Near-infrared polarimeter for the Subaru telescope

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ABSTRACT

We report the development and performance of a near-infrared polarimeter for the Subaru 8.2-m telescope. The polarimeter is currently used with one of the Subaru instruments, CIAO, the stellar coronagraphic imager with adaptive optics. CIAO is the instrument specialized to obtain high contrast images of faint objects in the vicinity of bright objects. For achieving both high spatial resolution and high dynamic range, the instrument is used with the Subaru adaptive optics and has a dedicated cold coronagraphic capability.

The polarimeter comprises two components. One component consists of an achromatic (1 - 2.5 micron) half-waveplate, an achromatic quarter-waveplate, and a calibration wire grid. Both half- and quarter-waveplates are rotatable and retractable, while the calibrator is only retractable. This component is placed upstream of any optical components including adaptive optics system, which minimizes the effect of various mirrors on instrumental polarization. The other component consists of two analyzers, a cold wire grid and a cold Wollaston prism. These are placed in the filter wheels of CIAO cryostat and can be chosen. The whole system is remotely controlled.

The instrument has been commissioned on the Subaru telescope and its linear-polarization performance has been tested with/without the adaptive optics.

Keywords: infrared, polarimetry, coronagraph, adaptive optics, Subaru telescope

1. CIAO AND POLARIMETER

CIAO is a near-infrared stellar coronagraphic imager for the Subaru 8.2 meter telescope. The purpose of this instrument is to obtain diffraction limited (~0.06 arcsec at wavelength of 2 micron) images of faint objects in close vicinity of bright objects. For achieving both high spatial resolution and high dynamic range, the instrument is used with the Subaru Cassegrain adaptive optics[1] and designed to have a cold coronagraphic capability. Polarimetric capability is very important with this instrument: scientific applications of high spatial resolution (sub-arcsecond) polarimetry with or without coronagraph are vast. Besides the scientific merits, there are some technical advantages. Extended structures around bright objects such as circumstellar disks and envelopes are often of scattered origin and expected to show a large polarization, while the PSF halo associated with bright point-sources should not show regular pattern of polarization vectors and their degrees of polarization are very small. Polarimetry makes it possible to distinguish the small extended structures and the PSF halo, which is often difficult by simple imaging. Therefore, we have developed a

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polarimeter as a part of the CIAO instrument development. Although the details of CIAO are described elsewhere[2,3,4], its brief description is provided at first.

CIAO is optimized for use at near-infrared wavelengths (1 - 5 micron) where the adaptive optics works most efficiently and the effect of scattering by telescope and instrument optics is smaller. The adaptive optics is placed upstream of CIAO, between the telescope flange and the CIAO entrance window. There are two optical modes for observations (high resolution mode with a pixel scale of 11 mas per pixel and medium resolution mode of 22 mas per pixel) and a pupil imaging mode for optical alignments. The optical elements are all refractive and composed of smallest number of surfaces as possible for reducing the scattering effect. Optical components for coronagraph, occulting masks and Lyot stops, are both cooled and various sizes and shapes of masks and stops are available. CIAO is equipped with the standard broad filters (*ZJHKKsL'M'*) as well as a number of narrow band filters. Slit spectroscopy with a grism of several hundred resolutions is also available. Choice of masks, filters and camera lenses and optical alignment with collimator and detector are made with cryogenic motors. CIAO utilizes one ALLADIN II (1024x1024 InSb) science-grade detector array. The instrument achieved its first light on the Subaru telescope in 2000 February and its first combination with the Subaru adaptive optics in 2001 January. It is under an open use from 2001 October.

