

RETROCAM: A VERSATILE OPTICAL IMAGER FOR SYNOPTIC STUDIES

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Received 2004 December 20; accepted 2005 February 7

ABSTRACT

We present RETROCAM, an auxiliary CCD camera that can be rapidly inserted into the optical beam of the MDM 2.4 m telescope. The speed and ease of reconfiguring the telescope to use the imager and a straightforward user interface permit the camera to be used during the course of other observing programs. This in turn encourages RETROCAM's use for a variety of monitoring projects.

Key words: cosmology: observations — instrumentation: detectors — techniques: photometric

1. INTRODUCTION

In an era of 8 m class telescopes, the potential for smaller telescopes to make significant scientific contributions can easily be overlooked. In fact, many institutions are ending long-standing relationships with smaller observatories in favor of fewer numbers of nights at larger telescopes. It is clear, however, that dedicated programs on 1–2 m class telescopes can still have enormous scientific impact either by conducting large homogeneous surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) or by creative exploration of the time domain. In particular, large-scale variability studies have enormous potential; Galactic microlensing studies such as MACHO (Alcock et al. 2000), EROS (Derue et al. 1999), and OGLE (Udalski et al. 1997) have placed constraints on the composition and structure of the Galaxy. Dense time sampling of gamma-ray burst (GRB) afterglows and supernovae has led to the likely conclusion that the GRB phenomenon is a by-product of supernova events (Matheson et al. 2003). The importance of variable star monitoring and its influence on the cosmic distance scale (e.g., Alcock et al. 1995) is well known. Time-delay measurements from monitoring multiply imaged quasars constrain the Hubble constant and the structure of galaxy halos in the important transition region between the baryon-dominated inner regions and the dark matter-dominated outer regions (Kochanek 2005). In addition, the uncorrelated variability due to microlensing of the images can be used to constrain the fraction of the transition region surface mass density in stars, the mean mass of these stars, and the size and structure of the quasar accretion disk (Kochanek 2004).

Rarely do programs of this type require an entire night of telescope time; in fact, many of these variability studies require less than 1 hr per night of observing time. Unfortunately, traditional scheduling and time-consuming instrument changes make it virtually impossible to pursue such programs at most observatories. Some observatories have overcome this problem with queue or remote observing, but most observatories have multiple primary instruments, some of which are spectrographs with no imaging capability. Hence, consistent synoptic surveys are difficult to accomplish. At some telescopes, the presence of auxiliary ports and bent foci have permitted relatively simple solutions

to this problem. The Auxiliary Port Camera (AUX)¹ on the 4.2 m William Herschel Telescope at La Palma is an excellent example of such a system.

RETROCAM, the Retractable Optical Camera for Monitoring, is a solution to this problem for the MDM Observatory 2.4 m Hiltner Telescope. Its primary advantage is that it can be used concurrently with any of the observatory's spectrographs and all but one of its imagers. We initially undertook this project to build a camera for monitoring gravitationally lensed quasar systems, and we demonstrate RETROCAM's suitability for this task. We also show that it is capable of much more than this; the primary purpose of this paper is to discuss how RETROCAM's design and capabilities provide an enormous potential for a variety of exciting scientific programs.

2. RETROCAM SPECIFICATIONS AND CONFIGURATION

2.1. Optomechanical Design

RETROCAM is installed in the 2.4 m Hiltner Telescope's Multiple Instrument System (MIS) at the MDM Observatory on Kitt Peak, Arizona. The MIS was originally conceived as a multi-function device to provide spectral calibration lamps, an intensified video finder camera, and an x-y stage for the telescope's autoguiding system camera. Our design preserved the comparison lamp and guider functions and replaced the antiquated finder camera (a nonfunctioning intensified Vidicon) with a science-quality imager whose quick readout time permits it to also serve as a finder camera, thus maintaining the full original functionality of the MIS and greatly improving its sensitivity. The layout of the MIS and RETROCAM is shown in Figure 1. Light from the telescope is sent to RETROCAM by reflection from a reflective optic that travels into the telescope's beam along two rails. We suppress scattered light with a threaded baffle tube and field stop assembly. The light then passes through a filter wheel equipped with four filters (*g*, *r*, *i*, and *z*) from the SDSS set (Fukugita et al. 1996) and one open position.

¹ Additional information about AUX can be found at <http://www.ing.iac.es/Astronomy/instruments/aux/index.html>.

