ARIES: Arizona infrared imager and echelle spectrograph

D. W. McCarthy, J. Burge, R. Angel, J. Ge, R. Sarlot, B. Fitz-Patrick, and J. Hinz

Steward Observatory, The University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721-0065

ABSTRACT

ARIES, a new 1-5 μm camera/spectrograph, is designed to capitalize on the exceptionally low thermal background and high optical throughput offered by the f/15 adaptive secondary system being built for the upgraded 6.5m MMT. With two state-of-the-art infrared arrays (1024^2 pixel), ARIES will provide diffraction-limited imaging in the JHKLM atmospheric windows and also echelle, long-slit, and multi-slit spectroscopy at resolutions of 2,000 and 30,000. ARIES will also supply global wavefront tip/tilt information to the adaptive system using cryogenic pickoff mirrors to access field stars over a 50 arcsec diameter field at wavelengths from 1-2 μm.

Keywords: adaptive optics, infrared, high resolution imaging, spectroscopy

1. INTRODUCTION

In early 1999, the upgraded 6.5 m MMT will become operational with a uniquely powerful adaptive optics system[1] capable of matching or exceeding the spatial resolution of the Hubble Space Telescope at wavelengths from 0.5-5μm. This system features a Cassegrain secondary mirror as the deformable element and thereby provides high optical throughput and exceptionally low thermal background, essential for operation in the thermal infrared. The advantages for efficient astronomical spectroscopy are especially significant[2]. The ARIES instrument is designed to capitalize on these advantages for astronomical imaging and spectroscopy from 1-5 μm.

2. DESIGN PRINCIPLES

The primary consideration in the optical and mechanical design of ARIES is to preserve the low thermal background and high throughput offered by the adaptive optics system. As a result, ARIES will be a completely sealed, cryogenic, Cassegrain instrument. The only warm optical surfaces seen by the ARIES detectors are the two telescope mirrors and a dichroic entrance window which serves as the vacuum seal to the main instrument and a visible light (<1 μm) feed to the "Top-Box" wavefront sensors (*e.g.*, sodium laser guide star and on-axis natural star). All other components of ARIES (optics, internal baffles, detector subsystems) will be cooled to reduce their thermal emission. The initial f/15 focal plane will be located 25 cm below this window, followed by a cooled field stop and reflective Offner relay (1:1) for achromatic baffling of the telescope pupil.

An important feature of the MMT adaptive optics system is the use of field stars, **in the near-infrared**, to monitor global "tip/tilt" wavefront errors which are not sensed by the sodium laser[3]. This requirement not only improves the resulting Strehl ratio but also ensures broad sky coverage. Consequently any instrument using the adaptive optics system must be capable of measuring rapid centroid fluctuations of the faintest possible field stars over a total field of ~100 arcsec. ARIES accomplishes this task in the initial, cooled focal plane using a pair of small pick-off mirrors to feed a near-infrared quadrant detector. In order to avoid compromising imaging performance, strict tolerances are placed on the flexure of this mechanism.

ARIES is designed to utilize the adaptive performance of the MMT for both high spatial resolution and sensitive, efficient spectroscopy. These two functions allow ARIES to be modular: one section (Figure 1) being purely a camera/slit-viewer (1-2.5 μm) and the other (Figure 2) a camera/spectrograph (1-5 μm). The former can be used on other telescopes and also provides a first-light capability at the MMT to validate the performance of the adaptive system. Thus, the full capabilities of ARIES can be implemented progressively while still providing very significant first-light capabilities. Also, it will be possible to use some modules of ARIES on other telescopes to take full advantage of the large financial investment in the infrared focal plane arrays.

