Coronagraph Imager with Adaptive Optics (CIAO) for the Subaru 8-m Telescope

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ABSTRACT

CIAO is a stellar Coronagraph Imager with Adaptive Optics for use on the Subaru 8.2-m telescope, whose aim is to obtain diffraction limited images of faint objects in close vicinity of bright objects at infrared wavelengths. The instrument is a near-infrared camera with a sophisticated coronagraph capability optimized for use between 1 and 5 micron and is used in conjunction with the adaptive optics system. A number of occulting masks and pupil masks with various sizes and shapes are selectable, all cooled down to below 80 K. Care is taken to minimize the diffraction and scattering effects both in the telescope and in the instrument. Great care is also taken to design the tension-strap supported cryostat which minimizes the flexure within the cryostat. The camera will utilize an SBRC 1024×1024 InSb detector array. Facilities are also provided for polarimetry and grism spectroscopy. CIAO will be a very powerful instrument to study circumstellar disks around both young stellar objects and main-sequence stars, companion brown dwarfs and other kinds of companions, extra-solar planets, jets and outflows from both young stars and evolved stars, circumnuclear regions around AGNs, and host galaxies of QSOs.

Keywords: Infrared, Astronomy, Adaptive Optics, Coronagraph, Polarimetry, Grism

1. INTRODUCTION

With a goal of its first light in 1998, the construction of the Subaru 8.2-m telescope is now in progress at the top of Mauna Kea, Hawaii. The development of the seven (three optical and four infrared) scientific instruments for the Subaru telescope is in progress in Japan and Hawaii. Of the four infrared instruments, CIAO is specialized in providing high spatial resolutions for coronagraphic/direct imaging, polarimetric imaging, narrow-band imaging, and grism spectroscopy, covering the wavelengths of 1 to 5 μm. CIAO will be attached to the F/12 Cassegrain focus of the Subaru telescope and used in conjunction with the adaptive optics system. The details of the Subaru adaptive optics system are described elsewhere[1,2].

Coronagraphy is a powerful technique to suppress the halo of bright object and to obtain a higher contrast between the faint nearby target and the bright central object[3]. Application of the coronagraph other than the Sun has not been extensive, but already brought exciting discoveries such as the dust disk around β Pic[4] and the cold brown dwarf around Gliese 229[5]. Unfortunately, since the previous stellar coronagraphs have been subjected to natural or at most tip/tilt-corrected seeing, the size of the occulting masks is normally larger than about 2 arcseconds. However, the combination of the 8-m telescope and the adaptive optics now makes it possible to use much smaller occulting masks (~0.1 - 1 arcsecond diameter) in the coronagraph and therefore to observe objects very close to the central source. CIAO will also be merited from the excellent seeing at Mauna Kea and the superb image quality of the telescope to which great care is taken for dome seeing control and primary mirror cleaning.

In this paper we report the technical description of CIAO, emphasizing its optics, mechanics, and cryostat.

2. INSTRUMENT DESCRIPTION

2.1 Optics and Mechanics

2.1.1 Optics modes

Four optics modes are provided, i.e. high resolution mode (HRM), medium resolution mode (MRM), spectroscopy mode (SPM), and pupil imaging mode (PIM). HRM and MRM are for obtaining diffraction limited images at J-band and at K-band, respectively, on the Subaru telescope. Imaging spectroscopy is also available for HRM and MRM with the grisms at spectral resolution from 300 to 1200. SPM[6] is for spectroscopy of extended objects with lower spectral resolution of 300 - 600. PIM is for acquiring the pupil (Lyot stop) image to monitor the Subaru secondary image on the Lyot stop. Table 1 shows specifications for the four modes.

Table 1: Specifications of the Four Optics Modes

mode	magnification	pixel scale (arcsec/pixel)	FOV (arcsec)	wavelength coverage (μm)
HRM	63.8	0.012	12.3 × 12.3	0.9 - 5.0
MRM	31.9	0.024	24.6 × 24.6	0.9 - 5.0
SPM	4	0.019	30 (106 pixels)	1.0 - 2.5
PIM	-	-	-	1.0 - 2.0

The optical and opto-mechanical layout is shown in Figure 1. The optics are linearly arranged along the optical axis. The masks, Lyot stops, filters, and camera lenses have several options selectable in real time, and the collimator lens can be adjusted in its x-y position. The real time selections and adjustment are performed with conventional wheels or sliding mounts which are driven by cryogenic motors.