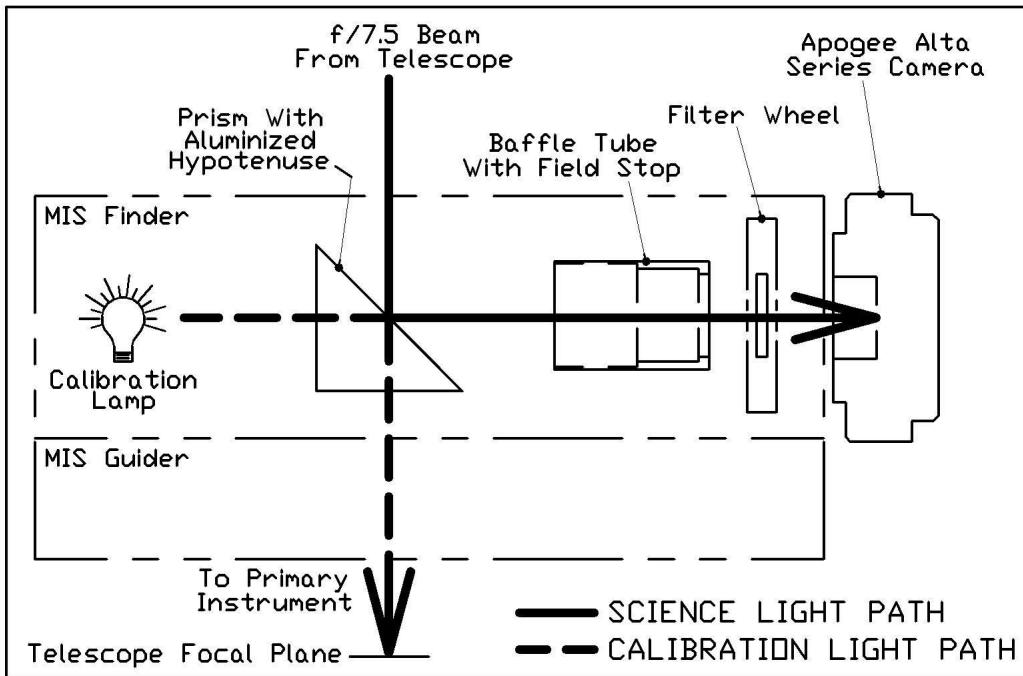


FIG. 1.—Schematic of the RETROCAM and MIS optical paths. With the RETROCAM prism inserted, light from the telescope is reflected orthogonally into the camera. Light from MIS calibration lamps is directed to the primary instrument below via the prism's internal reflection path.

RETROCAM uses an Apogee Instruments, Inc., Alta E-Series² CCD camera with the Kodak KAF-1001E-2 CCD array. The CCD has $24\text{ }\mu\text{m}$ pixels in a 1024×1024 array. When installed on the 2.4 m Hiltner Telescope with the f/7.5 secondary mirror, the pixel scale is $0''.276\text{ pixel}^{-1}$. The array reads out in $\sim 6\text{ s}$ with $21\text{ }e^{-}\text{ pixel}^{-1}$ readout noise at a gain of $7.6\text{ }e^{-}\text{ DN}^{-1}$. The camera employs a two-stage Peltier Thermoelectric Cooler (TEC) capable of maintaining a differential temperature of 45°C with only ambient air cooling. The detector is normally maintained at $-20.0^\circ\text{C} \pm 1^\circ\text{C}$ and operates with a dark current of $1.5\text{ }e^{-}\text{ s}^{-1}\text{ pixel}^{-1}$ at this temperature. At the sky brightness levels typically seen at MDM in the g , r , i , and z bands, noise for all but the shortest exposures is dominated by the contribution from the night sky. The camera is mounted on a manually adjustable focusing mechanism that is not meant for frequent adjustment; the focus was adjusted during installation to conjugate the focus of the telescope's most commonly used spectrograph. The observer accomplishes precise focusing on a nightly basis using the telescope's secondary mirror.

As shown in Figures 1 and 2, the “finder” section of the MIS is located above the guider section. As a result, when the folding optic is in place, it casts a shadow on a significant fraction of the guide field. In order to maintain the ability to guide during RETROCAM exposures, the folding optic was made as small as possible, preserving ~ 100 arcmin² of available guide field that is vignetted by $<20\%$. The original MIS design used the back of the finder mirror to reflect light from the calibration lamps into the spectrographs below. In order to preserve this function while removing the need for a bulky mounting frame, we selected a BK7 prism with an aluminized hypotenuse as our folding optic. The stiffness of the prism allows it to be mounted using the vertical face only. Light from the telescope reflects directly off the aluminized surface, while light from the calibration lamps is sent downward into the primary instrument via the prism's internal reflection path. A weakness of this design

is that the BK7 attenuates the calibration lamp light by $\sim 40\%$ at 4000 \AA compared to the previous design, so longer comparison lamp exposure times are necessary. We consider this to be of minimal impact, given the relatively short times typically required for comparison lamp exposures. Spectral quality is otherwise unaffected.

