ANIR : Atacama Near-Infrared Camera for the 1.0-m miniTAO Telescope

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Abstract

We have developed a near-infrared camera called ANIR (Atacama Near-InfraRed camera) for the University of Tokyo Atacama Observatory 1.0-m telescope (miniTAO) installed at the summit of Cerro Chajnantor (5,640 m above sea level) in northern Chile. The camera provides a field of view of 5′/1 × 5′/1 with a spatial resolution of 0′′/298 pixel⁻¹ in the wavelength range from 0.95 to 2.4 μm, using Offner relay optics and a PACE HAWAII-2 focal plane array. Taking advantage of the dry site, the camera is capable of hydrogen Paschen-α (Paα, λ = 1.8751 μm in air) narrow-band imaging observations, at which wavelength ground-based observations have been quite difficult due to deep atmospheric absorption mainly from water vapor. We have been successfully obtaining Paα images of Galactic objects and nearby galaxies since the first-light observation in 2009 with ANIR. The throughput at the narrow-band filters (N1875, N191) including the atmospheric absorption show larger dispersion (~10%) than those at broadband filters (a few percent), indicating that they are affected by temporal fluctuations in Precipitable Water Vapor (PWV) above the site. We evaluate the PWV content via the atmospheric transmittance at the narrow-band filters, and derive the median and the dispersion of the distribution of the PWV of 0.40 ± 0.30 and 0.37 ± 0.21 mm for the N1875 and N191 data, respectively, which are remarkably smaller (49 ± 38% for N1875 and 59 ± 26% for N191) than radiometry measurements at the base of Cerro Chajnantor (an altitude of 5,100 m). The decrease in PWV can be explained by the altitude of the site when we assume that the vertical distribution of the water vapor is approximated at an exponential profile with scale height within 0.3–1.9 km (previously observed values at night). We thus conclude that miniTAO/ANIR at the summit of Cerro Chajnantor indeed provides us an excellent capability for a ground-based Paα observation.

Key words: site testing — infrared: Paschen-α — infrared: general — instrumentation: detectors

1. Introduction

1.1. Paα emission as a tool for Unveiling the Dust-obscured Universe

To explore the formation and the evolution of the present-day “normal” galaxies like our Galaxy, it is important to characterize where and how star formation occurs in a galaxy. In the local universe, it is well known that star formation rate (SFR) correlates with dust opacity (Takeuchi et al. 2010; Bothwell et al. 2011), where intensely star-forming regions and galaxies are obscured by a huge amount of dust, and become optically thick (Alonso-Herrero et al. 2006; Piqueras...
Therefore, the UV continuum emission and hydrogen recombination lines in the optical ranges such as Hα at 0.6563 µm and Hβ at 0.4861 µm emitted from those dusty star-forming regions are easily attenuated, and then it would be complicated to correctly understand the distribution of star-forming regions in the whole galaxy, especially when the galaxy has a patchy distribution of dust (García-Marín et al. 2006). On the other hand, Paschen-α (Paα) at 1.8751 µm (in air; 1.8756 µm in vacuum), the strongest emission line in the near-infrared (NIR, λ ∼ 0.8–2.5 µm) wavelength range, is less affected by dust thanks to its longer wavelength than the optical lines (Kennicutt 1998), and becomes a powerful and direct indicator of SFR, especially in dusty regions. In particular, the observed Paα emission becomes stronger than Hα at E(B − V) > 1.2 (A_V > 3.7) and than Brγ at E(B − V) < 28.0 (A_V < 86.2) with an assumption of a Milky-Way-like extinction curve and A_V/E(B − V) = 3.08 (Pei 1992), while the intrinsic Paα luminosity is 0.12 of Hα, 2.14 of Paβ (1.2818 µm in air), and 12.4 of Brγ (2.1655 µm in air) for Case B recombination with an electron temperature of 10^4 K and density of 10^4 cm^−3 (Osterbrock 1989).

However, Paα observations from the ground have been quite difficult so far due to deep atmospheric absorption features around their wavelength, mostly caused by water vapor, and hence most Paα observational studies have been limited to those by Near Infrared Camera and Multi-Object Spectrometer (NICMOS, Thompson et al. 1998) on board the Hubble Space Telescope (HST). For example, Alonso-Herrero et al. (2006b) use the NICMOS Paα narrow-band (F187N and F190N) imaging data to study star formation properties of dusty star-forming galaxies in the local universe with a high spatial resolution, and find the compact distributions of Paα emission along various galaxy structures such as nucleus and spiral arm. They also establish a linear empirical relation between Paα and 24 µm luminosity as well as the total infrared luminosity as an indicator of SFR for those galaxies. In addition, a wide-field Paα imaging survey of the Galactic Center (Wang et al. 2010; Dong et al. 2011) produces a high spatial-resolution map of stars and an ionized diffuse gas with a possible new class of massive stars not associated with any known star clusters. Recently, a NIR camera and spectrograph, FLITECAM (MClean et al. 2012), for NASA’s Stratospheric Observatory for Infrared Astronomy (SOFIA) has been developed, and will support Paα imaging observations with two narrow-band filters centered at 1.875 and 1.900 µm.

