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THE GUIELOA ADAPTIVE OPTICS SYSTEM FOR THE OBSERVATORIO ASTRONÓMICO NACIONAL

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RESUMEN

Se describen los avances para construir un sistema de óptica adaptativa para el telescopio de 2.1-metros del Observatorio Astronómico Nacional en la Sierra de San Pedro Mártir. El sistema utilizará un espejo deformable de tipo bimorfo de 19 elementos montado sobre una plataforma articulada y un sensor de frente de onda tipo curvatura para estrellas guía naturales. Guieloa tendrá dos modos de operación. En modo de óptica adaptativa se espera que proporcionará una corrección excelente en longitudes de onda mayores a $1.0\,\mu$m y una corrección buena entre 0.6 y $0.9\,\mu$m dependiendo de las condiciones del seeing, aunque la cobertura del cielo será restringida. En el modo de óptica activa y guiado rápido se espera que proporcionará imágenes en el límite del seeing natural o mejor, y con una cobertura de cielo mucho mayor. Actualmente el sistema se encuentra en la fase de pruebas en el laboratorio y se espera que sea entregado en el observatorio en 2009.

ABSTRACT

We describe progress in the construction of an adaptive optics system for the 2.1-meter telescope of the Observatorio Astronómico Nacional on Sierra San Pedro Mártir. The system will use a 19 element bimorph deformable mirror mounted on an articulated platform and a curvature wavefront sensor with natural guide stars. Guieloa will have two modes of operation. In adaptive optics mode, the system is expected to give excellent correction above $1.0\,\mu$m and good correction down to 0.6–$0.9\,\mu$m, depending on the seeing, although the sky coverage will be limited. In "active optics and fast guiding mode", the system should give images at or better than the natural seeing of the site and have much greater sky coverage. The system is currently undergoing laboratory testing and should be commissioned in 2009.

Key Words: **INSTRUMENTATION: ADAPTIVE OPTICS**

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1. INTRODUCTION

The current shift in optical and infrared astronomy from seeing-limited telescopes to diffraction-limited telescopes is probably as important as the shift from lenses to mirrors a century ago. Indeed, it may be more important, because while mirrors, hypersensitized photographic plates, image intensifiers, CCDs, and many of the other technological advances of the last century allowed observers to study increasingly fainter objects, they did little to improve spatial resolution; fuzzy images continued to plague interpretation.

Optical and near-infrared telescopes achieve their diffraction limit only in space or when they use adaptive optics (AO) systems. These alternative technologies have very different technical and economic trade-offs. Telescopes in space have good sky coverage, stable point spread functions (PSFs), and can work well at short wavelengths, whereas ground-based telescopes with AO systems have limited sky coverage, PSFs that vary with time and with field position, and work best at longer wavelengths. However, a ground-based telescope with an AO system is one or two orders of magnitude less expensive than a space telescope, so economics dictate that there are more ground-based telescopes with AO systems than space telescopes and that the ground-based telescopes are larger and therefore have potentially finer images when working at their diffraction limit. Indeed, except for applications which need extremely high contrast, such as imaging planets, space telescopes are increasingly uncompetitive with ground-based telescopes with AO systems; despite the unprecedented success of the *Hubble Space Telescope*, its successor seems optimized more for low thermal background than for high spatial resolution.

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The Mexican astronomical community has very limited experience with AO; none of our current telescopes has an AO system, our instrument builders have never constructed an AO system, and very few of our observers have used AO systems on other telescopes. Therefore, several years ago the the UNAM began a program to construct an AO system for the 2.1-meter telescope of the Observatorio Astronmico Nacional (OAN) on Sierra San Pedro Mártir (SPM), Baja California. The system is called Guieloa, which means "our eyes" in the Zapotec language indigenous to the state of Oaxaca. Despite being conceived primarily as a tool for learning about AO and despite being on what is now a small telescope, we anticipate that Guieloa will offer the possibility for interesting science in a number of niches. In this contribution we describe Guieloa, its current status, and its expected performance, and we outline its scientific potential.

2. GUIELOA

2.1. *Description*

Guieloa will be mounted on the 2.1-meter telescope in the position of the current guider. It will take the aberrated f/13.5 input beam, remove low-order aberrations, expand the beam to f/50, and feed this beam to one of the instruments described in § 3. Guieloa will operate in either "adaptive optics mode" or "active optics and fast guiding" mode. These modes are described in §§ 4 and 5.