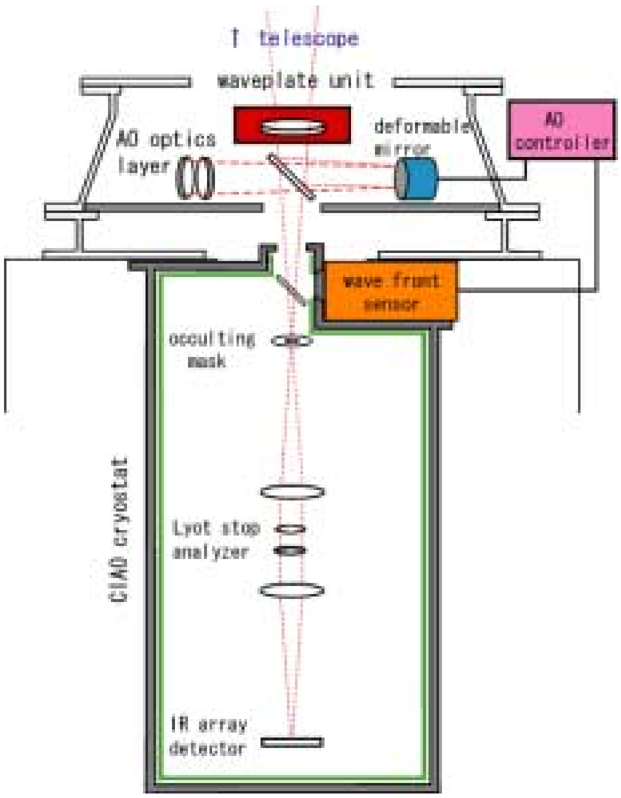

Fig. 1. Optical layout of the polarimeter, adaptive optics, and CIAO systems.

The requirement for the polarimeter is as follows: (1) Polarimetric observations are possible with any combinations of the above optical modes, filters, and coronagraphic modes. (2) Rather conventional optical layout of the polarimeter is employed, comprising rotating waveplates and fixed analyzers. Both wire grid and Wollaston prism are available as analyzers. (3) The polarimeter is achromatic at near-infrared wavelengths. (4) Instrumental polarizations due to the telescope, adaptive optics, and instrument optics are minimized. (5) The control of the polarimeter is completely remote. Resultantly, the polarimeter consists of two units: one is a rotating waveplate unit and the other is a fixed analyzer unit. The former is placed upstream of the adaptive optics and the CIAO camera (therefore warm), and the latter is installed in the CIAO camera (therefore cold). Fig. 1 shows the optical layout of these systems.

2. OPTICAL LAYOUT AND MECHANICS OF THE CIAO POLARIMETER

2.1 Waveplate unit

The rotating waveplate unit of the polarimeter (hereafter the WP unit) is placed upstream of any parts of the CIAO optics as well as adaptive optics such as deformable mirror and tip-tilt mirror. Although all the CIAO optics are refractive with their optical axis straight and thus instrumental polarizations are expected to negligible, the reflective optics within adaptive optics could be the source of instrumental polarization. Therefore, the WP unit is placed upstream of adaptive optics.

The WP unit consists of three parts: (1) Most upstream is a wire grid analyzer for calibration of the polarization efficiency that is retractable from the optical path from the telescope to the downstream adaptive optics and CIAO. (2) Middle is a half-waveplate that is retractable and rotatable. (3) Most downstream is a quarter-waveplate that is retractable and rotatable. Currently the quarter-waveplate is not installed in the unit yet.

The three parts are assembled by a rigid frame whose dimension is about 460 mm x 410 mm x 160 mm (see Fig. 2). These mechanical parts are manufactured by Apex, Inc. Because of the space limitation between the telescope flange and the adaptive optics, the height of the polarimeter is tight. Also the other diagonal side of the same height level is used for a calibration lamp system for the adaptive system (AO CAL) that is retractable. Both the polarimeter and the AO CAL are not easily accessible once the whole adaptive optics is attached to the Cassegrain focus of the telescope. Therefore, great care must be taken on an interlock between the polarimeter and the AO CAL as well as the telescope auto guider system.

The half- and quarter-waveplates are composed of quartz and MgF_2 and achromatic between the wavelengths of 1 and 2.5 micron. Their clear aperture is 95 mm. They are manufactured by Bernhard Halle.

Five 5-phase stepping motors are used for rotation and retraction motions. The mechanical parts including these motors have been robust under normal temperatures at the Mauna Kea (> -10 degrees of Celsius).

2.2 Analyzer unit

There are two analyzers for the polarimeter, both of which are installed in the cold filter wheels of CIAO. Since the test observations of the Wollaston prism are not finished, it is not described here. The wire grid is the same as the calibration wire grid (IGP-227 manufactured by SPECAC). Its diameter is 38 mm. The efficiency of the polarization of the analyzer is measured to be 90.5%, 93.2%, and 95.2% at *J*, *H*, and *K* bands, respectively.