As described above, Paα observations are quite useful for a variety of targets obscured by dust and can provide a new insight into those studies, yet the amount of observing time and facilities available for that purpose are still very limited. Therefore, we have developed a new instrument at an appropriate astronomical site for ground-based Paα observations.

### Table 1. Specification of the ANIR NIR Unit.

| Wavelength | 0.95–2.4 µm |
| Detector | PACE HAWAII-2 |
| Pixel format | 1024 × 1024* |
| Pixel pitch | 18.5 µm |
| Field of view | 5.1 × 5.1 |
| Pixel scale | 0′/298 pixel−1 |
| Broad-band filters | Y, J, H, Ks |
| Narrow-band filters | N128, N1785, N191, N207 |

* The actual format size of HAWAII-2 FPA is 2048 × 2048 pixels, of which we use only 1024 × 1024 pixels.
† The J, H, and Ks filters are those of Mauna Kea Observatories (MKO) infrared filter set (Simons & Tokunaga 2002; Tokunaga et al. 2002).

1.2. ANIR: Ground-based Paα Imager for the miniTAO 1.0-m Telescope

The University of Tokyo Atacama Observatory (TAO, Yoshii et al. 2010) 1.0-m telescope, called miniTAO, is an optical/infrared telescope installed in 2009, located at the summit of Cerro Chajnantor (an altitude of 5,640 m or 18,500 ft above sea level) in northern Chile as the world’s highest astronomical observatory (Sako et al. 2008a; Minezaki et al. 2010). The site was expected to be very dry from satellite data reported by Erasmus & Sarazin (2002) (precipitable water vapor, PWV, of 0.5 mm at 25th percentile) and from radiosonde measurements by Giovanelli et al. (2001b) (0.5 mm at a median above an altitude of 5,750 m). Figure 1 shows a comparison of simulated atmospheric transmittances between the TAO site and the thesis.
other sites at lower altitudes, in which there are remarkable improvements of the transmittance at gaps between conventional broad atmospheric windows, especially around 1.9 \( \mu \)m, i.e., Pa\( \alpha \) wavelength.

The Atacama NIR camera (ANIR)\(^1\) is one of the instruments for the Cassegrain focus of the miniTAO telescope. It is capable of wide-field Pa\( \alpha \) narrow-band (NB) imaging observations as well as ordinary broad-band imaging one. It also has a capability of optical imaging and slitless spectroscopic observations simultaneously with the NIR imaging using a retractable dichroic mirror. We have achieved first-light observations using NB filters targeted on the Pa\( \alpha \) emission line (Figure 4) in 2009, and now ANIR is in operation mainly for Pa\( \alpha \) observations of the Galactic center/plane and nearby starburst galaxies in order to understand the star formation activities hidden in thick dust clouds (e.g., Tateuchi et al. 2012b; Komugi et al. 2012).

\(^1\) ANIR web site: http://www.ioa.s.u-tokyo.ac.jp/kibans/anir/en/

In this paper, we describe the overall design of ANIR in Section 2, its performance evaluated through laboratory tests and actual observations at the TAO site in Section 3, and a site evaluation through the Pa\( \alpha \) imaging data in Section 4. We refer the reader to Tateuchi et al. (2012a) and Tateuchi et al. (2014) for a detailed description of data reduction processes and quantitative analysis of Pa\( \alpha \) data.

2. Instrument

2.1. Near-infrared Imager Unit

Here we describe the design of the NIR unit providing broadband and NB imaging functions in the NIR. A hardware design of the optical unit is described in Section 2.2.

2.1.1. Overview

Figure 2 shows a cross-sectional view of ANIR, and a block diagram of the hardware is shown in Figure 3. The specifications of the NIR unit are summarized in Table 1. The unit
covers a field of view (FoV) of $5'1 \times 5'1$ with a spatial resolution of 0''298 pixel$^{-1}$ using an engineering grade Producible Alternative to CdTe for Epitaxy (PACE) HAWAII-2 array detector, which is a 2048 $\times$ 2048 pixel HgCdTe NIR focal plane array (FPA) manufactured by Teledyne Scientific & Imaging LLC. Note that only a single quadrant with 1024 $\times$ 1024 pixels is used. The filter set consists of four standard broad-band filters ($Y$, $J$, $H$, and $K_s$) and four NB filters ($N_{128}$, $N_{187}$, $N_{191}$, and $N_{207}$) as listed in Table 2. The $N_{187}$ filter has a central wavelength of $\lambda_c = 1.8759 \mu$m and a bandwidth of $\Delta \lambda = 0.0079 \mu$m, which covers the Pa$\alpha$ ($\lambda = 1.8751 \mu$m) with radial velocities within $-580$ to $+680$ km s$^{-1}$. On the other hand, the $N_{191}$ filter ($\lambda_c = 1.911 \mu$m, $\Delta \lambda = 0.033 \mu$m) corresponds to redshifted Pa$\alpha$ lines with recession velocities of $cz \sim 2900$–$8200$ km s$^{-1}$. The $N_{191}$ filter is also used for taking off-band (continuum) data for the $N_{187}$ data, and vice versa.