RETROCAM's relatively small field of view greatly simplified the overall optical design. No field flattener or off-axis correction lenses were necessary to produce a design Strehl ratio $>70\%$ across the entire field of view. The current Kodak detector is a square array and is larger than the design field of view in the east-west direction. The unvignetted region of the detector is a 714×1024 array of $22.5\text{ }\mu\text{m}$ pixels, corresponding to a 3.29×4.72 field of view. The current detector is a proxy for the design model, an Apogee camera employing the E2V CCD55-20 thinned and back side-illuminated CCD. We will install this new detector once it becomes available from the manufacturer. The E2V CCD provides a 30% improvement in quantum efficiency and is properly sized to avoid the vignetting that occurs at the edges of the larger Kodak array.

2.2. Data Acquisition and Instrument Control Software

The Apogee Alta E-Series CCD camera uses an embedded 100-baseT network interface, which is connected directly to the MDM mountain network via a fiber optic ethernet repeater mounted on the telescope. The filter wheel we use is an Optec, Inc.,³ Intelligent Filter Wheel (IFW). This filter wheel holds up to five 2 inch (5 cm) diameter filters and can be operated remotely via an RS-232 serial port using a simple command language provided by Optec. We access this interface via a Comtrol⁴ DeviceMaster RTS four-port network serial port server mounted directly on the MIS box, making the IFW a network-addressable

² See <http://www.ccd.com/alta.html>.

³ See <http://www.optecinc.com>.

⁴ See <http://www.comtrol.com>.