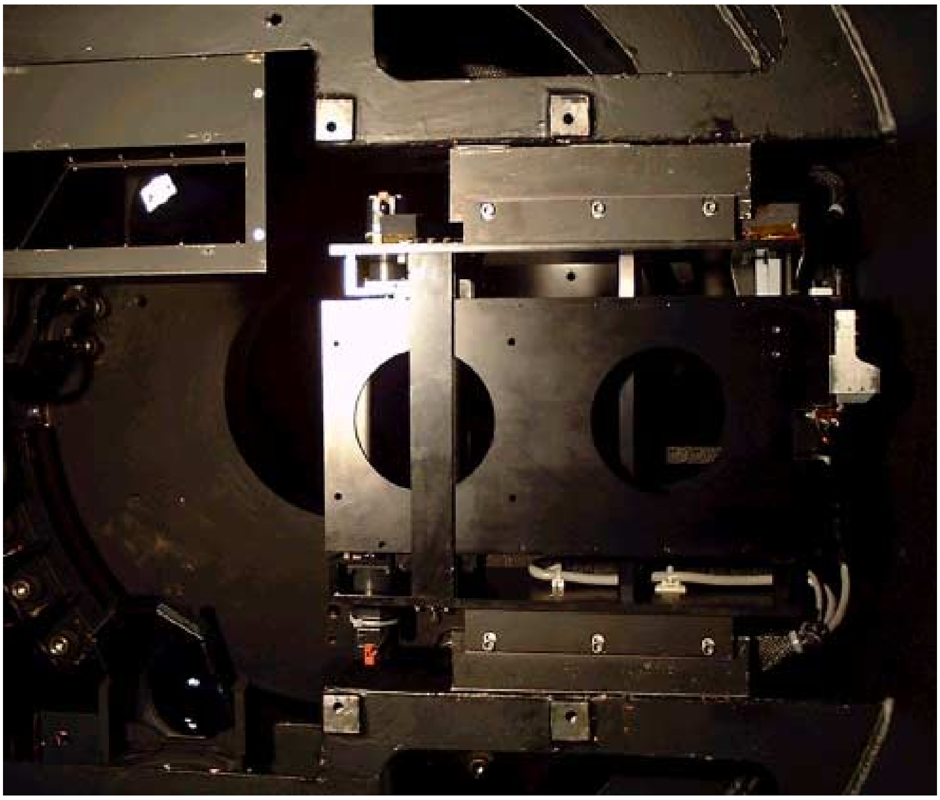

Fig. 2. The waveplate unit of the polarimeter seen from the downstream (the adaptive optics side).

3. PERFORMANCE ON THE SUBARU TELESCOPE

The observational procedure for the polarimeter is rather standard. The half-waveplate is stepped by 0, 45 , 22.5, and 67.5 degrees in sequence and images are obtained at each position (I_0, I_{45}, $I_{22.5}$, and $I_{67.5}$). The Stokes parameters, I, Q, and U are obtained as follows: $I = I_0 + I_{45} = I_{22.5} + I_{67.5}$, $Q = I_0 – I_{45}$, and $U= I_{22.5} – I_{67.5}$. The degree of polarization (p) and the position angle of polarization (PA) are $p = (Q^2 + U^2)^{1/2} / I$ and $PA = (1/2) \tan^{-1}(U/Q)$, respectively. PA is measured from north to east projected on the sky. The test observations have been conducted first without adaptive optics and then with adaptive optics. The image reduction at each position angle follows the standard infrared image reduction with dark subtraction and flat field. In our system, the dome flat field in one position angle of the waveplate is applicable for every position angles.

