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A New Acquisition and Autoguiding Camera for the ANU 2·3 m Telescope

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Abstract: A new, direct CCD acquisition and autoguiding camera is in use on the ANU 2·3 m telescope Nasmyth foci. The camera is a model AP7 manufactured by Apogee Instruments Inc. and is controlled by the MaxIm CCD camera control and image processing software developed by Diffraction Ltd. The factors influencing our choice of this new camera are discussed, and its performance, operation, and commercial control software are described. The new camera allows stellar objects as faint as $B = 21\cdot5$ to be acquired on the Double Beam Spectrograph slit in $1\cdot4''$ seeing. The camera has far superior performance to the Fairchild intensified CCD cameras that it replaces. The improved acquisition and guiding permitted by this camera has already allowed several new scientific programs to begin on the telescope, including the use of aperture plates with the Double Beam Spectrograph.

Keywords: instrumentation: miscellaneous — instrumentation: photometers — techniques: image processing

1 Introduction

The Double Beam Spectrograph (DBS; Rodgers, Conroy & Bloxham 1988) is the premier instrument on the Australian National University (ANU) 2·3 m telescope. It can measure low resolution spectra of objects down to $R \sim 20$ mag. The acquisition system used with this instrument until recently has been based on a Fairchild intensified CCD camera. This system suffered from (1) high dark current in warm weather, (2) high pattern noise with a moonlit sky, and (3) the lack of an autoguiding capability. Consequently, the performance of the DBS on faint objects typically measured at low spectral resolution was limited by the capabilities of the acquisition system.

This system has recently been replaced by an Apogee Instruments Inc. model AP7 direct CCD camera which is controlled by the MaxIm CCD camera control and image processing software developed by Diffraction Ltd in Canada. This paper describes the factors used to select the AP7 camera, and its operation and performance for acquisition and autoguiding with the DBS. The camera has been so successful on the DBS that recently it was adapted for use with the Nasmyth B Imager on the 2·3 m telescope as well.

2 Requirements

2.1 Acquisition Camera

In replacing the Fairchild camera system, we sought an acquisition system that could be configured with a scale of $\sim 0\cdot5''$/pixel and have a field-of-view greater than the previous $2\cdot3' \times 1\cdot3'$. We wanted as much as possible of the $6\cdot6' \times 80''$ DBS slit assembly to be viewed in a single exposure, while adequately sampling images obtained in below average seeing. Such a system requires a CCD with at least 280×160 pixels. Ideally the camera should update the image in $\leq$1 s. However, it was realised early-on that this requirement would be difficult to meet with the most sensitive large-format CCDs. Given this restriction, it was important that the camera could be operated in a sub-frame mode in which a windowed region is read out at high frame rate for focussing and autoguiding. The potentially slow full-frame update time also suggested that manually centering objects on the DBS slit using pushbuttons would be tedious. We therefore required a system that could automatically offset a selected object onto a predefined DBS slit position.

Our aim in replacing the Fairchild system was to be able to comfortably acquire objects as faint as

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Table 1. Camera performance model