The correction system will employ a nineteen-element bimorph deformable mirror mounted on a fast, articulated platform. The control system will employ a curvature wavefront sensor (WFS) with avalanche photodiodes (APDs). These components are very similar to those of PUEO on CFHT (Rigaut et al. 1998). This similarity is not accidental; to minimize risk, we decided to base Guieloa on a working and well-characterized system. The correction and WFS components were largely acquired from Laplacian Optics Inc., but the lens array for the WFS was built in the optical shop of the Instituto de Astronomía UNAM (see the contribution by Chapa et al. this volume). The only major modification we will make to the acquired components is to run the real-time control software on modern VME single-board computers running a real-time Linux. This modification is necessary as the original Force computers are no longer manufactured and so we cannot obtain spares.

The WFS will use natural guide stars and will sense from 0.6 to 0.9 μm. Light will be fed to the WFS using a dichroic or one of several beamsplitters (e.g., 10%/90%, 50%/50%, or 90%/10%) according to whether the instrument works in the optical or near infrared and the guide star magnitude. We hope to be able to use guide stars at least 90″ from the optical axis. Obviously, stars this far will not be suitable for higher-order adaptive optics correction, but may well be useful for fast guiding (see §5).

Fig. 1. Guieloa on an optical bench in the laboratories of the Instituto de Astronomía UNAM. The deformable mirror mounted on the articulated platform is at the far left. The wavefront sensor lens array is at the far right. The vibrating mylar mirror is the third component from the right.

The quality of the Guieloa optics is expected to be better than $\lambda/30$ at 0.65 μm within a 30″ diameter field and $\lambda/10$ at 0.65 μm within a 180″ diameter field. These correspond to Strehl ratios of 0.95 and 0.70 at 0.65 μm. The optical quality will be proportionately better at longer wavelengths. An atmospheric dispersion corrector (ADC) will correct atmospheric dispersion in broad-band filters to within a fraction of the Airy disk at zenith distances of up to 60° at wavelengths from 0.6 to 2.5 μm.

With the exception of the ADC and the dichroic or beamspliter, Guieloa will use all-reflecting optics in order to work from the optical to the near-infrared. However, aluminum coatings are unsuitable because of their relatively low reflectivity from 0.6 to 0.9 μm where the WFS APDs are most sensitive. Gold is also not ideal because it has such poor reflectivity in the blue. Instead, we expect to use protected silver coatings with the potential to achieve transmittance's to the instrument of greater than 75% from 1.0 to 2.5 μm and greater than 50% from 0.5 to 1.0 μm. The transmittance to the WFS from 0.6 to 0.9 μm is also expected to be above 50%. Unfortunately, these good transmissions at longer wavelengths will come at the cost of relatively poor trans-

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TABLE 1

IMAGERS

Instrument	Detector	Field	Pixel Scale	Good Sampling[a]
Cataviña $f/50$	HAWAII 1024 × 1024	36″ square	0.″035	$\geq 0.72\,\mu$m
Cataviña $f/17$	HAWAII 1024 × 1024	57″ diameter[b]	0.″106	$\geq 2.16\,\mu$m
Mexman $f/50$	e2v 2048 × 2048 CCD	54″ square	0.″026	$\geq 0.54\,\mu$m
Mexman $f/33$	e2v 2048 × 2048 CCD	81″ square	0.″039	$\geq 0.54\,\mu$m

[a]Wavelengths for which the sampling is $\lambda/2D$.

[b]The field of the Cataviña $f/17$ camera is limited by vignetting by the collimator.

mittance to the instrument of 15%–50% from 0.3 to $0.5\,\mu$m. However, correction will be relatively poor in this region.

A CCD field-viewing camera will aid with the acquisition of the target and a suitable guide star. It will be possible to steer the output beam of Guieloa independently of the telescope to ease target centering and dithering.

2.2. *Status*

The summer of 2005 saw the completion of the last component, the assembly that mates the WFS lens array to the fibers that connect to the APDs (see the contribution by Chapa et al. in this volume). The correction and control systems were then mounted on an optical bench in the laboratories of the Instituto de Astronomía UNAM (see Figure 1). There then followed several frustrating weeks chasing aberrations in the ancillary optical components.