Figure 4 shows details of the atmospheric transmittances shown in the top panel of Figure 1 at the wavelength range of interest for the Pa$\alpha$ NB filters. While there are absorption features mostly by water vapor even at the altitude of 5,640 m, several windows with a high transmittance exist. The average atmospheric transmittances at the PWV of 0.5 mm are approximately 0.48 and 0.64 within the bandpasses of the $N_{187}$ and $N_{191}$ filters, respectively.

2.1.2. Cryogenics

The cryostat is a compact cube with approximately 260 mm on a side, in which Offner relay optics (Section 2.1.3), a filter box with two wheels, and the HAWAII-2 FPA are housed, as shown in Figure 2. All the components in the cryostat are cooled down to 70 K to reduce thermal radiation, especially for observations in the $K_s$-band. A single-stage closed-cycle mechanical cooler with a cooling capacity of 25 W at 77 K is equipped. A cold head anti-vibration mount and bellows are inserted between the cold head and the cryostat to reduce vibration caused by the cold head. In addition, a Teflon plate and a sapphire plate are inserted to electrically insulate the cryostat from the cold head. It takes approximately 24 hours to cool down and stabilize the cryostat ($\Delta T < 0.05$ K at the detector box) from the ambient temperature down to 70 K.

The two filter wheels are installed just after the focal plane of the telescope. Each filter wheel has five slots with $\Phi 34$ mm. A stepping motor controls its rotation, and neodymium magnets and a hall-effect sensor sense the position of the slots.

2.1.3. Optics

Reflective Offner relay optics are employed for re-imaging, consisting of two (concave primary and convex secondary) spherical mirrors. The primary mirror forms an image of the telescope pupil on the secondary mirror, which works as a cold Lyot stop. The specifications of the mirrors are summarized in Table 3. These mirrors are gold-coated to achieve high reflec-
Table 2. NIR narrow-band filters.

| Name   | Wavelength [μm] | Targeted Line                  | Specification | Measurement* |
|--------|-----------------|--------------------------------|---------------|--------------|
|        |                 |                                | Center (λc)   | Width (Δλ)   |
|        |                 |                                | Center        | Width        |
| N128   | 1.2818          | Paβ (1.2818 μm)                | 1.2814        | 0.0217       |
| N1875  | 1.8751          | Paα (1.8751 μm)                | 1.8759        | 0.0080       |
| N191   | 1.9010          | Paα off-band§                  | 1.9105        | 0.0306       |
| N207   | 2.0750          | C IV (2.078 μm)                | 2.0742        | 0.0400       |

* Measured at 77 K.
† Isophotal wavelength (Tokunaga & Vacca 2005).
‡ Full-width at half maximum.
§ Also corresponding to Paα rest-frame wavelength emitted from extra-galactic objects within cz ~ 2900–8200 km s⁻¹.

Fig. 4. Atmospheric transmittances at the TAO site simulated with the PWV of 0.5 mm are shown for the N1875 (left) and N191 (right) filters, respectively. The shaded region in the top panels represents the effective transmittance including the atmospheric transmittance (solid line) and the filter transmittance measured at 77 K (shown in the bottom panel). The vertical dashed line indicates the position of Paα wavelength (1.8751 μm). The average atmospheric transmittance within the bandpass (Δλ) around the center (λc) listed in Table 2 is 0.48 and 0.64 at the N1875 and N191 filters, respectively.
Figure 5 shows spot diagrams at $\lambda = 1.65 \mu m$ across the FoV. Sharp image quality is achieved at any positions within the FoV. As shown in the right-hand panel of Figure 5, even with a dichroic mirror inserted for simultaneous optical-NIR observations (Section 2.2), spot sizes are still smaller than or comparable to the size of the Airy disk. Figure 6 shows encircled energy distributions, the fraction of energy in a given radius to the total energy from a point source, for the center and off-center spots with the dichroic mirror inserted, compared to that of a diffraction-limited spot. We confirm that the diameter encircling the 80% energy is less than 1.7 pixels ($\sim 31.5 \mu m$) or 0.5′ across the FoV.

### 2.1.4. Data Acquisition and Control System

ANIR is operated by two Linux PCs (named uni and uni2); one is dedicated to control HAWAII-2 FPA (TAO Array Controller, TAC), and the other handles all the other tasks, including operation of the filter wheels and the optical unit (see Section 2.2), acquisition of house keeping information such as temperature and vacuum pressure, and management of various functionalities.