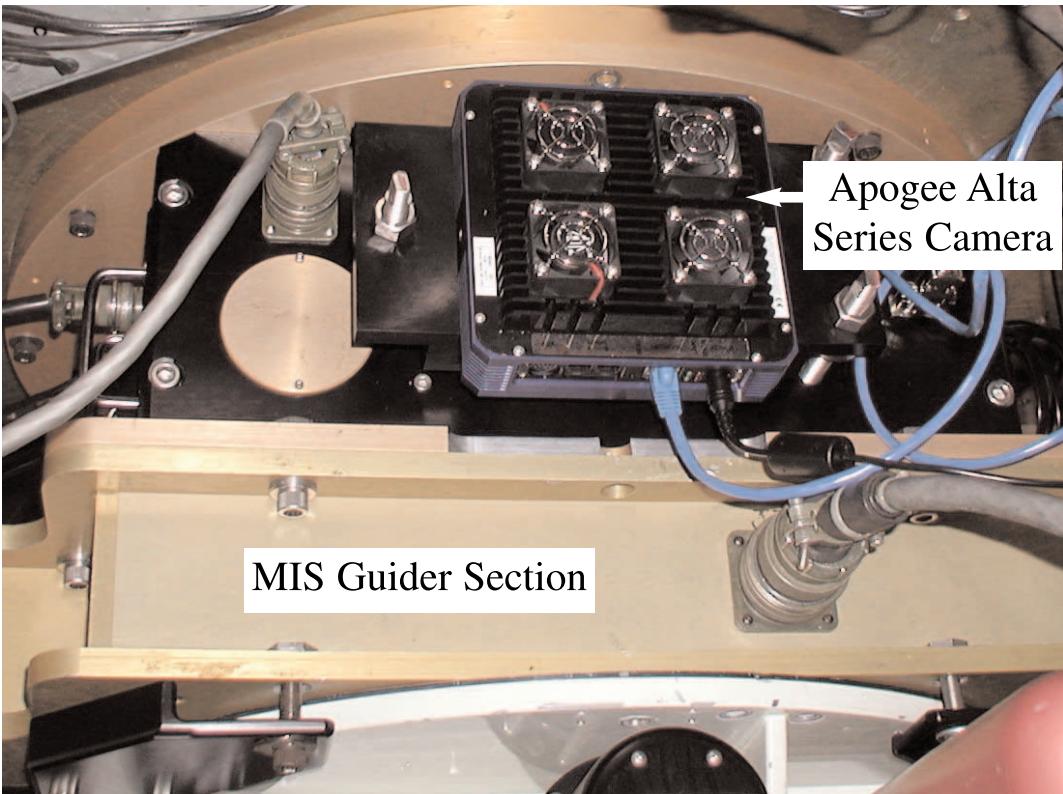
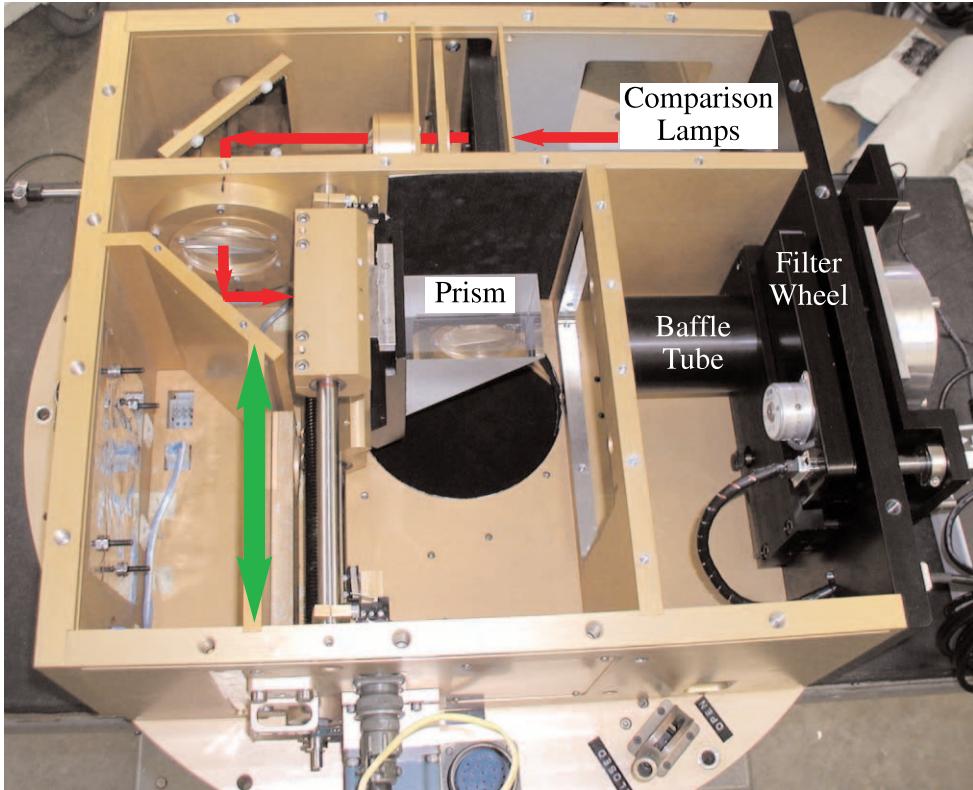


FIG. 2.—*Top:* Upside-down internal photograph of the MIS finder section during RETROCAM installation. The prism is shown in the fully inserted position. The circular aperture beneath the prism allows light from the telescope to enter the MIS. The prism travels in and out of the optical beam along a set of stainless-steel rails. The baffle tube and filter wheel assembly are fastened to the side wall of the MIS (*right*). The compartments at the top of the image house spectral comparison lamps and optics. The red line indicates the comparison lamp light path. The green arrow indicates the prism's direction of motion. *Bottom:* Photograph of RETROCAM following installation on the 2.4 m Hiltner Telescope. The MIS guider is contained in the gold anodized section of the MIS located beneath the camera. The white painted structure at the bottom of the photograph is the Boller & Chivens CCDS.