In the immediate future we will determine safe light levels and operating procedures for the APDs. We then expect to begin to operate the correction system, first flattening the deformable mirror without turbulence and then attempting to correct for dynamic aberrations introduced by rotating phase plates.

2.3. *Schedule*

Guieloa is approaching its system-level tests in the laboratory. However, there remains a great deal of work to transfer it to the telescope. We expect to proceed with design, fabrication, and testing in the Instituto de Astronomía UNAM and CIDESI and hope to commission the system in 2009.

3. INSTRUMENTS

Constraints on our budget and the availability of man-power do not afford us the luxury of constructing instruments dedicated to Guieloa. Therefore, Guieloa will be used with the existing suite of seeing-limited optical and infrared instruments. The beam will be expanded from $f/13.5$ to $f/50$ to provide good sampling. The slower beam will also reduce aberrations in the instruments.

3.1. *Near Infrared Imaging*

Near-infrared imaging between $0.9\,\mu$m and $2.5\,\mu$m will be performed with the Cataviña instrument, which is the current Camila instrument (Cruz-González et al. 1994) with its NICMOS-3 detector replaced by a HAWAII 1024 × 1024 array (see Table 1). The only modification necessary to use the instrument with Guieloa will be to replace the $f/13.5$ pupil stop with one appropriate for an $f/50$ input beam. The instrument has two cameras which will give final beams of $f/50$ and $f/17$. The $f/50$ camera will have a 36″ field with 0.″035 pixels and the $f/17$ camera will have a 57″ diameter field (limited by vignetting by the collimator) with 0.″106 pixels. These pixel scales correspond to $\lambda/2D$ sampling from 0.72 and $2.16\,\mu$m.

Cataviña will be equipped with JHK_s broad-band filters and a few narrow-band filters. The read-noise of the detector has not yet been measured. One worry is that the instrumental background may be high above $2\,\mu$m. The detector and filters are in a dewar and are efficiently cooled by liquid nitrogen, but the optical bench is not so well-isolated and operates at significantly higher temperatures. Originally the optical bench was cooled by refrigerated alcohol to about −20 C. Recent modifications allow the use of liquid nitrogen to achieve much cooler temperatures, and the instrumental background in K_s at $f/13.5$ is now reported to be similar to the sky background. Even so, the instrumental background in K_s at $f/50$ is likely to be an order of magnitude higher than the sky background.

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TABLE 2

SPECTROGRAPHS

Instrument	Detector	Slit Width[a]	Pixel Scale[b]	Resolution[c]
Cataviña $f/17$	HAWAII 1024 × 1024	0″.20	0″.11	500
Cataviña $f/50$	HAWAII 1024 × 1024	0″.20	0″.04	1500
Cataviña F-P	HAWAII 1024 × 1024	···	0″.11	13,000
B&Ch	SITe 1024 × 1024 CCD	0″.36–0″.52	0″.17	400–2800
Puma	SITe 1024 × 1024 CCD	···	0″.09	15,000
REOSC	SITe 1024 × 1024 CCD	0″.27	0″.16	23,000
Mezcal	SITe 1024 × 1024 CCD	0″.30–0″.14	0″.05	30,000–60,000

[a]The slit width to give at least 2 pixels per FWHM spectral sampling. This information is not given for the Fabry-Pérot spectrographs PUMA and Cataviña F-P.

[b]The pixel scale parallel to the slit is given for the slit spectrographs.

[c]The spectral resolution $\lambda/\Delta\lambda_{\rm FWHM}$ at Hα or Brγ as appropriate.

3.2. *Optical Imaging*

Optical imaging up to $1.0\,\mu$m will be performed with the Mexman filter wheel and the e2v 2048×2048 CCD (see Table 1). The final $f/50$ beam will give a $54''$ square field with 0″.026 pixels. The Mexman also has an optional focal reducer that will give a final beam of $f/33$, which will give an $81''$ square field with 0″.039 pixels. These pixel scales correspond to $\lambda/2D$ sampling at all wavelengths above $0.54\,\mu$m and $0.81\,\mu$m.

The e2v CCD is arguably the best CCD at the OAN. It has excellent quantum efficiency and linearity and a read noise of only 7 electrons. It is not optimized for use in the red, but the fringes in I are only about 3% peak-to-valley at full moon. The filter wheel accepts 50 mm diameter filters and currently holds Johnson-Cousins *UBVRI* photometric filters (using the Bessel (1990) recipe, but with S8612 instead of BG39) and a range of nebular filters.