### Table 3. Specification of the Offner relay optics.

| Primary mirror | Radius of curvature | 140 mm |
|----------------|---------------------|--------|
|                | Effective diameter  | 90 mm  |
| Secondary mirror | Radius of curvature | 70 mm  |
|                | Effective diameter  | 9 mm   |
| Offset of optical axis | 24 mm |

Figure 6. Encircled energy distributions of the point spread functions of the NIR unit at the positions (0′, 0′) and (0′, ±2′6) from the center of the FoV (0′, 0′) (thick lines) in the case that the dichroic mirror is inserted, compared to that of a diffraction-limited image (thin solid line).
instrument status. The TAC system (see Sako et al. 2008b for more details) is a high-speed and flexible array controller using a real-time operating system instead of conventional dedicated processor devices such as digital signal processors (DSPs). One core of a dual-core CPU in uni is assigned to the real-time data processing, and engages in clock pattern generation and processing of acquired frame data. This allows us to control the FPA in real time without affecting the performance of the operating system and other software. A rate to read a pixel (Pixel rate) can be set to 3 to 8 µs. Considering increasing readout noise with faster readout (slower Pixel rate), the rate of 4 µs is usually used, corresponding to a readout time of 1024 × 1024 pixels of 4.2 s, which is the shortest exposure time of the NIR unit.

Figure 7 summarizes the functions and gives a command/data flow diagram of the control system. To efficiently handle status data increasing with time, we adopt a relational database management system, MySQL. An successful example of the application of MySQL in astronomical instrumentation is described in Yoshikawa et al. (2006). Several database tables are prepared in MySQL, and information concerning instrument status (filters used, insertion of the dichroic mirror, temperatures/pressures) is stored into the respective tables every minute. When the exposure command is executed, a FITS (Flexible Image Transport System) header is constructed by collecting the latest information from those tables.

2.2. Optical Unit

To benefit from the advantages of the site, such as good seeing condition with 0''7 at V-band at a median (Motohara et al. 2008; see also Giovanelli et al. 2001a), ANIR is capable of optical and NIR simultaneous imaging observations by inserting a dichroic mirror in front of the entrance window of the cryostat of the NIR unit (the upper part of Figure 2).

The specifications of the optical unit are summarized in Table 4. The unit covers a FoV of 6'0'' × 5'9'' with a spatial resolution of 0''343 pixel⁻¹ using a commercial, peltier-cooling CCD camera unit incorporating a E2V backside-illuminated CCD, Proline PL4710-1-MB, fabricated by Finger Lakes Instrumentation. Four Johnson-system broad-band filters (B, V, R, and I) for imaging and a low-resolution transmission grating (grism) with 75 lines mm⁻¹ and a blaze angle of 4.3° for slitless spectroscopy are available. The dichroic mirror has a dimension of 50 × 71 × 10 mm with a wedge angle of 0.78° to minimize astigmatism in the NIR image. Its reflectance at 0.4–0.86 µm is higher than 0.9 with an incident angle of 45°, while its transmittance at 0.95–2.4 µm is kept higher than 0.9. Figure 8 shows spot diagrams of the optical unit at the final focal plane. Due to chromatic aberration of the re-imaging refractive optics, the focal position is offset by ∼0.2 mm in the I-band, which can be effectively compensated as shown in the right-hand panel of Figure 8 by shifting the camera optics mounted on a linear stage. The dichroic mirror is mounted on a linear stage, and can be retracted to derive better-quality (higher efficiency, lower thermal background) NIR data when no simultaneous optical observation is required.

3. Performance

In this section, we describe the imaging performance of the NIR and optical units obtained through observations carried out in 2009–2011.

3.1. Detector Performances

We measure the conversion factor of the HAWAII-2 FPA readout system using flat frames with increasing exposure time.
in the laboratory, and obtain 3.2 $e^- \text{ ADU}^{-1}$ from the calculated mean and dispersion of pixel values. The linearity of the FPA is evaluated from other flat images taken by increasing exposure time. We ensure that the linearity is kept within $\sim 1\%$ up to 18,000 ADU or 57,600 $e^-$. The readout noise is measured on the telescope in dark frames with the shortest exposure (i.e., 4.2 s) which are images with the $J$-band and $NI$875 filter inserted, where no photons fall on the FPA because those band-passes do not overlap each other. We obtain 16.6 $e^-$ as the rms of their median values with the Correlated Double Sampling (CDS) readout method. A multiple readout ("up-the-ramp" sampling) method is also examined, and we obtain 13.9 $e^-$ with 16 readouts. The dark current derived from dark frames with 300–500 s exposures is 0.28 $e^- \text{ s}^{-1} \text{ pixel}^{-1}$. We should mention that the dark current of HAWAII and HAWAII-2 FPAs have persistence and that the level of the persistence tends to be dependent on incident flux (Hodapp et al. 1996; Finger et al. 1998; Motohara et al. 2002). For example, the persistence of a dark current pattern would appear strongly on frames with a NB filter taken after exposures of high background, such as ones with a broad-band filter. The TAC system continues to reset the FPA with an interval of $\sim 0.1$ s in order to reduce the persistence effect even if no exposure command is issued.