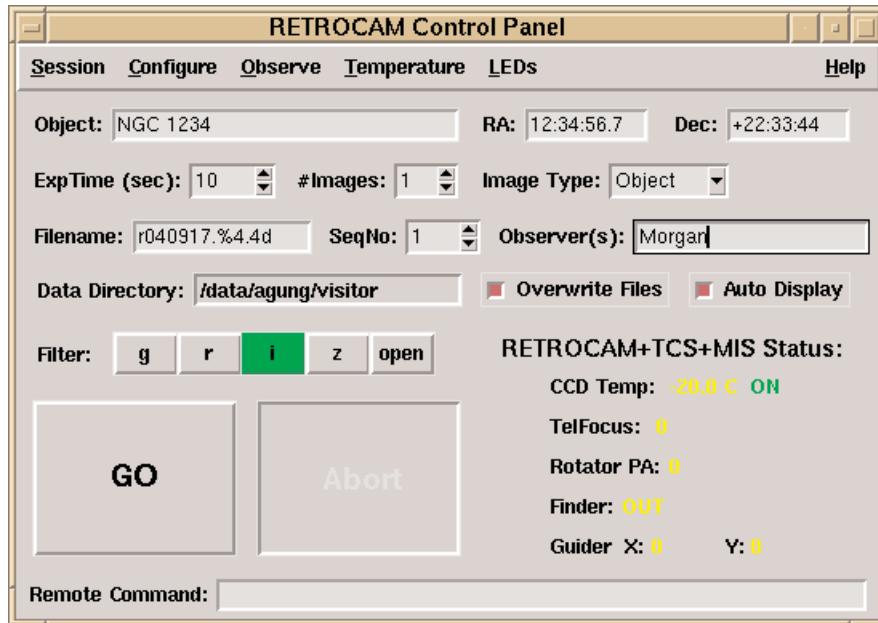


FIG. 3.—RETROCAM GUI.

device. We connect this to the mountain network using the same fiber optic repeater line that services the Alta CCD camera.

The data acquisition software for the Alta camera runs on a Linux workstation located in the 2.4 m control room. The user interface is a custom Tcl/Tk application that is based on a slightly modified version of Apogee drivers for Linux, using code provided by D. Mills.⁵ Our graphical user interface (GUI) is based on Mills's original gui.tcl script, but it is substantially modified to incorporate remote control of the Optec IFW via the network port server and to provide other RETROCAM-specific functions (e.g., TEC control). Data from RETROCAM are written to the hard drive on the Linux workstation in standard FITS format. The data acquisition system also provides a simple TCP-socket interface for remote command operation from other hosts. A screen shot of the beta release version of the RETROCAM data acquisition GUI is shown in Figure 3. This version of the system is being used during the initial deployment phase and will be updated based on user feedback from actual use at the telescope.

The RETROCAM data acquisition system queries the 2.4 m Telescope Control System for the relevant pointing information and derives its UT time/date information from the data acquisition computer's clock, which is synchronized with the Kitt Peak mountain network time server. Future versions of the RETROCAM software will be capable of sending commands, such as focus offsets, to the Telescope Control System. This remote command capability will permit a high degree of automation, which will in turn improve the efficiency of observations with RETROCAM. Inclusion of these functions must await the upgrade of the MDM computer system, currently planned for the summer of 2005.

3. PERFORMANCE AND USAGE

3.1. Commissioning and Testing

RETROCAM was installed in 2004 August and commissioned in 2004 September. We measured a total system (RETROCAM +

telescope optics) throughput of 54% in the *r* band using the current Kodak CCD. In the *r* band, the camera registers $3.11 \times 10^5 e^- s^{-1}$ from an *r* = 12.0 mag star. Once the front side-illuminated Kodak CCD is replaced by the thinned, back-illuminated E2V CCD, we expect that the efficiency will improve by a factor of ~ 1.4 .

We evaluated the flatness of the RETROCAM optical system (folding optic + filter + CCD) by measuring the system's response to the flux from an SDSS standard star (Smith et al. 2002) in a uniform 5×6 grid on the CCD. First, dark current and bias frames were subtracted from each exposure. Next, we measured

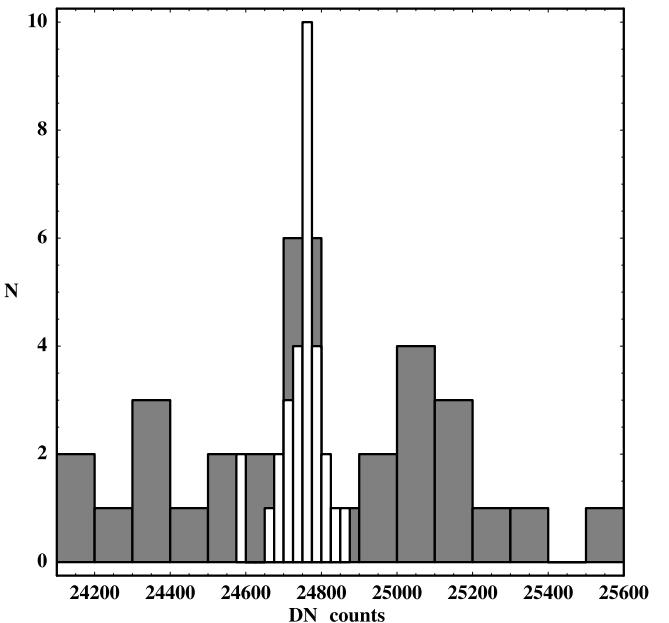


FIG. 4.—Histogram of photometric measurements of the SDSS standard star SA 113 339. Measurements were made at locations in a uniform 5×6 grid on the detector. White bars represent the ensemble of aperture photometric measurements made prior to flat-field correction, and gray bars represent those following flat-field correction.