3.3. *Spectroscopy*

The 2.1-meter telescope of the OAN/SPM is blessed with a wide range of spectrographs: an optical intermediate-resolution grating spectrograph (the B&Ch), an optical Fabry-Pérot spectrograph (PUMA), an optical cross-dispersed échelle spectrograph (the REOSC), an optical long-slit échelle spectrograph (Mezcal), an infrared low-resolution grating spectrograph (Cataviña), and an infrared Fabry-Pérot spectrograph (Cataviña F-P). We expect that it will be possible to use these with Guieloa, although there may be problems with the heaviest instruments (e.g., Mezcal) and the Cassegrain optics of some instruments (e.g., the REOSC and the B&Ch) may require these instruments to be tilted. The characteristics of the spectrographs when used with Guieloa are summarized in Table 2.

4. ADAPTIVE OPTICS MODE

In AO mode the control loop gains are set to attempt to correct the rapidly changing aberrations caused by atmospheric turbulence. Slower aberrations, from guiding errors, wind shape, and telescope figure errors, are corrected as a side effect.

4.1. *Image Quality*

The final delivered image quality will depend on the atmospheric conditions (the seeing, the wind speed, and the effective height of the turbulence), telescope aberrations and tracking errors, instrument aberrations, the magnitude of the guide star, and the position of the object relative to the guide star. When AO mode achieves good correction, the PSF should have a diffraction-limited core with extended wings. The fraction of light in the core will be approximately equal to the Strehl ratio.

We have modeled the expected image quality using François Rigaut's yao simulator. Our model is somewhat idealized in that we assume that the telescope optics are perfect (or, at least, can be perfectly corrected), that there are no non-common-path aberrations, that the dome seeing has a Kolmogorov spectrum, and the target is at the zenith. However, we conservatively use the current dome seeing, ignoring ongoing efforts to improve this. We take atmospheric profiles of turbulence from Avila et al. (2003), which show the strongest contributions from the ground layer and from the tropopause at 12 km.

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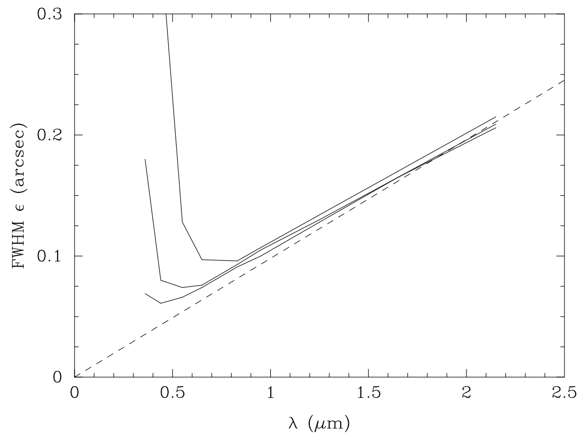

Fig. 2. The expected on-axis FWHM ϵ with a magnitude 10 guide star in AO mode. The solid lines are the expected performance of Guieloa in first-quartile, median, and third-quartile conditions. The dashed line is the diffraction limit λ/D.

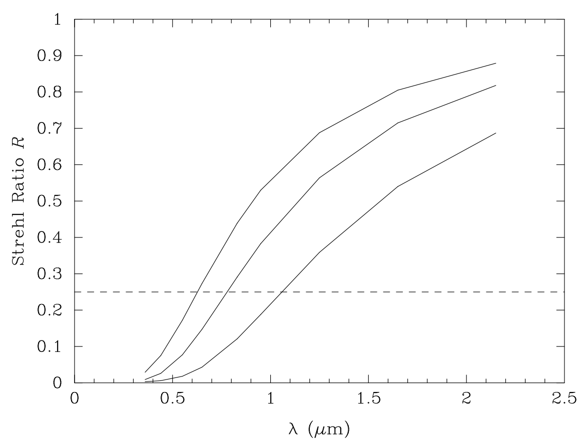

Fig. 3. The expected on-axis Strehl ration R with a magnitude 10 guide star in AO mode. The solid lines are the expected performance of Guieloa in first-quartile, median, and third-quartile conditions. The dashed line marks the limit for good correction $R \geq 0.25$.