The performance of the optical CCD are also evaluated in a similar manner to that described above. We take flat images with increasing exposure time in the laboratory, and obtain the conversion factor of 1.818 $e^- \text{ ADU}^{-1}$ from the calculated mean and dispersion of pixel values. The readout noise is measured from bias frames to be 14.5 $e^-$ rms. We obtain the dark current of 0.011 $e^- \text{ s}^{-1} \text{ pixel}^{-1}$ at the CCD temperature of $\sim 220$ K.

### 3.2. Imaging Quality

We evaluate the image quality of the NIR unit using bright (but unsaturated) and isolated field stars in images taken under good seeing condition. By matching positions on the image ($X_i$, $Y_i$) of about 20 point sources located over the FoV with coordinates ($\alpha_i$, $\delta_i$) obtained from the Two Micron All Sky Survey (2MASS) Point Source Catalog (PSC, Skrutskie et al. 2006), we obtain a pixel scale of 0.298 pixel$^{-1}$ with a fitting uncertainty of $\sim 0.2$ pixel$^{-1}$. Image distortion is confirmed to be negligible (< 1 pixel) over the FoV, as designed. We derive a typical FWHM size of 2.41 ± 0.24 pixels or $0.072 \pm 0.013$ in the $K_s$-band where ellipticities of the stars are small and uniform (0.08 ± 0.04).

The image quality of the optical unit is evaluated in a similar manner. Raw images have non-negligible image distortion, especially at their corners. We evaluate and correct for the distortion in the similar manner for the NIR unit as described above, by matching the positions of stars with those in the HST Guide Star Catalog (GSC, Lasker et al. 2008) version 2.3 and fitting them to the latter using fifth-order polynomials to take into account the image distortion. The mapping uncertainties are $\sim 0.3$ pixels. We obtain a pixel scale of 0.343 pixel$^{-1}$ at the center of the FoV for all the broad-band filters ($B$, $V$, $R$, and $I$), and a typical FWHM size of 3.04 ± 0.22 pixels or $1.04 \pm 0.08$ with a homogeneous ellipticity distribution (0.04 ± 0.08) in the $V$-band.

Figure 9 shows the seeing distribution for images taken in the latter half of the observation in 2010 and the former half in 2011. The seeing size (FWHM) is measured using the IRAF psfmeasure task. The median seeing size of $\sim 1''$ or less is obtained for all the bands. When we consider the diffraction-
limited size and Hartmann constant (0″19) of the telescope optics (Minezaki et al. 2010) and suppose that some data may be undersampled (FWHM \( \lesssim 2 \) pixel) due to good seeing condition, the actual seeing distributions at the TAO site are expected to have a peak at a smaller size.

### 3.3. Throughputs and Limiting Magnitudes

Throughput is defined as the ratio of the number of photons coming from an object into the Earth atmosphere of an aperture of the telescope to that of electrons detected, where atmospheric extinction is included. The former is calculated with the effective collecting area of the telescope to that of electrons detected, where atmospheric extinction is included. The latter is simply obtained by multiplying a count rate of an object (ADU s

**Figure 9.** Seeing statistics in the optical (left) and NIR (right) for miniTAO/ANIR. The histograms are normalized at their peak, and their median value is represented as the vertical dashed line. A number below the respective filter name indicates the number of frames used for the statistics.

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Table 5. Throughputs and limiting magnitudes*.

|       | Throughput [%] | Limiting magnitude [mag]@ 60 s | Limiting magnitude [mag]@ 600 s | Sky brightness [mag arcsec\(^{-2}\)] | \(T_{\text{BLIP}}\) [s] |
|-------|----------------|-------------------------------|-------------------------------|----------------------------------|-----------------|
|       |                | @ 60 s |                          |                               |                 |
| \(B\) | 17.5           | 21.3   | 23.5                       | 22.0                           | 2600            |
| \(V\) | 29.2           | 21.4   | 23.2                       | 20.8                           | 800             |
| \(R\) | 29.4           | 21.5   | 23.2                       | 20.3                           | 450             |
| \(I\) | 20.1           | 20.6   | 22.0                       | 18.1                           | 70              |
| \(Y\) | 14.3           | 18.8   | 20.1                       | 16.8                           | 130             |
| \(J\) | 18.9           | 19.5   | 20.9                       | 16.4                           | 50              |
| \(H\) | 29.1           | 18.4   | 19.7                       | 14.6                           | 10              |
| \(K_s\) | 30.3          | 18.7   | 20.0                       | 15.3                           | 20              |
| \(N_{128}\) | 17.0       | 16.9   | 18.3                       | 14.7                           | 80              |
| \(N_{1875}\) | 18.0      | 15.6   | 16.9                       | 13.5                           | 100             |
| \(N_{191}\) | 17.7       | 16.9   | 18.3                       | 15.0                           | 120             |
| \(N_{207}\) | 27.7       | 17.6   | 18.9                       | 15.5                           | 100             |