Parameter	B	V	R	I	Total
Zero magnitude flux (Jy)	4260	3640	3080	2550	...
Adopted wavelength (Å)	4360	5450	6380	7970	...
Adopted width (Å)	1130	800	1500	2500	...
Transmission of atmosphere	0·72	0·84	0·88	0·94	...
Transmission of optics	0·46	0·46	0·46	0·46	...
Object brightness (mag)	22·4	21·6	21·0	20·5	...
Object signal at CCD (photon/s)	25·1	29·6	73·4	136·6	...
Sky brightness (mag/arcsec^2)	22·5	21·5	20·8	19·3	...
Sky signal at CCD (photon/s/arcsec^2)	22·9	32·5	88·2	412·6	...
AP7 camera:					
Q.E.	0·67	0·80	0·85	0·78	...
Object current (e/s)	16·8	23·7	62·4	106·6	209·5
Sky current (e/s/pix)	2·0	3·4	9·7	41·7	56·8
Dark current @ −40 C (e/s/pix)	1	1	1	1	1
Read noise (e)	15	15	15	15	15
Time for RN = (sky+dark) noise (s)	**75·0**	**51·1**	**21·0**	**5·3**	**3·9**
SPH3 camera:					
Q.E.	0·70	0·90	0·93	0·70	...
Object current (e/s)	17·6	26·7	68·3	95·6	208·1
Sky current (e/s/pix)	2·1	3·8	10·6	37·4	53·9
Dark current @ −10 C (e/s/pix)	50	50	50	50	50
Read noise (e)	15	15	15	15	15
Time for RN = (sky+dark) noise (s)	**4·3**	**4·2**	**3·7**	**2·6**	**2·2**
KX260 camera:					
Q.E.	0·10	0·30	0·38	0·35	...
Object current (e/s)	2·5	8·9	27·9	47·8	87·1
Sky current (e/s/pix)	0·2	0·9	3·0	13·0	17·1
Dark current @ −5 C (e/s/pix)	3	3	3	3	3
Read noise (e)	15	15	15	15	15
Time for RN = (sky+dark) noise (s)	**70·3**	**57·7**	**37·5**	**14·1**	**11·2**

could be measured at low spectral resolution with the DBS. In practice, this means detecting stars with $R \leq 21$ mag and galaxies with $R \leq 20$ mag arcsec^{-2} on the DBS slit jaws unfiltered in single integrations of up to ~30 s duration in 1·5″ seeing and a dark sky. With this faint magnitude limit, CCD dynamic range limitations make the bright limiting magnitude problematic. We required a system that was also capable of recording unsaturated images of bright stars with $R \geq 3$ mag unfiltered, at least in the sub-frame read-out mode and preferably in the full-frame read-out mode. This is necessary for convenient telescope pointing calibration. It was likely that a range of neutral density filters would be needed to do this. The use of a direct CCD as an acquisition camera for the DBS also offered the potential for obtaining quantitative $BVRI$ photometry of objects imaged on the DBS slit. A mechanism for recording full frame images to computer disk was therefore required.

2.2 Autoguiding

A further strong driver for replacing the Fairchild camera was the need to autoguide objects on the DBS slit. Manual guiding with the Fairchild system was tedious, but more importantly it was imperfect. This led to significant uncertainties in flux measurements for faint objects and to uncertainties in the precise location of the slit with respect to the object being measured. The new system was required to operate as an autoguider, but it was recognised that in many cases it would be necessary to offset-autoguide; that is, to autoguide on a different object to the one located within the DBS slit. This meant that, in general, it would not be possible to view the science object on the slit jaws while offset-autoguiding on a different object.

3 System Design Study

3.1 Commercial CCD Camera Options

The availablity of sensitive commercial CCD cameras aimed at the amateur astronomy community, as well as limited access to in-house workshop resources, made it desirable to seek an off-the-shelf camera system. Our requirement for high quantum efficiency excluded cameras on offer from the Santa Barbara Instrument Group (SBIG). Our budget cap of order \$US10K excluded other manufacturers, such as PixelVision, Photometrics, and Princeton Instruments. Three possible CCD cameras manufactured by Apogee Instruments Inc.[1] were considered; the AP7 camera selling for ~\$US7500, the SPH3 camera selling for ~\$US9000, and the KX260 camera selling for ~\$US4000. Each uses a mechanical shutter.

[1] http://apogee-ccd.com.