3. EXPECTED PERFORMANCE OF THE ADAPTIVE SECONDARY SYSTEM

The performance of the adaptive optics system at the Mt. Hopkins site has been modelled extensively to aid in the practical design of ARIES. We have simulated a variety of realistic observing situations involving wavefront sensing (sodium laser guide star or visible light from the on-axis astronomical object) and the use of near-infrared guide stars at various off-axis angles for global

Part of the SPIE Conference on Infrared Astronomical Instrumentation • Kona, Hawaii • March 1998
SPIE Vol. 3354 • 0277-786X/98/$10.00

tip/tilt sensing. Under median atmospheric conditions at 2.2 μm (r_0 = 1.0m, t_0 = 21 ms, $theta_0$ = 15 arcsec, and d_0 = 25 m) and with typical adaptive performance criteria, the expected Strehl ratios range from ~0.3-0.6 in the J,H,K,L, and M bands. About 40-60% of the photons from an unresolved source should fall within a 0.2 arcsec diameter circle. Thus, the spectrograph entrance slit width should match the 0.2 arcsec image to obtain high throughput. However, higher spectral and spatial resolution can be achieved by reducing the slit width to match the diffraction-limited core of the image at a cost of about a factor two in throughput.

Higher Strehl ratios can be achieved by using the 1-2 μm light from an on-axis, natural guide star for wavefront sensing. In this mode, 40-70% of the photons are concentrated within 0.1 arcsec so that an even narrower slit would provide higher spatial resolution and a reduction of sky background for observations of faint objects.

Because of the limited atmospheric isoplanatic angle in the JHK bands, the encircled energy within 0.2 arcsec diameter drops from 40-60% when the object is nearly on-axis to 20-40% at an angular separation of 30 arcsec. Therefore, the useful full field-of-view for multiple object spectroscopy is ~60 arcsec.

Differential atmospheric dispersion blurs the stellar image by as much as ~0.1-0.2 arcsec in the J and H bands at zenith angles greater than ~30 degrees. In order to avoid transmission losses at the slit of a spectrograph, ARIES will incorporate an atmospheric dispersion corrector.

4. HIGH ANGULAR RESOLUTION IMAGING

ARIES has two cameras for diffraction-limited resolution from 1-5 μm. These can be used simultaneously to provide well registered imaging at both 1-2.5 μm and 2.8-5.0 μm. The first camera (Figure 1) incorporates a 1024^2 pixel HAWAII detector[4] for wavelengths between 1-2.5 μm. It provides two scales for the reimaged focal plane, f/15 and f/30, to achieve Nyquist sampling (λ/2D pixels) of the diffraction-limits (0.04-0.07 arcsec) in the JHK bands. An initial lens triplet (BaF_2, SF6) provides an extended collimated space which can accomodate standard filters, a Lyot mask for coronagraphy, low resolution (R~200-400) grisms, and potentially a Fabry-Perot etalon. The final focal plane scales are then generated by switchable, refractive elements of the same materials immediately ahead of the detector array. This camera can also be used as a slit-viewer for object centering and guiding during spectroscopic observations. It will also be able to image the cold pupil stop to assist in precisely aligning ARIES on the telescope.

The second camera (Figure 2) senses the wavelength range from 1-5 μm. By switching between grating assemblies and a flat mirror, one can select between various spectroscopic modes and an imaging configuration. All share a single collimating mirror and a three element reflective camera. This combination reimages at f/5.6 (0.1 arcsec pixels). Two other imaging scales (f/10.3, 20.6) are provided for Nyquist sampling of the diffraction-limits at HKLM. These incorporate switchable refractive doublets (ZnSe, CaF_2).

Two 1024^2 pixel detectors are under consideration for the long wavelength channel: InSb (ALADDIN; 27 μm pixels) from Santa Barbara Research Corp. and a HgCdTe array (MBE process; 18.5 μm pixels) from Rockwell. The latter is an exciting new alternative which requires cooling only to ~60 K, thus eliminating the need for liquid helium cryogens or mechanical coolers. We have completed optical designs for either possibility.

5. SPECTROSCOPY

Several spectroscopic modes are available in ARIES. Typically all modes will use a 0.2 arcsec slit with 0.1 arcsec pixels. However, in excellent seeing conditions and especially when the on-axis target can be used for wavefront sensing, a slit width of 0.1 arcsec can be selected. The optical design is a completely reflective, nearly littrow configuration. It includes a single-mirror collimator (50 mm beam diameter), interchangeable gratings with prism cross-dispersers, and a three-mirror camera. The camera optics form an additional, but somewhat degraded, pupil image ahead of the final focal plane. This image can help in baffling the entire optical train.

