log(I_{\lambda_1}) - \log(I_{\lambda_2}))/\log(\lambda_2) - \log(\lambda_1)$, where $\lambda_1 = 2.875$–$2.89$\textmu{}m and $\lambda_2 = 3.7$–$4.0$\textmu{}m, and the obtained APD counts and continuum index ($\alpha$) are plotted in Figure 9. As shown with a dashed circle, both the APD count and the $\alpha$ index are located in the lower-left area for the two epochs of 2009 August 17 UT and 2012 September 17 UT, in which the different feature of the water ice absorption profile is exhibited in the wavelength region of 3.20–3.25\textmu{}m. Although systematic errors are not taken into account for the APD count and the slope index, this correlation may imply the real change of the water ice absorption feature in PDS 453.

### Table 2

| Object | Spectral Type | Inclination Angle (°) | Disk Diameter (°) | Possible Association | Distance (pc) | References |
|--------|---------------|-----------------------|-------------------|----------------------|---------------|------------|
| PDS 144N | A2V | 83 ± 1 | 0.8 | Upper Scorpius | 145 ± 2 | Perrin et al. (2006); Hornbeck et al. (2012); Vieira et al. (2003) |
| PDS 144S | A5V | 73 ± 7 | 0.8 | Upper Scorpius | 145 ± 2 | Perrin et al. (2006); Hornbeck et al. (2012); Vieira et al. (2003) |
| PDS 453 | F2V | 79 ± 3 | 3.1 | Scorpius–Centaurus | 140 | Perrin et al. (2010) |

### Figure 7

Water ice optical depth as a function of the inclination angle of the disks. Black squares are for the edge-on disks around the Herbig Ae stars. Gray squares show optical depths of the water ice detected in the silhouette disks of the Orion nebula cluster and M43 taken from Figure 9 of Terada et al. (2012b). For clarity, data points for d121-1925 and d053-717 are not shown because the detection toward d121-1925 is attributed to foreground ice and d053-717 is suspected to be not in the silhouette disk. The shaded area corresponds to the critical inclination angle range suggested by Terada et al. (2012b) for disks around low-mass YSOs. In this figure, the critical inclination angle to show the water ice in the Herbig Ae disks is found to be 73°–79°, which is shown by the diagonal lines. The area in yellow shows a key inclination angle (76°–80°) to exhibit the wider water ice absorption in the protoplanetary disks shown in Figure 8 and discussed in Section 4.3.

### Figure 8

Comparison between the water ice absorption profiles of PDS 453 and d216-0939. The best-quality data are chosen among the multi-epoch data set. Both the profiles are nearly identical around the peak of the optical depth.

### 5. SUMMARY

We summarize the results of this study as follows.

1. Shallow 3\textmu{}m water ice absorption features of two Herbig Ae stars with edge-on disks, PDS 144N and PDS 453, are detected. The absorption originates from the protoplanetary disks.

2. No water ice absorption is detected toward PDS 144S, indicating that the critical inclination angle to show the water ice absorption is larger in Herbig Ae disks than in low-mass YSOs. The larger critical inclination angle and shallower water ice absorption could be due to the photodesorption of ice by the harsher FUV radiation from the Herbig Ae stars.

3. The unusual profile of the water ice absorption detected in PDS 453 is very similar to the water ice absorption found in d216-0939. The observations suggest that an inclination angle of 76°–80° is needed to show this feature, which is attributed to larger ice grains with high crystallinity.

4. Water ice absorption features detected in multi-epoch 2.8–4.2\textmu{}m spectra of PDS 453 show a possible variation correlated with the L continuum slope and optical brightness, which may be caused by variable absorption at the disk surface.
We thank the entire support staff at the Subaru Telescope for their efforts in keeping this very complicated facility operational—in particular, the instrument maintenance staff, whose efforts kept the instrument stable and allowed us to obtain reliable monitoring observations over a long period of time. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

**Facility:** Subaru (IRCS, AO 188).

### REFERENCES

Boogert, A. C. A., Gerakines, P. A., & Whittet, D. C. B. 2015, *ARA&A*, 53, 541

Hayano, Y., Takami, H., Oya, S., et al. 2010, *Proc. SPIE*, 7736, 21

Honda, M., Inoue, A. K., Fukagawa, M., et al. 2009, *ApJL*, 690, L110

Honda, M., Kudo, T., Takatsuki, S., et al. 2016, *ApJ*, 821, 2

Hornbeck, J. B., Grady, C. A., Perrin, M. D., et al. 2012, *ApJ*, 744, 54

Kobayashi, N., Tokunaga, A. T., Terada, H., et al. 2000, *Proc. SPIE*, 4008, 1056

Oka, A., Inoue, A. K., Nakamoto, T., et al. 2012, *ApJ*, 747, 138

Pojmansky, G. 2002, AcA, 52, 397

Perrin, M. D., Duchêne, G., Kalas, P., & Graham, J. R. 2006, *ApJ*, 645, 1272

Perrin, M. D., Schneider, G., Duchêne, G., et al. 2010, *BAAS*, 42, 346

Pontoppidan, K. M., Dullemond, C. P., van Dishoeck, E. F., et al. 2005, *ApJ*, 622, 463

Terada, H., & Tokunaga, A. T. 2012a, *ApJ*, 753, 19

Terada, H., Tokunaga, A. T., Kobayashi, N., et al. 2007, *ApJ*, 667, 303

Terada, H., Tokunaga, A., Pyo, T.-S., et al. 2012b, *AJ*, 144, 175

Tielens, A. G. G. M. 2008, *ARA&A*, 46, 289

Tokunaga, A. T., Sellgren, K., Smith, R. G., et al. 1991, *ApJ*, 380, 452

Tokunaga, A. T., Kobayashi, N., James, B., et al. 1998, *Proc. SPIE*, 3354, 512

Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, *PASP*, 115, 389

van Diedenhoven, B., Peters, E., van Kerckhoven, C., et al. 2004, *ApJ*, 611, 928

Vieira, S. L. A., Corradi, W. J. B., Alencar, S. H. P., et al. 2003, *AJ*, 126, 2971

---

**Figure 9.** APD counts of the AO 188 system vs. the $L$ continuum slope index of PDS 453 spectra.