* All magnitudes are described in the AB magnitude system.
† For a point source with \(S/N = 5\) and \(\phi 1''5\) aperture.
‡ Approximate exposure time required for background-limited performance (BLIP). We define BLIP as when the background noise becomes twice as large as the readout noise.

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![Fig. 10. Throughputs of the ANIR optical and NIR unit on the mini- TAO telescope. The filled (open) circles show those of the broad-band (narrow-band) filters. The horizontal error bars represent the bandwidths, and the vertical error bars show 1σ dispersions. Note that atmospheric extinction is not corrected.](image)

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et al. 2000), we consider their influence on our result to be small because we perform aperture photometry with local sky subtraction for each source.

The limiting magnitudes for the optical and NIR units are estimated using the dark current, readout noise, throughputs obtained above, and sky brightness (photons cm\(^{-2}\) s\(^{-1}\) \(\mu\)m\(^{-1}\) arcsec\(^{-2}\)). The sky brightness is measured on a "sky" frame made by combining unregistered subsequent frames with objects masked. Table 5 gives the estimated limiting magnitudes for a point source with \(S/N = 5\), \(\phi 1''5\) aperture, and two different exposure times (60 and 600 s). Also listed is an approximate exposure time (\(T_{\text{BLIP}}\)) required to achieve background-limited performance (BLIP) that means the \(S/N\) of data is dominated by the background noise. We define BLIP as when the Poisson noise of the sky background becomes twice as large as the readout noise.

3.4. \(\text{Pa\alpha}\) Imaging Performance

Here we briefly demonstrate the performance of the mini- TAO/ANIR ground-based \(\text{Pa\alpha}\) observations. The reduced \(\text{Pa\alpha}\) emission image of the nearby starburst galaxy, IC5179 taken with the \(N_{191}\) filter, is shown in Figure 11, demonstrating that the TAO site indeed provides access to the \(\text{Pa\alpha}\) emission line from the ground. Star-forming regions associated with the spiral arm and the nucleus are clearly seen. For a comparison of its sensitivity, the same galaxy taken by the \(HST/NICMOS\) F190N filter is also shown in the right-hand panel of Figure 11, from which the F187N image is subtracted as a continuum emission. A quantitative comparison confirms the consistency of \(\text{Pa\alpha}\) fluxes obtained with ANIR and NICMOS within an accuracy of 10% (Tateuchi et al. 2012a). We refer the reader to Tateuchi et al. (2012a) and Tateuchi et al. (2014) for the data reduction processes, verification, quantitative analyses, and comparison of the performance with NICMOS, of \(\text{Pa\alpha}\) emission line data taken by the \(N_{1875}\) and \(N_{191}\) filters.
4. Site Evaluation through Paα Narrow-band Observations

Finally, we evaluate how the site is suitable for the infrared astronomy in terms of PWV by using the N1875 and N191 data taken between 2009 and 2011. We note that our approach using the NB filters around 1.9 μm which are sensitive to PWV is independent of any previous studies carried out at the Chajnantor Plateau (e.g., Giovanelli et al. 2001b; Erasmus & Sarazin 2002; Peterson et al. 2003; Tamura et al. 2011).

The throughputs derived in Section 3.3 (hereafter \(\eta_{\text{obs}}\)) consist of the following factors: (i) the reflectivity of the telescope mirrors (\(T_{\text{Tel}}\)), (ii) the system efficiency of ANIR excluding the filter transmittance (\(T_{\text{ANIR}}\)), (iii) the filter transmittance (\(T_{\text{filter}}\)), (iv) atmospheric transmittance (\(T_{\text{atm}}\)) at the zenith which is dependent on PWV. Then, the throughput is described as:

\[
\eta_{\text{obs}} = T_{\text{Tel}}^{\text{band}} \times T_{\text{ANIR}}^{\text{band}} \times T_{\text{filter}}^{\text{band}} \times (T_{\text{atm}}^{\text{PWV}}, \text{band})^{X}
\]