In its cross-dispersed echelle modes, ARIES provides efficient wavelength coverage. The complete JHK bands can be sampled simultaneously at a spectral resolution ($R=\lambda/\Delta\lambda$) of 2000. The order separation varies from 10 arcsec in the K band to 26 arcsec in the J band. A higher resolution (R=30,000) mode covers these bands in two grating settings where the order separation ranges from 2.4-5.2 arcsec. At this same resolution with a different cross-disperser, four wavelength settings will cover the LM bands.

The limiting magnitudes of this system are impressive. Assuming a spectrograph efficiency of 15%, average sky backgrounds (J=14.8 mag/arcsec^2, H=13.5, K=13), and a combined sky/telescope emissivity of 20% from 4-5 μm, we expect to reach the following 10σ limiting magnitudes in one hour integrations:

Wavelength (μm)	R=2000	R=30,000
1.25	20.7mag	18.5 mag
2.2	19.3	17.4
3.6	15.3	13.8
4.8	12.9	11.4

The f/5.6 camera also yields a ~107 arcsec field-of-view for long- and multi-slit observations. Low resolution (R=200-400) grism spectroscopy is available with the 1-2.5 μm camera system.

6. TIP/TILT WAVEFRONT SENSING

In its initial cooled focal plane ARIES can access field stars to provide active centroid measurements which are necessary to stabilize overall image motion in the adaptive system. A pair of small (~2 mm) pickoff mirrors and lenses, mounted on spider assemblies to x,y translation stages to cover a 50 arcsec diameter field, can intercept the 1-2 μm light from such stars and direct a collimated beam onto a fixed lens which then refocuses the light onto an infrared quadrant detector. To ensure broad sky coverage and excellent performance with the adaptive optics system, this detector must combine high speed capability (~ 20-100 Hz) with low readnoise (<5 electrons) and high quantum efficiency. Several options are under consideration including small format arrays of InGaAs, HgCdTe, and InSb.

7. ACKNOWLEDGEMENTS

The authors are grateful to Drs. G. and M. Rieke for helpful suggestions and for the background levels expected at Mt. Hopkins. Dr. F. Low and the staff of Infrared Laboratories, Inc. have assisted in characterizing and specifying the infrared detectors. The development of ARIES is sponsored by grants from the NSF (AST-9623788) and AFOSR (F 49620-96-1-0366).

8. REFERENCES

1. Barrett, T.K. *et al.* 1998, "Adaptive secondary mirror for the 6.5m MMT", this conference.
2. Ge, J., Angel, R., Sandler, D., Shelton, C., McCarthy, D., and Burge, J., "Adaptive optics spectroscopy: preliminary theoretical results", Proc. SPIE, 3126, in press.
3. Sandler, D., Stahl, S., Angel, J.R.P., Lloyd-Hart, M., and McCarthy, D., " Adaptive optics for diffraction-limited infrared imaging with 8m telescopes", JOSA A, 11, 925-945, 1994.
4. Kozlowski, L.J. *et al.*, "2.5 μm PACE-I HgCdTe 1024x1024 FPA for infrared astronomy", Proc. SPIE, 2268, 353-364, 1994.

Further author information -
D.W.M. (Correspondence): Email: dmccarthy@as.arizona.edu; Telephone: 520-621-4079; Fax 520-621-9843; WWW: http://athene.as.arizona.edu:8000/caao