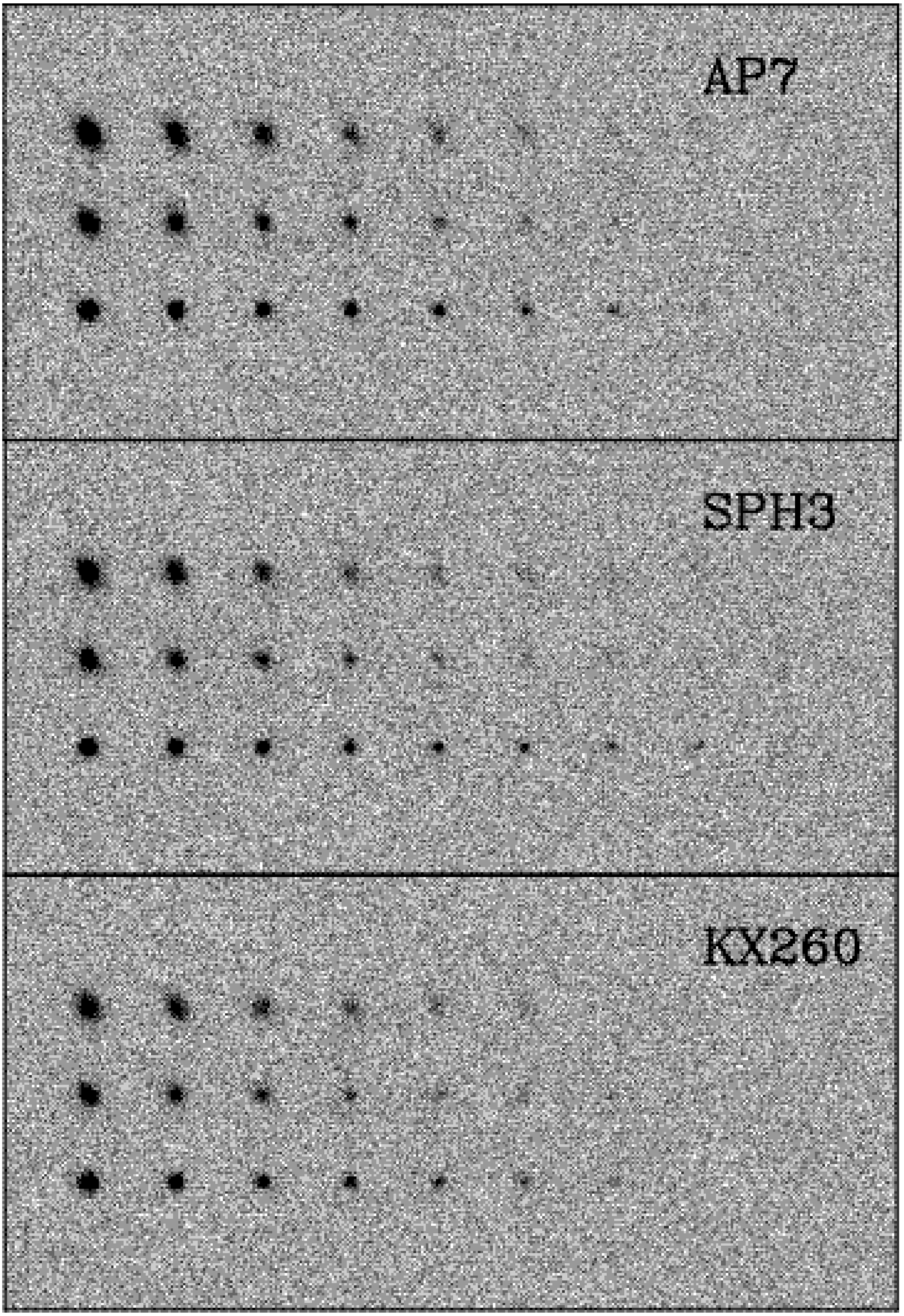

Figure 1—Simulated 30 s exposure in $1\cdot5''$ seeing for the AP7 camera (*top frame*), SPH3 camera (*middle frame*), and KX260 camera (*bottom frame*). Objects are (from top to bottom in each frame) elliptical galaxies, spiral galaxies, and stars with total R magnitudes (left to right) of $18\cdot0$ to $22\cdot0$ in steps of $0\cdot5$ mag. Greyscales range from -3σ to $+5\sigma$ in each frame.

The AP7 camera was considered for its high quantum efficiency (QE) and low dark current. It uses a SITe SIA502AB, 512×512, 24 μm pixel back-side illuminated, full-frame CCD. It has a peak QE of ~85%, 15 e read noise, 1 e/s/pix dark current at $-40°$C, and a well depth of $> 350,000$ e. The full-frame readout time was calculated to be 8·7 s.