We also take values of r_0 at $0.5\,\mu$m from Avila et al. (2003), specifically 0.181 m for first-quartile conditions, 0.132 m for median conditions, and 0.096 m for third-quartile conditions.

The most optimistic case is on-axis with a bright guide star. Figure 2 shows the expected on-axis FWHM ϵ as a function of wavelength for Guieloa in AO mode with a magnitude 10 guide star. Results for first-quartile, median, and third-quartile seeing are shown. The core of the image is expected to be essentially diffraction limited at all wavelengths above $0.9\,\mu$m even under third-quartile conditions. As the seeing improves, the FWHM is expected to be almost diffraction limited down as far as $0.6\,\mu$m. Figure 3 shows the expected on-axis Strehl ratio R as a function of wavelength for Guieloa in AO mode with a bright guide star. In this optimal observing scenario, Guieloa is expected to deliver excellent Strehl ratios in JHK_s and acceptable Strehl ratios in Iz.

As the guide star becomes fainter, the measurements of the residual aberrations become increasingly prone to error and the quality of correction decreases. Figure 4 shows the expected decrease in on-axis Strehl ratio R against the guide star magnitude m_R in median conditions. As we can see, the decrease is gradual. However, we can identify the "limiting magnitude for good correction" as the point at which core of the PSF is no longer close to the diffraction limit. Figure 5 shows the normalized on-axis FWHM $\epsilon D/\lambda$ as a function of the on-axis Strehl ratio R for simulations at different wavelengths between 0.36 and $2.15\,\mu$m and guide stars between magnitudes 9 and 16. The points define a clear locus and show that provided the Strehl ratio R is greater than about 0.25, the FWHM ϵ is less than $1.33\lambda/D$ and hence is close to the diffraction limit. Once the Strehl ratio falls below about 0.25, the partially corrected beam becomes sufficiently incoherent that the FWHM ϵ is much wider than the diffraction limit. The observed performance of PUEO mirrors our simulations (see Figure 11 of Rigaut et al. 1998). Thus, we will define the limiting magnitude for good correction to be the point at which the Strehl ratio drops to 0.25. The limiting magnitudes for good on-axis correction in median seeing range from 11.0 in I to 15.5 in K_s.

However, the quality of correction will also depend on the distance of the target from the guide star. Again, we adopt the point at which the Strehl ratio drops to 0.25 to define the size of the corrected field. Figure 6 shows the radius θ at which the Strehl ratio drops to 0.25 against the guide star magnitude m_R. The corrected fields are tiny at short wavelengths, but for brighter guide stars can be roughly two arcminutes in diameter at K_s. These fields may seem small, but they are roughly twice the radii of the fields of comparable systems on larger telescopes. The reason is that larger telescopes need higher-order AO systems to achieve the same Strehl ratios as Guieloa, but higher-order modes have less angular correlation (Valley & Wandzura 1979; Chassat 1989; Roddier et al. 1993; Chun 1998).

The wider field of view translates into better sky coverage. Taking star densities from Simon (1995),

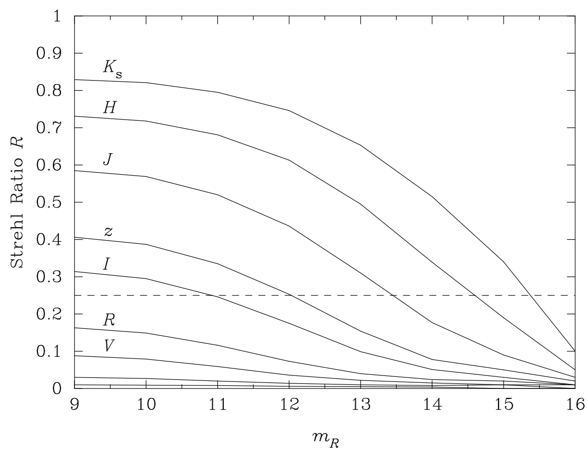

Fig. 4. The expected on-axis Strehl ratio R against the guide star magnitude m_R in AO mode and in median conditions. The dashed line marks the limit for good correction $R \geq 0.25$.