where the superscript “band” denotes that the factor depends on the wavelength measured and \(X\) is the airmass which is necessary for considering the optical path length of the atmosphere during the observation. For the sake of simplicity, we assume a homogeneous atmosphere in terms of airmass to obtain the atmospheric transmittance at a given airmass by scaling that at the airmass of 1.0. In fact, such a simple scaling tends to overestimate the atmospheric extinction at \(X > 1\) due to the non-linear dependence of the amount of extinction on airmass (Manduca & Bell 1979; Tokunaga et al. 2002). Thus, the resultant quantities, \(T_{\text{atm}}\) and PWV, are considered to be lower and upper limits, respectively. \(T_{\text{filter}}\) is measured at 77 K in the laboratory (Table 2). We calculate \(T_{\text{atm}}^{\text{PWV}}\) using the ATRAN model. As the atmospheric transmittances at the \(H\) and \(K_s\)-bands are largely independent regardless of PWV (see Figure 1), the factor \(T_{\text{Tel}}^{\text{band}} \times T_{\text{ANIR}}^{\text{band}}\) can be calculated, for example, for the \(K_s\)-band as the following:

\[
T_{\text{Tel}}^{K_s} \times T_{\text{ANIR}}^{K_s} = \frac{\eta_{\text{obs}}^{K_s}}{T_{\text{filter}}^{K_s} \times (T_{\text{atm}}^{K_s})^{X}}
\]

In the same way, we calculate the factor for the \(H\)-band (\(T_{\text{Tel}}^{H} \times T_{\text{ANIR}}^{H}\)). Since the factor for the \(H\)-band is much the same as that for the \(K_s\)-band with a dispersion of a few percent, indicating that the factor has small dependence on wavelength, we then interpolate \(T_{\text{Tel}}^{H} \times T_{\text{ANIR}}^{H}\) and \(T_{\text{Tel}}^{K_s} \times T_{\text{ANIR}}^{K_s}\) to estimate the same factor for a NB filter (\(N1875\) or \(N191\)), \(T_{\text{Tel}}^{\text{NB}} \times T_{\text{ANIR}}^{\text{NB}}\). Finally, we obtain PWV by iteratively calculating the left-hand integral in Equation (3) within the bandpass \([\lambda_1, \lambda_2]\) of the NB filter with changing PWV to make it equal to the right-hand value.

\[
\frac{\int_{\lambda_1}^{\lambda_2} \eta_{\text{obs}}^{\text{NB}}}{T_{\text{Tel}}^{\text{NB}} \times T_{\text{ANIR}}^{\text{NB}}} = \frac{\int_{\lambda_1}^{\lambda_2} d\lambda}{T_{\text{Tel}}^{\text{PWV}} \times (T_{\text{atm}}^{\text{PWV}}, \text{NB})^{X}}
\]

The evaluated PWV values and the corresponding atmospheric transmittances at the \(N1875\) (\(N191\)) filter are shown in the left- and right-hand ordinates of Figure 12a (12b), respectively. Each data point is calculated by using a reduced uncertainty of the throughput of the NB data and (ii) frame-by-frame fluctuations of the throughput in the same dithering sequence. We evaluate the latter factor by processing individual frames in the same manner as described above for two objects: one with a higher (~0.8 mm) and another with a lower (~0.2 mm) PWV evaluated from their stacked image. We find a frame-by-frame fluctuation of about 0.14 mm for both objects, and we thus introduce a constant factor of 0.14 mm as the frame-by-frame fluctuation for all the data in Figure 12. Our result tends to show lower PWV values (the median and its 1σ dispersion are 0.40 ± 0.30 for \(N1875\) and 0.37 ± 0.21 mm for \(N191\)) than those reported.
For a quantitative comparison of the result, we use archival PWV data measured by a radiometer of Atacama Pathfinder EXperiment (APEX, Güsten et al. 2006) located near the base of Cerro Chajnantor at an altitude of 5,100 m. We extract the APEX PWV data during our $N_{1875}$ observations for each object (typical integration time $\sim 1200$ s including overheads). The dashed line indicates a one-to-one relation and the dotted line shows the best-fitting linear relation with a slope of 0.47. The shaded region shows the possible region expected from the exponential distribution of the water vapor with a scale height of $0.3–1.9$ km. Right: Same as the left-hand panel, but for the $N_{191}$ data. The best-fitting (dotted) line has a slope of 0.60.