The SPH3 camera was considered for its high QE and rectangular geometry which matches the DBS slit geometry. It uses a Hamamatsu S7030–0908, 512×250, 24 μm pixel, back-side illuminated, full-frame CCD. It has a peak QE of ~93%, 10–15 e read noise, 50–100 e/s/pix dark current at $-10°$C, and >600,000 e well depth. Digitisation is to 16 bits with a gain of 5 e/ADU, giving an effective full well of ~320,000 e. The full-frame readout time was estimated to be 4·3 s.

The KX260 camera was considered for its fast, pseudo real-time, read speed. It uses a Kodak KAF-260 512×512, 20 μm pixel, front-side illuminated CCD. It has only 38% peak QE, 15 e read noise, and 3 e/s/pix dark current at $-10°$C. The controller uses a 14-bit, 1·3 MHz ADC so the estimated full-frame readout time is only 0·2 s. It has a gain of 8 e/ADU, so only just digitises read noise, but can sample up to 120,000 e of the CCD well depth.

3.2 Pixel Scales

Modification to the DBS slit viewing optics was required to produce an accessible focus for any of these cameras. The simplest proposed modification produced a pixel scale of ~0·36″/pix. The AP7 and SPH3 cameras would then image the full width of the DBS slit and 184″ along the DBS slit (i.e., just under half of the 400″ slit length) with ~50% vignetting in the corners. The ability to image this large fraction of the DBS slit length in one CCD exposure was seen as a significant advantage for identifying suitable offset guide stars, and for making accurate measurements of their offsets from the science object. The Fairchild camera had imaged 140″ along the DBS slit. With the same slit viewing optics, the KX260 camera would produce an image scale of 0·30″/pixel and would image a field-of-view of 153″ × 153″.

3.3 Faint Object Performance

Approximate performance figures for each camera are listed in Table 1. The object brightness is that of a typical $R = 21 \cdot 0$ mag K giant star, which is likely to be the faintest object observed. We adopt a system optical throughput of 46% which is based on five reflections and six air–glass surfaces.

When operated unfiltered on a dark sky, Table 1 shows that the AP7 camera would be largely sky-noise limited (read noise equals sky plus dark current shot noise in 3·9 s), the SPH3 camera would be largely dark current limited (dark current approximately equals sky signal), and the KX260 camera would be read noise limited for exposures shorter than 11 s unfiltered and for most filtered exposures on a dark sky. In 30 s unfiltered exposures in 1·5″ × 1·5″ seeing, a star with $R = 21 \cdot 0$ mag has formal signal-to-noise ratios of 34, 26, and 18 with the AP7, SPH3, and KX260 cameras, respectively. These relative performances are shown visually in Figure 1. This figure shows simulated 30 s exposures in 1·5″ seeing for the three cameras containing stars (*bottom row*), spiral galaxies (*middle row*), and elliptical galaxies (*top row*) with total R magnitudes from left to right of 18·0 to 22·0 in steps of 0·5 mag. On the basis of these calculations, the AP7 camera is to be preferred. It should outperform the SPH3 and KX260 cameras by 0·3 and 0·7 mag, respectively. However, all three cameras appear to be capable of achieving the required limiting magnitude of $R \sim 20$ on stars and galaxies in reasonable seeing.

3.4 Bright Object Performance

Performance on bright objects was also compared. The minimum integration time is 0·03 s for each of the cameras. We again use our performance model for unfiltered exposures to crudely estimate the saturation magnitudes in 1·0″ seeing; these are 6·9, 7·0, and 6·7 mag for the AP7, SPH3, and KX260 cameras, respectively. Given the uncertainties in bias levels and point spread functions, these are essentially indistinguishable and a more conservative number of ~7·5 mag is probably appropriate. It is clear, therefore, that a neutral density filter (at least ND2 = 5 mag) is needed with any of these cameras to reach the required bright limit of $R \sim 3$ mag.

3.5 Readout Speed

A major shortcoming of the AP7 and SPH3 cameras is their relatively slow readout times (8·7 and 4·3 s full-frame, respectively). The DBS slit face is ~ 80″ wide, so would occupy only 225 pixels in height on the AP7 or SPH3 CCDs with an imaging scale of 0·36″/pixel. Both cameras can be windowed (see below) so the effective readout times for the illuminated regions were estimated to be ~3·8 s. Nevertheless, this would not appear at all like a real-time display to the observer, and could be a major inconvenience when working at high resolution on relatively bright objects.