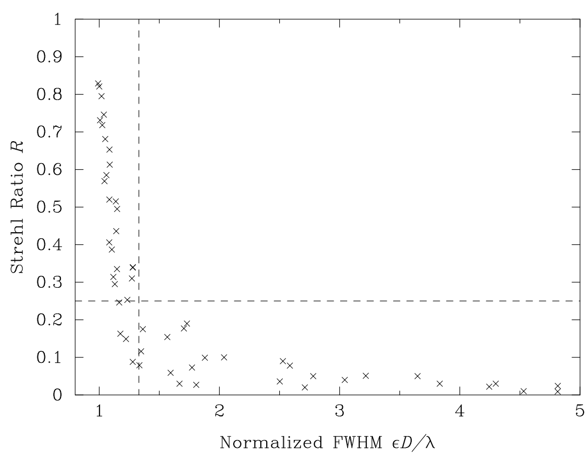

Fig. 5. The expected on-axis normalized FWHM $\epsilon D/\lambda$ against the expected on-axis Strehl ratio R mode with guide stars between magnitudes 9 and 16 in AO mode and in median conditions. The dashed lines show the limits for good correction $\epsilon \leq 1.33\lambda/D$ and $R \geq 0.25$.

we expect sky coverage in K_s of roughly 40% in the Galactic plane and about 5% at the Galactic pole. Sky coverage at shorter wavelengths will be correspondingly smaller.

The expected performance of the AO mode of Guieloa is summarized in Table 3. Guieloa should provide excellent correction in JHK_s and good correction in Iz. However, the sky coverage, while better than that of many systems on larger telescopes, will still be small away from the plane of the Galaxy.

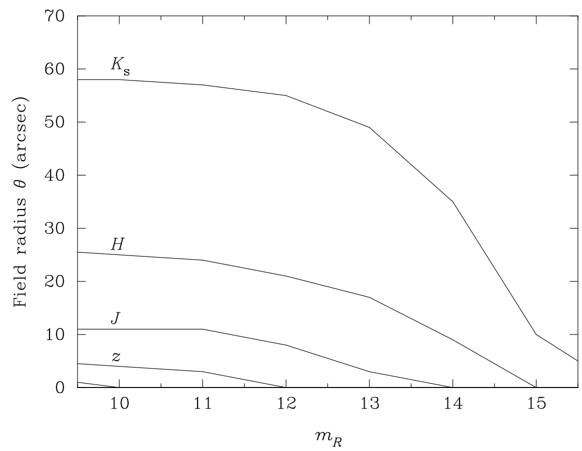

Fig. 6. The expected field radius θ for a Strehl ratio of 0.25 against the guide star magnitude m_R in AO mode and in median conditions.

4.2. *Science*

Given the need for a nearby guide star, observations in AO mode are likely to be largely limited to the environments of relatively bright stars and the plane of the galaxy. This suggests work in binaries and star-forming regions, for example. These fields have been well-tilled over the last few years by AO systems on larger telescopes, so at first sight it seems that Guieloa will have little to contribute. However, the 2.1-meter telescope is shared between a relatively small community of observers, and it is quite possible to obtain large amounts of time. This suggests projects that observe larger samples than previous studies or that require synoptic monitoring.

An example might be observations of morphological variability in edge-on disks around young stars. In these objects, the disk acts as a natural coronagraph high above the atmosphere and occults the star completely. Thus, observations require high spatial resolution but not high contrast, and as such AO systems are ideal provided there is a suitable nearby guide star. Fortunately, several disks are known in binary systems with magnitude 10–13 primaries.

Figure 7 shows morphological variability in HH 30 (Burrows et al. 1996; Wood & Whitney 1998; Stapelfeldt et al. 1998; Watson & Stapelfeldt 2007). At some epochs the left and right sides of the disk are seen to be roughly equally bright. At other epochs, one side or the other is dominant. The timescale for changes is known to be less than six months, which suggests a mechanism within 1 AU of the star. Wood & Whitney (1998) have suggested asymmetric hot spots on the star, while Stapelfeldt et al. (1998) have suggested warps in the inner disk. However, to

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TABLE 3

SUMMARY OF AO MODE

Wavelength	Filter	R_{10}[a]	θ_{10}[b]	m_{limit}[c]
$0.36\,\mu$m	U	0.01	⋯	⋯
$0.44\,\mu$m	B	0.03	⋯	⋯
$0.55\,\mu$m	V	0.08	⋯	⋯
$0.65\,\mu$m	R	0.15	⋯	⋯
$0.83\,\mu$m	I	0.30	$2''$	11.0
$0.95\,\mu$m	z	0.39	$5''$	12.0
$1.25\,\mu$m	J	0.57	$10''$	13.5
$1.65\,\mu$m	H	0.72	$25''$	14.5
$2.15\,\mu$m	K_{s}	0.82	$60''$	15.5

[a]The on-axis Strehl ratio with a magnitude 10 guide star in median conditions.