Let us now consider the vertical distribution of the water vapor to discuss possible causes of the difference in the PWV between the APEX (PWV$_{\text{APEX}}$) and the TAO (PWV$_{\text{TAO}}$) sites. When the water vapor is assumed to be distributed exponentially, PWV is derived by integrating an exponential profile, $ho = \rho_0 \exp[-(h-h_0)/h_e]$, over altitude $h$, where $\rho$ is the water vapor density (in kg m$^{-3}$) at a given altitude $h$ above sea level (in km), $\rho_0$ the density at a reference altitude $h_0$, $h_e$ the scale height at which the water vapor density decreases by a factor of $e$. Giovanelli et al. (2001b) have measured the vertical distribution of the water vapor above the Chajnantor plateau by a combination of radiometric (at both 183 and 225 GHz) and radiosonde measurements, and derived the median scale height $h_e \sim 1.13$ km by fitting the individual distributions to the exponential profile with $h_0$ of 5.0 km (i.e., Chajnantor Plateau). By using a scale height of 1.13 km, the PWV at the TAO site is calculated for a given PWV at the APEX site, as follows (see also Otárola et al. 2010, 2011). The density $\rho_0$ is found by integrating the above equation above 5,100 m since the integral equals to the PWV at the APEX site. For example, the PWV at the APEX site of 1.0 mm leads to $\rho_0 \sim 1.44$ g cm$^{-3}$. Then, the PWV at the TAO site is derived, to be $\sim 0.62$ mm in the case of the example, by integrating the equation above 5,640 m with $\rho_0$ substituted. Using the measurements of the exponential scale height at night time (the peak-to-peak values in $h_e$ of $\sim 0.3–1.9$ km) by Giovanelli et al. (2001b), we derive the corresponding PWV values at the TAO site as a function of the PWV at the APEX site, which are shown in Figure 12 with a shaded region. We find that almost all of the data points are in excellent agreement, within the uncertainties, with the expectation of such exponential distributions of the water vapor having the measured scale heights. Note that there are a few outliers above the region, which might be caused by liquid phase of water (fog or clouds) in the atmosphere which is not detected by the APEX radiometer operating at 183 GHz, as suggested...
by previous studies (Matsushita & Matsuo 2003; Tamura et al. 2011). We should also note the possible influence of the presence of temperature inversion layers on the water vapor distribution. Giovanelli et al. (2001b) find that their radiosonde data often show temperature inversions which make the distribution far from the exponential shape, so that much of the water vapor would be trapped below the inversion layers. To explore the influence requires a large sample of radiosonde data (or any equivalent data on the vertical distributions of the water vapor) and it is far beyond the scope of this paper, but we consider that our conclusion of the advantage of the site remains unrevised, because temperature inversions often take place below the altitude of 5,500 m at night time (Giovanelli et al. 2001b), indicating systematically lower PWV content at the TAO site than at the APEX site, which is qualitatively the same trend as derived from Figure 12.

While there is relatively large uncertainties in our analysis, it is encouraging to see that the low PWV content at the TAO site is confirmed by independent methods (i.e., NB imaging and radiosonde), which suggests that the TAO site at the summit of Cerro Chajnantor is suitable for infrared astronomy, and in particular that miniTAO/ANIR has an excellent capability for $\lambda$ observations at around $\lambda = 1.9 \mu$m.

5. Summary

We have developed a near-infrared camera, ANIR (Atacama NIR camera), for the 1.0-m miniTAO telescope installed at the summit of Cerro Chajnantor (an altitude of 5,640 m) in northern Chile. The camera covers a field of view of 5.1' x 5.1' with a spatial resolution of 0.298 pixel$^{-1}$ in the wavelength range of 0.95 to 2.4 $\mu$m.

The unique feature of the camera coupled with advantages of the site is a capability of narrow-band imaging observations of a strong hydrogen emission line, Paschen-$\alpha$ (Pa$\alpha$), at $\lambda = 1.8751 \mu$m from the ground, at which wavelength it has been quite difficult to conduct ground-based observations so far due to deep atmospheric absorption mostly from water vapor. We have been successfully obtaining Pa$\alpha$ images of Galactic objects and nearby galaxies since the first light observation with ANIR in 2009.

The throughputs at the narrow-band filters (N1875 and N191) show larger dispersion (~10%) than those of the broadband filters (a few percent), indicating that they are affected by temporal fluctuations in Precipitable Water Vapor (PWV) above the site. Combining the atmospheric transmission model with the throughputs, we evaluated the atmospheric transmittance at the narrow-band filters and the PWV content at the site. We find that the median and the dispersion of the PWV are 0.40 ± 0.30 for N1875 and 0.37 ± 0.21 for N191 data. Comparing those data with the radiometer data taken by APEX, we find that the site has remarkably lower (49% ± 38% for N1875 and 59% ± 26% for N191) PWV values than the APEX site (5,100 m). The differences in PWV between those sites are found to be in excellent agreement with those expected from the exponential distribution of the water vapor with scale height within 0.3–1.9 km which has been measured using the radiosonde at night time (Giovanelli et al. 2001b). Although temperature inversions (which mostly take place below the summit at night-time) make the water vapor distribution far from exponential, it leads to lower PWV content above the inversion layers, which is qualitatively consistent with our findings described above. Taken all together, we conclude that miniTAO/ANIR and the site, the summit of Cerro Chajnantor, provides us with an excellent capability for ground-based $\lambda$ observations.

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References

Alonso-Herrero, A., Rieke, G. H., Rieke, M. J., Colina, L., Pérez-González, P. G., & Ryder, S. D. 2006b ApJ, 650, 835

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