3.6 Shuttering

Each of the three Apogee cameras is a full-frame device which must be shuttered. For a typical autoguiding exposure time of 5 s, continuous operation of the camera for 10 hr per night for 200 nights per year requires $1 \cdot 44 \times 10^6$ shutter openings per year. The AP7 camera uses a Vincent 25 mm blade shutter, with which the Research School

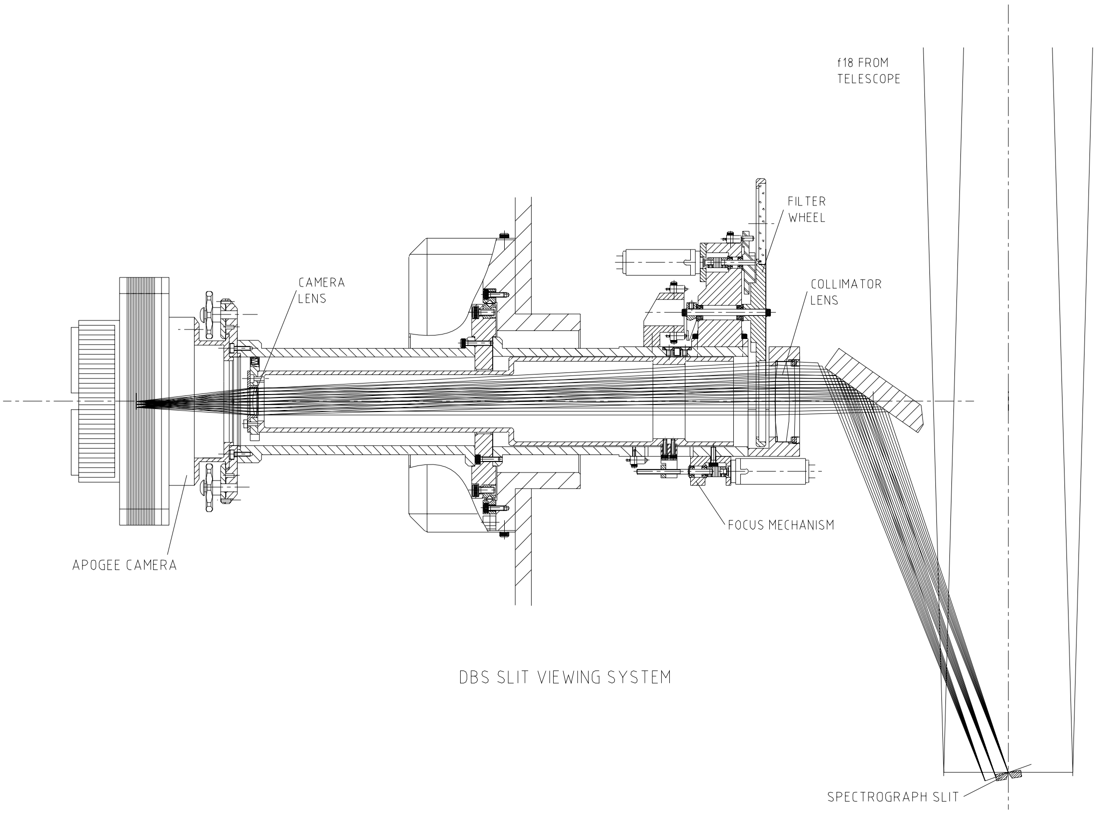

Figure 2—Modified DBS slit viewing assembly. The telescope beam enters at upper-right, and focuses on the DBS slit at lower-right. The tilted slit reflects the acquisition field to a fold mirror which directs the beam into the focal reducer. The AP7 camera is shown at left.

of Astronomy and Astrophysics (RSAA) has had no previous experience. RSAA has successfully operated several other Vincent mechanical shutters for extended periods, but never at this duty cycle. Vincent informed us that the mean time between failures for the VS25 is $\sim 1{\cdot}3 \times 10^6$ cycles. We therefore expect a shutter failure rate of ~ 1 per year and consequently have instigated a preventative maintenance plan.