In order to evaluate the linear-polarization performance of the polarimeter, we have conducted test observations on the Subaru telescope in 2001 January. First the instrumental polarizations are measured with several unpolarized stars and they are found to be less than 1%. The typical error of measured polarization degree is 0.5%. The accuracy is due to sky changes during the observations. Second the polarization efficiencies of the polarimeter are measured with several unpolarized stars and the calibration wire grid. After correcting the efficiency of the calibration wire grid, we have found that the polarization efficiencies are 89%, 92% , and 97% at *J*, *H*, and *K* bands, respectively. Third the position angles of the polarization are checked with several polarization standard stars. They are consistent with each other within accuracies. Forth the polarization patterns are checked with known celestial objects. We have observed HL Tau at *K* band without adaptive optics under a very good seeing condition (0.3 arcsec). The object has been infrared-polarimetrically studied by Yamashita et al. (1994)[5] and Weintraub et al. (1995)[6]. High resolution images have been obtained at near-infrared with adaptive optics (Close et al. 1997)[7] and at optical with HST (Stapelfeldt et al. 1995)[8].

Therefore, comparisons with our imaging and polarization results can be conducted. Fig. 3 shows our polarization data. Although our data have much higher resolution than the previous polarization data, we have found that the large-scale centrosymmetric pattern is consistent with the previous infrared polarization data. Also, the polarization patterns clearly show deviations from the circular pattern (e.g., polarization disk[9]) due to dense circumstellar disk suggested by the above imaging observations and millimeter observations[10]. More scientific details of the HL Tau data are presented by Fukagawa et al. (2002, in prep.)

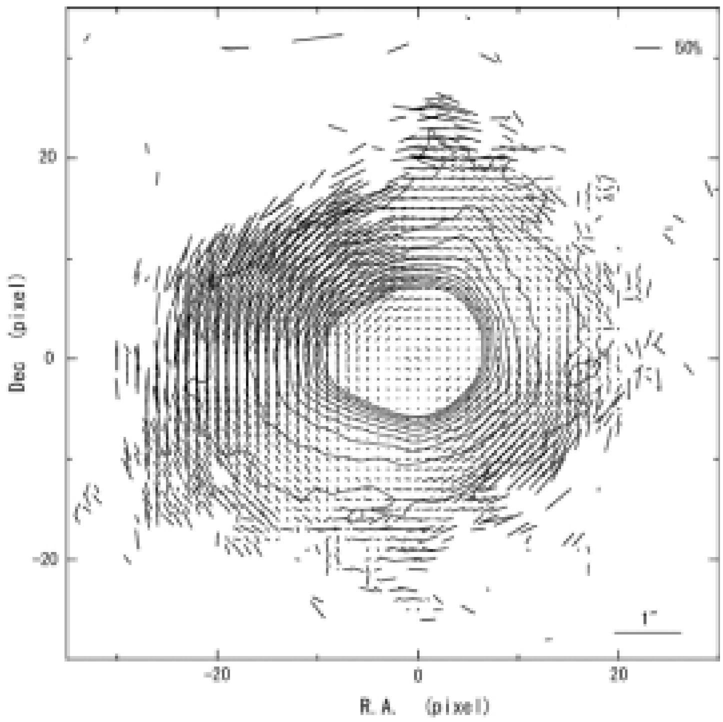

Fig. 3. The polarimetric image of HL Tau at *K* band, without adaptive optics. The total integration time was 4 minutes. Contour maps are overlaid with polarization vectors indicating polarization degree and position angle. The resolution of this vector map is 0.15 arcsec/pixel. Contours are spaced by 15.0 mag/arcsec^2, starting at the lowest contour at 3 sigma above the sky level. The intensity peak is located at the origin (0,0). North is up and east is to the left.

In order to evaluate the performance of the polarimeter with the adaptive optics, we have conducted test observations on the Subaru telescope in 2001 July and November. The experiments similar to those without adaptive optics described above are made. There are no significant changes in the instrumental polarizations and the polarization efficiencies. Therefore, the polarimeter is viable for the adaptive optics imaging polarimetry on the Subaru telescope.

ACKNOWLEDGEMENTS

We are grateful to the CIAO and AO teams, especially, N. Ebizuka, S. S. Hayashi, Y. Oasa, N. Kaifu, H. Takami, N. Takato, T. Otusbo, Y. Hayano, W. Gaessler, T. Kanzawa, Y. Kamata, and M. Iye. We also wish to thank the Subaru telescope teams for their support and encouragement and the telescope operators for their help during the observations.

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