[b]The radius from the guide star at which the Strehl ratio drops to 0.25 with a magnitude 10 guide star in median conditions.

[c]The guide star magnitude at which the on-axis Strehl ratio drops to 0.25 in median conditions.

advance, we need to better understand the temporal behavior of this phenomenon.

Ideally, we would like to observe HH 30 with a cadence that is appropriate to timescales of 1 day to 6 months and determine the timescale, periodicity, and stability of the variability. This requires a lot of observing time, more than is feasible for highly-over-subscribed telescopes such as *HST* or the AO-equipped large ground-based telescopes. HH 30 could not be observed by Guieloa, as it is not a (wide) binary and is in a dark cloud, but one could imagine investigating similar phenomena in the disks around HK Tau B (Stapelfeldt et al. 1998) and HV Tau C (Stapelfeldt et al. 2003), whose primaries can serve as guide stars.

5. ACTIVE OPTICS AND FAST-GUIDING MODE

The Sierra San Pedro Mártir has excellent seeing with a median seeing of around $0\farcs7$ at $0.5\,\mu$m (Avila et al. 2003). However, the 2.1-meter telescope rarely delivers image quality better then $1\farcs0$ FWHM. Even though the thermal environment of the 2.1-meter telescope is far from ideal, dome seeing is only about $0\farcs3$, which leaves the median effective seeing at the 2.1-meter at about $0\farcs8$. The remainder of the degradation is probably caused by static aberrations in the telescope and instrument optics and guiding errors.

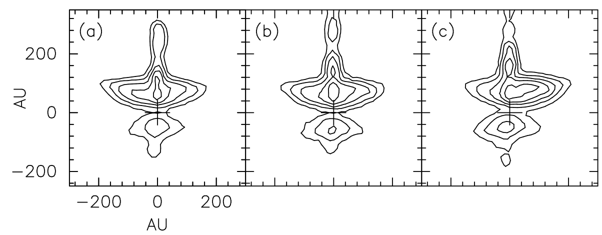

Fig. 7. *HST* observations in R of the circumstellar disk around HH 30 from Watson & Stapelfeldt (2007). The disk is seen as two nebulae extending horizontally. The jet is seen extending vertically. The images were taken at three different epochs. Note the morphological variability: in the left image, the left side of the upper nebula is brighter; in the middle image, both sides have similar brightness; and in the right image, the right side is brighter.

This suggests a use for Guieloa in an "active optics and fast guiding" (aO+FG) mode. In this mode, the control loop gains are set to run the bimorph mirror effectively at a few milli-Hz to correct low-order static aberrations and focus and to run the tip-tilt platform effectively at a few tens of Hz to correct guiding errors, wind shake, and perhaps some atmospheric motion. The slower $f/50$ beam will reduce the severity of aberrations in the instruments. Our inspiration here is HRCam (McClure et al. 1989), of which Jenkins (1998) writes "With hindsight, it seems that the considerable success of HRCam was achieved because it improved the tracking of the CFHT to the point where the superb optical seeing on Mauna Kea became apparent for the first time". We expect that the aO+FG mode will deliver image quality similar to that which could be achieved by a modern telescope on Sierra San Pedro Mártir.

5.1. *Image Quality*

The image quality in aO+FG mode will again depend on the magnitude of the guide star. If the star is sufficiently bright, Guieloa will be able to correct for atmospheric motion, wind shake, and guiding errors. Simulations suggest that stars as faint as magnitude 14 will be adequate for this type of correction. As the isokinetic angle is expected to be around one arcminute, this mode will have much greater sky coverage than pure AO mode. Taking star densities from Simon (1995), we expect essentially 100% sky coverage in the Galactic plane and 10% sky coverage at the Galactic pole.