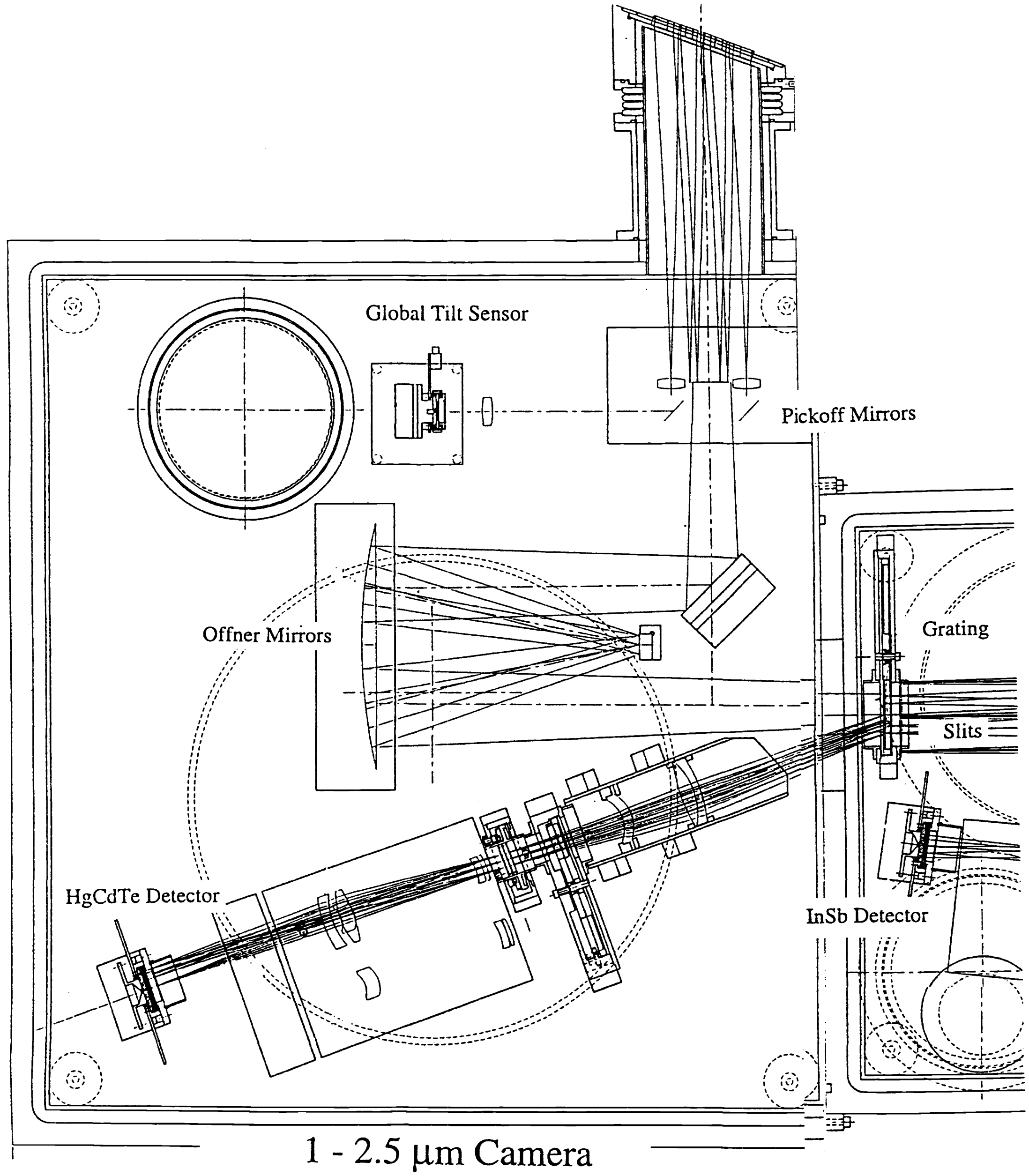

Figure 1. The 1-2.5 μm camera module of ARIES. Converging light from the adaptive secondary mirror enters the ARIES dewar directly to minimize thermal background. A dichroic entrance window reflects wavelengths <1 μm into the "Top-Box" for wavefront sensing while the longer wavelengths are transmitted and form an initial cooled focal plane (f/15) 25 cm below. Over a 50 arcsec diameter field, the 1-2 μm light from natural field stars is picked-off and sent to a global tip/tilt wavefront sensor for active centroid measurements. An Offner relay produces a sharp, achromatic pupil image for thermal baffling and reimages the focal plane onto the slit/dichroic assembly. A 1024^2 pixel HgCdTe (1-2.5 μm) camera provides diffraction-limited imaging, coronagraphy, grism spectroscopy, and slit-viewing for accurate positioning and guiding onto the main spectrograph which attaches to the side.