2.1.2 Window, beam splitter, and compensator

The entrance window is a CaF_2 disk with 130 mm diameter. It is mounted with a tilt in order to make the ghost image by the window well off the center (19.3 arcsec) of the detector.

Both of the beam splitter and the compensator are made of CaF_2 glass. The beam splitter reflects visible light (0.6 - 0.8 μm) to the AO wavefront sensor, and transmits the infrared light (0.9 - 5 μm) to the compensator. The compensator is for correcting the astigmatism and chromatic aberration caused by the beam splitter. Ghost images due to these plates are 10 arcsec off the detector center, and their intensity is less than 10^{-4} of the original image.

2.1.3 Occulting masks, collimator lens, and stops

The occulting masks are placed at the telescope focal point. The mask pattern is made by evaporating chromium on the sapphire plates. Several mask patterns or slit sizes are available in the wheel, and the optimal occulting size (0.1 - 2 arcsec) or slit size (0.1 - 2 arcsec) can be chosen according to the seeing condition and the object brightness/size.

The collimator is composed of a meniscus LiF and a convex BaF_2 lens pair. It makes the telescope secondary image on the Lyot stop. The pair is housed in the mount on the x-y translation stage, and its x-y position is remotely controlled for achieving the precise location of the telescope secondary image onto the Lyot stop.

The Lyot stop pattern is made by evaporating chromium on the sapphire plate. Apodized and non-apodized patterns are fabricated and six patterns are available in the stop wheel. Several patterns are shown in Table 2. The stop itself rotates around the optical axis to compensate the rotation of the telescope spider image, too.

Table 2: Lyot Stops

pattern	effective diameter	gradation width	spider pattern	remark
1	0.8	0.0	no	hard stop
2	0.9	0.0	no	hard stop
3	0.8	0.1	yes	apodizer
4	0.7	0.1	yes	apodizer for SPM

2.1.4 Filters, grisms, polarizers

Two wheels in tandem are provided for selection of the filters and the grisms. The standard broad-band infrared filters (J, H, K, K_s, L’, M’-bands, made by OCLI) and a number of narrow-band filters are available. The wheels also house polarizers. The sizes of the filters and polarizers are 38 mm in diameter.

Two grisms called type A and type B are prepared for medium/high resolution imaging modes, and others optimized for spectroscopy mode are being developed. The resolving power ranges from 300 to 1200. The grism types A and B were ruled directly by diamond cutter. Its efficiency is 65 % at K band (2nd order), 70 % at J-band (3rd order), and 70 % at H-band (4th order).

Table 3: Resolving Power of Grisms

slit width	type A	type B	remark
0.06 arcsec/2.5 pixel	1200	600	
0.12 arcsec/5.0 pixel	600	300	
0.03 arcsec/2.5 pixel	2400	1200	HRM, J-band
0.06 arcsec/5.0 pixel	1200	600	HRM

Table 4: Spectral Range of Grisms

band	order	spectral range (μm)	band width (μm)	pixel*
J	4	1.07〜1.33	0.26	650
H	3	1.38〜1.82	0.44	825
K	2	1.92〜2.88	0.96	1200
L’, M’	1	3.20〜6.40	3.20	2000

*Total number of pixels required to observe entire free spectral range (HRM, Type A).

The polarimeter unit is installed upstream of the adaptive optics system, which minimizes the instrumental polarization caused by the reflective optics in the adaptive optics. The unit is composed of three slots for half-wave plate, quarter-wave plate, and calibration polarizer. Each slot is retractable. The waveplates in the two slots are independently rotated by a compact stepping motor mounted on each slot, thus enabling us to make both linear and circular polarimetry.

2.1.5 Camera lens

Camera lens unit is in the turret containing four cylindrical housings for the modes; HRM, MRM, SPM, and PIM. HRM is composed of a pair of meniscus BaF_2 lens and meniscus LiF lens, and MRM is composed of a pair of convex BaF_2 lens and meniscus LiF lens. Strehl ratios for the on-axis point are all higher than 0.98. PIM is composed of a pair of meniscus quarts lens and convex CaF_2 lens.