⁵ Ver. 1.1. See <http://sourceforge.net/projects/apogee-driver> for the most recent version of Mills's driver.

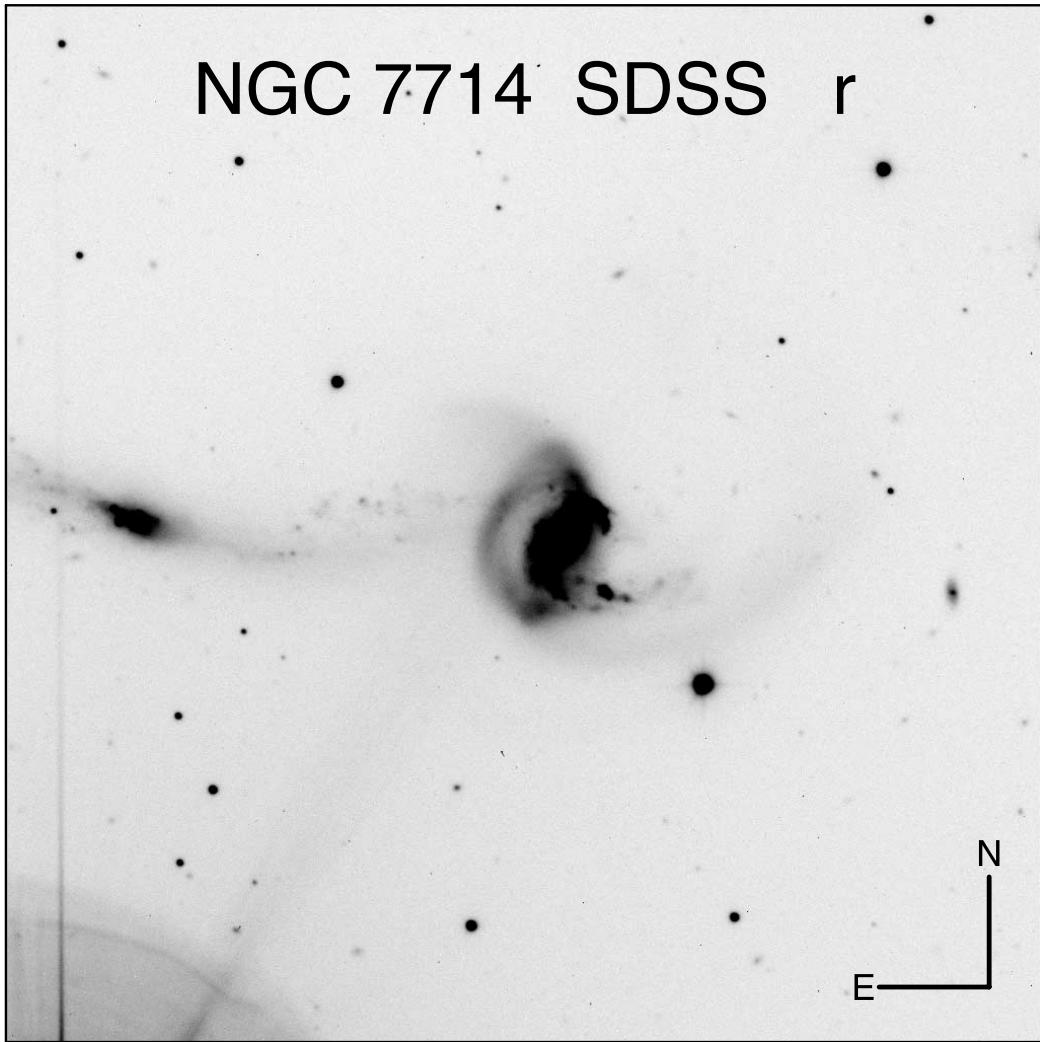


FIG. 5.—SDSS *r*-band image of NGC 7714/15 taken on 2004 August 25. Orientation axes are 30" in length.