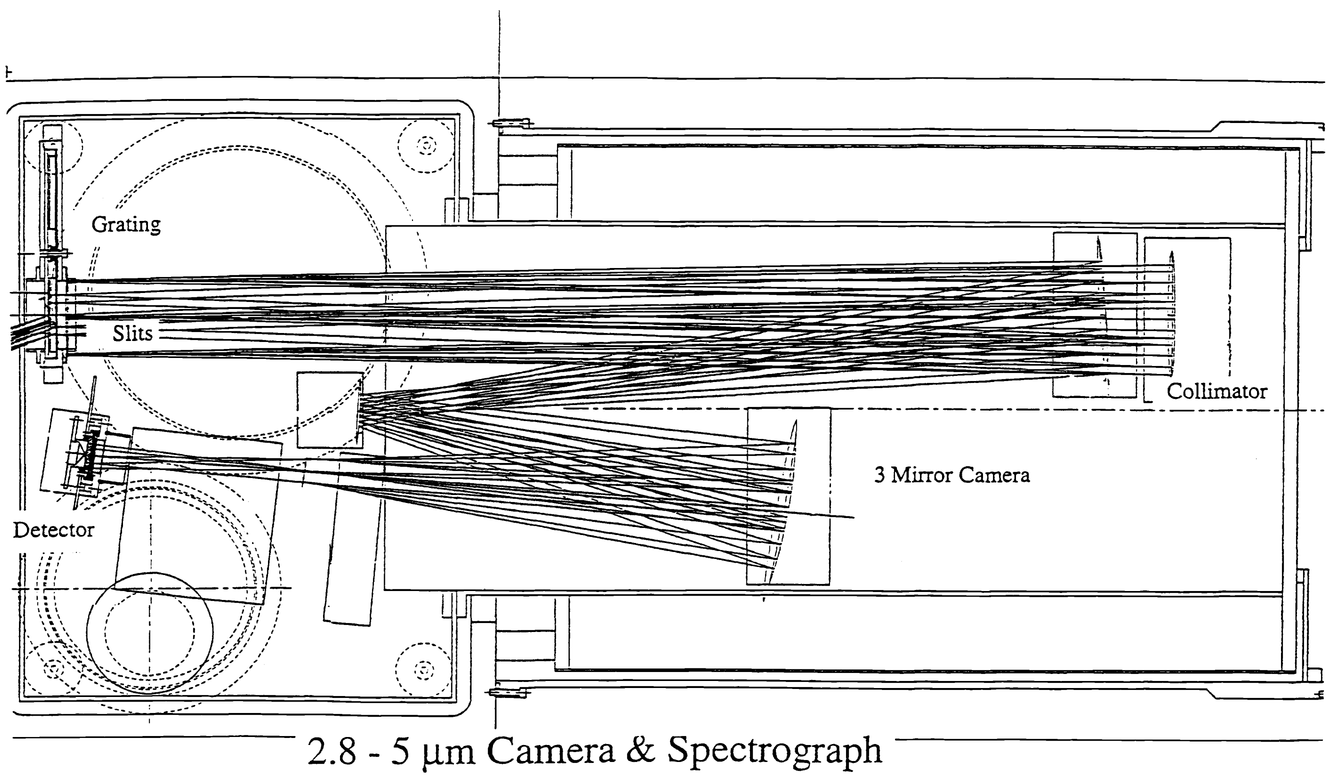

Figure 2. The 2.8-5 µm camera and spectrograph. Using a reflective collimator (50 mm beam diameter) and a three-mirror camera, this module provides echelle, long- and multi-slit spectroscopic modes at resolutions of 2,000 and 30,000. The grating assembly lies above the plane of this figure and consists of a carousel of gratings, prism cross-dispersers, and a flat mirror for direct imaging. A slit assembly switches between 0.1 and 0.2 arcsec slits and a dichroic. The latter permits simultaneous imaging with both camera subsystems.