2.2 Cryostat and Cooling system

The cryostat is designed to be cylindrical in order to achieve stiffness. Since the dimension of cryostat is 1 m diameter and 1.6 m length and the total weight of CIAO is nearly 2000 kg, the cryostat needs a very rigid support against the deformation due to its gravity. Symmetrical tension support is capable to hold heavy equipment firmly. Figure 2 is a schematic view of holding the CIAO cryostat at the telescope Cassegrain focus. Two meter square interface plate is attached to the cell. The cryostat is supported through eight stainless pipes to this plate. The base panel under the cryostat is linked to the plate with the four wires and holds up the cryostat with the eight pipes. These structures are included in the container prepared for auto-mobile transfer for the Cassegrain instruments.

The optical bench has dimension of about 1240 mm (l) x 450 mm (w) x 20 mm (t), and weight of over 100 kg. Two rigid rings are bound in front and back of the optical bench, and the GFRP tension straps hold each ring to the wall of the cryostat (Figure 3).

The shifts of the optical components from their nominal positions are designed as shown in Table 5. Our holding structure composed of tension support makes the shifts as small as <1 μm when the telescope swings 1 degree. Both cryostat and cold optical bench were made by Sumitomo Heavy Industries, Inc.

Table 5: Shift due to the Telescope Elevation

telescope elevation	shift parallel to the optical axis	shift perpendicular to the optical axis
20° — 70°	27 μm	47 μm
10° change 90° — 80° 30° — 20°	 1 μm 9 μm	 9 μm 4 μm
1° change	<1 μm	<1 μm

The GM cycle refrigerator (SRDK 408, Sumitomo Heavy Industries, Inc.) is used to cool both optics and detector. The InSb array detector is cooled to its optimal temperature 35 K with the refrigerator's second stage, and the optical components in the cryostat are cooled to 70 K with its first stage. SRDK 408 has refrigeration capacity of 1 W at 4 K and 42 W at 40 K, which is enough for the CIAO inner heat dissipation of 5 W.

LN_2 circulation pipe runs under the optical bench. The liquid nitrogen are poured to the pipe in the early cooling stage to boost the cooling.

Cooling tests have proved that it takes eight hours to cool the array part to 32 K and the optical bench to the 81 K with pre-consumption of 151 litter of liquid nitrogen.

2.3 Detector, Array holder, and Array electronics

An SBRC InSb 1024x1024 array detector is used. This is one of the ALADDIN II arrays made with a foundry run conducted by the Subaru project. An array cassette is used for handling the array. The cassette is mounted on the linear stage that is remotely adjustable in the direction along the optical axis. A linear stage and a compact stepping motor are employed. They work at LN_2 temperature with molybdenum coating over the sliding shaft as lubricant. An array electronics control system based on digital signal processors is used to control the 1024x1024 InSb array. The system is composed of the VME64 control computer, the cryostat mounted electronics, and array electronics power supply. The system will satisfy the low-noise (<23 e) and relatively fast (20 frames per second) readout.

3. SCIENTIFIC TARGETS AND COMPUTER SIMULATIONS

CIAO will be a very powerful instrument for a number of astronomical applications which need not only high spatial-resolution and high sensitivity but also high dynamic range. Our main scientific interests are young brown dwarfs and extra-solar planets around young stars, matured brown dwarfs around nearby stars, protoplanetary disks around young stars, disks around nearby main-sequence stars, jet and outflows from both young stars and evolved stars, circumnuclear regions of AGNs, host galaxies of quasars, and gravitational lensing.

In order to evaluate the performance of CIAO, we have conducted extensive computer simulations. The simulations take into account of atmospheric turbulence based on the Kolmogorov theory and the Subaru telescope aberration. The results quantitatively show that the observations with CIAO will surpass the previous ones in a number of the fields listed above. The details of the simulations are beyond the scope of this paper and described elsewhere[7].

4. REFERENCES

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Fig. 1. Optics and mechanics layout of CIAO.

Fig. 2. Support structure of CIAO on the Cassegrain focus of the Subaru 8.2-m telescope.

Fig. 3. Cryostat of CIAO.