the number of detected photons in each image using the Image Reduction and Analysis Facility (IRAF) *qphot* aperture photometry routine. We divided the standard deviation of this sample by the mean and found that $\sigma_{\text{sample}}/\mu_{\text{sample}} = 0.0057$. Hence, RETROCAM is flat to within 0.6% across the entire field of view without application of a flat-field correction. The expected value of $\sigma_{\text{sample}}/\mu_{\text{sample}}$ due to photon flux Poisson noise is 5.7×10^{-4} , which is an order of magnitude smaller than what we find. However, it is unlikely that the common procedure of dividing by a normalized flat field (sky or dome flat) will help us approach this theoretical flatness limit. For example, to reach within a factor of 3 of the theoretical limit, a flat field would need an S/N ≈ 600 and no systematic (scattered light, etc.) effects greater than $\sim 0.1\%$. Obtaining a flat field with such a high S/N and without systematic errors is quite difficult in practice. As a result, applying a standard flat-field correction to RETROCAM images will likely introduce more error than it will remove.

We tested this flat-field hypothesis by generating a night sky flat using a median combination of a large number of equal-length exposures. We normalized this flat and applied it to the SDSS standard star images. We then reperformed the measurement described above and found that $\sigma_{\text{sample}}/\mu_{\text{sample}}$ increased to 0.011, an increase of nearly a factor of 2. This effect is demonstrated graphically in Figure 4. Despite the relatively small number of data points (30), the histogram of the mea-

surements before flattening is obviously narrower than the histogram of the flux measurements following application of the flat field. We assert that the remarkable flatness of the RETROCAM system is yet another quality that makes it an ideal detector for synoptic studies, since time-consuming flat-field corrections are unnecessary for most projects.

In the standard RETROCAM observing procedure, primary observers use the telescope with the instrument of their choice for the majority of the night. At a mutually convenient time, the on-site observers take 15 minutes to reconfigure the telescope and collect data for a dedicated RETROCAM monitoring project, then resume where they left off with very little time lost from their own program. None of the settings of the primary instrument have been changed, allowing a rapid return to the primary observing plan. One complication of this simple plan is that not all primary instruments at the MDM 2.4 m are parfocal. RETROCAM was installed and adjusted to be parfocal with the Boller & Chivens CCD Spectrograph (CCDS).⁶ We have measured the secondary mirror focus offsets between RETROCAM and the other primary instruments at the observatory. A table of these offsets is provided to the observer to improve the efficiency of the focusing procedure. In an attempt to optimize the

⁶ More information about the CCDS can be found at <http://www.astronomy.ohio-state.edu/MDM/CCDS>.