With fainter stars, Guieloa will only be able to correct for wind shake and guiding errors, and the

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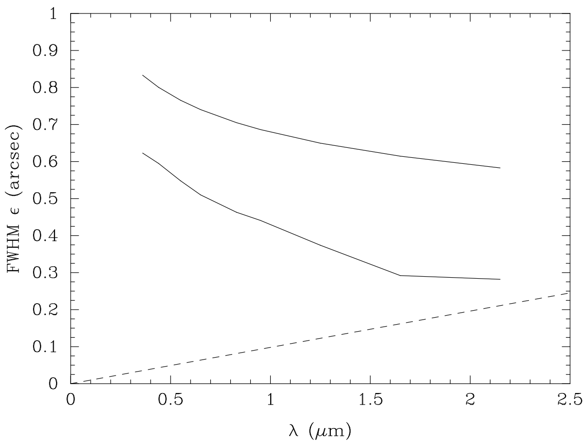

Fig. 8. The expected on-axis FWHM ϵ in aO+FG mode with magnitude 14 and 16 guide stars in median conditions. The dashed line is the diffraction limit λ/D.

TABLE 4

SUMMARY OF FG MODE

Wavelength	Filter	ϵ_{14}[a]	ϵ_{16}[b]
0.36 μm	U	0.62	0.83
0.44 μm	B	0.60	0.80
0.55 μm	V	0.55	0.77
0.65 μm	R	0.51	0.74
0.83 μm	I	0.46	0.71
0.95 μm	z	0.44	0.69
1.25 μm	J	0.37	0.65
1.65 μm	H	0.29	0.61
2.15 μm	K_s	0.28	0.58

[a]On-axis FWHM with a magnitude 14 guide star in median conditions.

[b]FWHM with a magnitude 16 guide star in median conditions.

image quality will be essentially the true seeing. We are currently unable to adequately model the faint limit for this regime, as we do not have a clear understanding of the power spectrum for wind shake and guiding errors at the 2.1-meter telescope, but experience with other telescopes suggests that stars as faint as magnitude 16 or 17 will be adequate. Taking star densities from Simon (1995), we expect about 30% sky coverage at the Galactic pole.

Figure 8 and Table 4 summarize the expected on-axis FWHM with magnitude 14 and 16 guide stars.

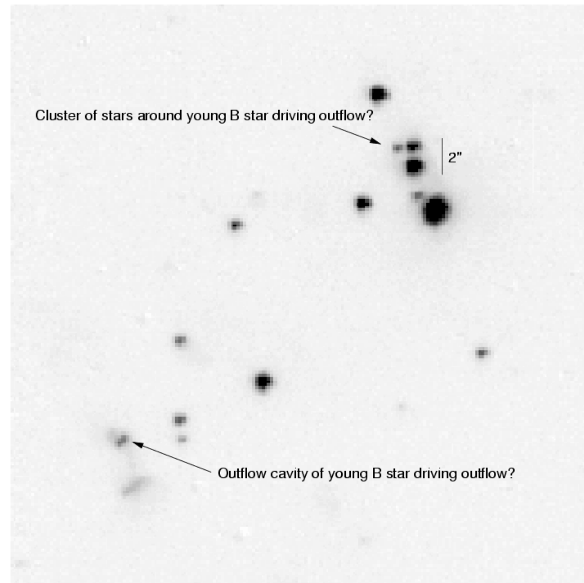

Fig. 9. K_s image of the intermediate-mass star-forming region G173.58+2.45 obtained with NIRIM on the WIYN telescope. The FWHM is 0.″33, similar to that which should be obtained with Guieloa in active optics and fast guiding mode.

5.2. *Science*

The science we can do with Guieloa in aO+FG mode is essentially everything we currently do with the 2.1-meter telescope, but better. For example, Figure 9 shows a K_s image of the intermediate-mass star-forming region G173.58+2.45 obtained with NIRIM on the WIYN telescope. The FWHM is 0.″33, similar to that which should be obtained with Guieloa in aO+FG mode. A compact cluster of stars is seen at the base of a molecular outflow; in this image it is possible to separate the cluster members and attempt to identify the outflow source, something that is not possible in the lower resolution images of Shepherd & Watson (2002) obtained at the 2.1-meter telescope with 1.″7 seeing.

6. SUMMARY

We have described Guieloa, an AO system being built for the 2.1-meter telescope of the Observatorio Astronmico Nacional on Sierra San Pedro Mártir. Being on a small telescope and using natural guide stars, the system will not be directly competitive with state-of-the-art AO systems on large telescopes. Nevertheless, the quantity of time available on the 2.1-meter telescope will lead to interesting science in projects that require large samples or temporal monitoring.

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