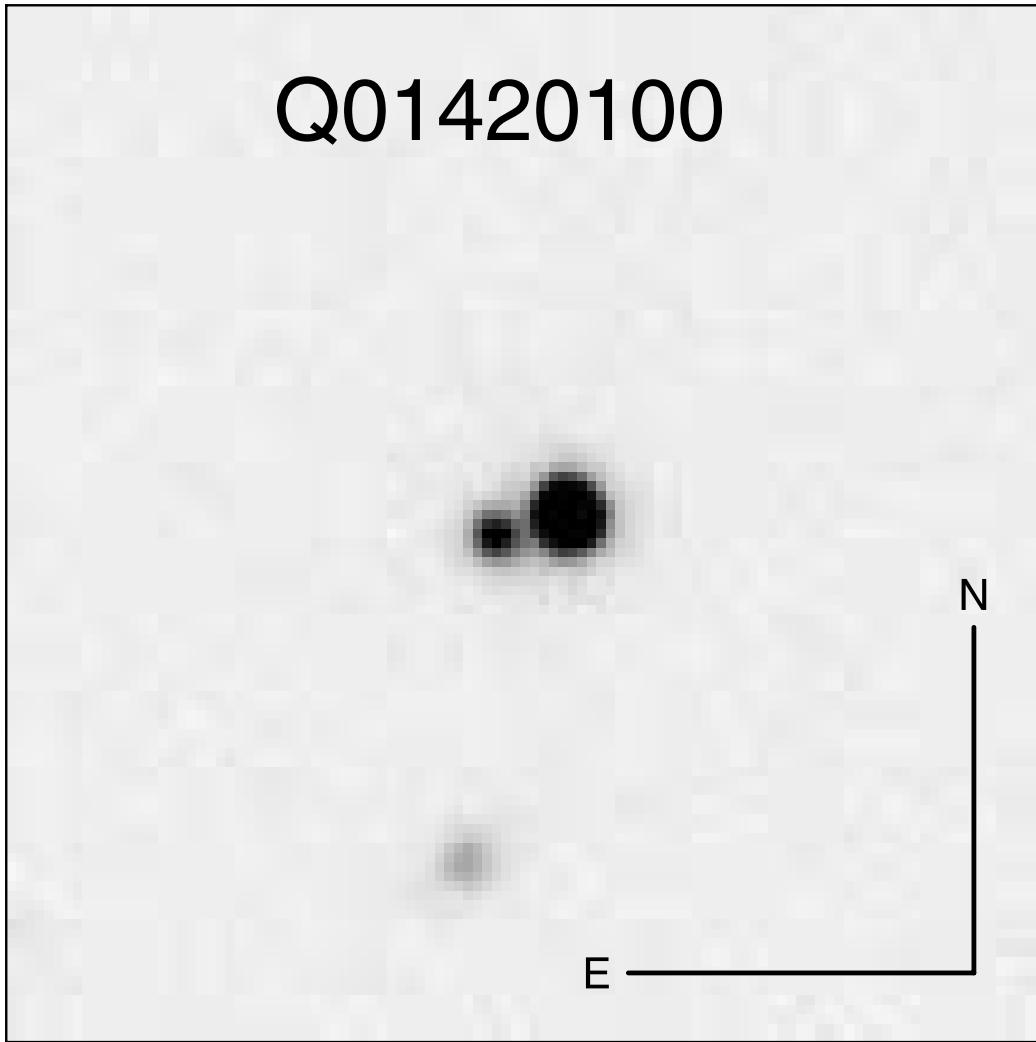


FIG. 6.—Image of the gravitationally lensed quasar system Q01420–100 taken with RETROCAM on 2004 October 2. The two images are separated by 2".4. Orientation axes are 10" in length. Some diffuse light from the lens galaxy can be seen between the two images. This image was taken under 1".1 seeing conditions.

efficiency and accuracy of the lensed quasar monitoring project, future improvements to the RETROCAM control software will automate the insertion of the prism, focus offsets, guide star selection, image capture, and system restoration.

3.2. Sample Results

An example of RETROCAM's high image quality is shown in Figure 5, an image of NGC 7714/15 taken in the r band on 2004 August 25. The image of NGC 7714/15 ($V = 13.3$ mag) was taken under 1".0 seeing conditions. Figure 6 shows an r -band image of the gravitationally lensed quasar system Q01420–100 taken on 2004 October 2 under 1".1 seeing conditions. The images are separated by 2".4. The brighter image has $R \approx 16.6$ mag, and the fainter image has $R \approx 18.7$ mag. Diffuse light from the lens galaxy can be seen between the two images.

4. CONCLUSIONS AND DISCUSSION

This paper describes the RETROCAM instrument and demonstrates that it is fully capable of executing the function for which it was designed, but we believe that it will reap returns far beyond lensed quasar monitoring. RETROCAM represents a significant improvement in the capabilities of the MDM Observatory in the following ways:

1. It provides the capability to take science-quality images and spectra of the same object on the same night.

2. It provides an imager that is nearly always available for targets of opportunity such as supernovae, gamma-ray bursts, and microlensing events.

3. Its field of view and performance are comparable to those of most of the direct imagers at the observatory. For many projects, RETROCAM could be used instead of these imagers, reducing the frequency of primary instrument changes and freeing the observatory staff for other activities. RETROCAM will not completely replace these other imagers, since it cannot be easily outfitted with observer-supplied filters.

RETROCAM is currently in use for several variability studies. C. Morgan and C. S. Kochanek are monitoring a sample of gravitationally lensed quasar systems. A. Gould is using RETROCAM to collect data for the Ångstrom Project,⁷ a microlensing study of the M31 bulge. We expect that other members of the MDM consortium will begin other programs soon. RETROCAM represents an important step forward in the design and operational paradigms of the MDM Observatory. Its

⁷ More information about the Ångstrom Project can be found at <http://www.astro.livjm.ac.uk/Angstrom>.

design could easily be reproduced at other observatories for a relatively low cost. The availability of commercial “off-the-shelf,” high-quality CCD cameras with network capability has greatly simplified this task.

We appreciate Bob Barr’s assistance during RETROCAM installation and testing. We are very grateful to Dave Mills of

The Random Factory in Tucson, Arizona, who provided us with a prerelease copy of his Linux drivers for Apogee cameras and graciously answered our many questions. Having his code to serve as a base greatly accelerated the development of the RETROCAM data acquisition system, enabling us to get onto the telescope quickly. We also thank Apogee Instruments, Inc., for providing us with a loan of an Alta E6 CCD camera until our E55 camera is completed.

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