3.7 Control Software

Diffraction Ltd[2] offer MaxIm CCD camera control and image processing software for Apogee Instruments Inc. hardware running under Windows NT. In limited cross-evaluation this software appeared superior to the only other strong contender, CCDSoft by Software Bisque Inc., in its overall integration and ease of use. Furthermore, Diffraction Ltd agreed to modify MaxIm CCD to output the control sequences necessary to interface the autoguiding function of MaxIm CCD to the 2·3 m telescope control system (Section 4.2).

MaxIm CCD acquires data in one of several acquisition modes, as well as monitoring and controlling the CCD temperature. The user can easily switch between these modes. In 'Expose' mode, a windowed region of the CCD is read out and the result can be written to disk in FITS format (Wells, Greisen & Harten 1981). On-chip binning is supported, as well as on-line bias subtraction, dark subtraction, and flat fielding. In 'Focus' mode, a windowed subframe of the CCD is continuously read out. This mode can be used for focussing as well as for manual guiding. 'Inspect' mode allows users to continuously monitor the centroid coordinates, peak intensity, full width half maximum, and profile of the images obtained in 'Focus' mode. 'Guide' mode is the most appropriate when operating as an acquisition camera. Both wide-field acquisition exposures and narrow-field guiding exposures can be initiated from 'Guide' mode. Wide-field exposures are used for selecting offset guide stars. Narrow-field exposures are used for autoguiding. The standard autoguiding sub-frame is 32×32 pixels.

MaxIm CCD also has excellent features for combining tricolour images. This has proved invaluable for difficult acquisition tasks, such as aligning aperture plate masks.

4 Implementation

The AP7 camera with a boost box for driving long lines was chosen as it offered the best sensitivity of the three contenders. However, it also offered potentially the worst real-time response. In the final system, a pixel scale of $0{\cdot}5''$/pixel has been adopted due to the availability of suitable commercial lenses.

[2] http://www.cyanogen.com/maximccd.html

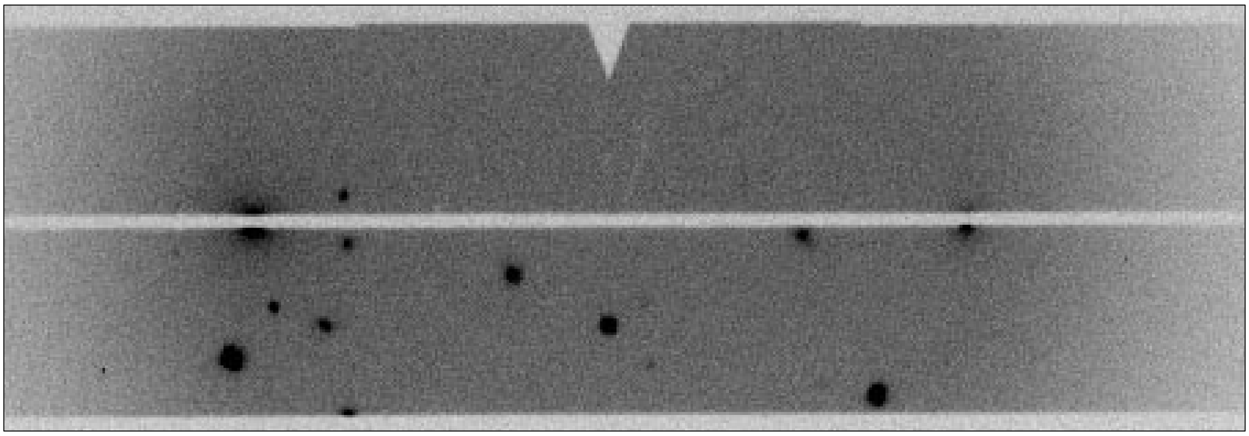

Figure 3—A 10 s unfiltered acquisition exposure of the field APM 821 showing two galaxies positioned on the DBS slit. The faintest stars visible are ∼17 mag.

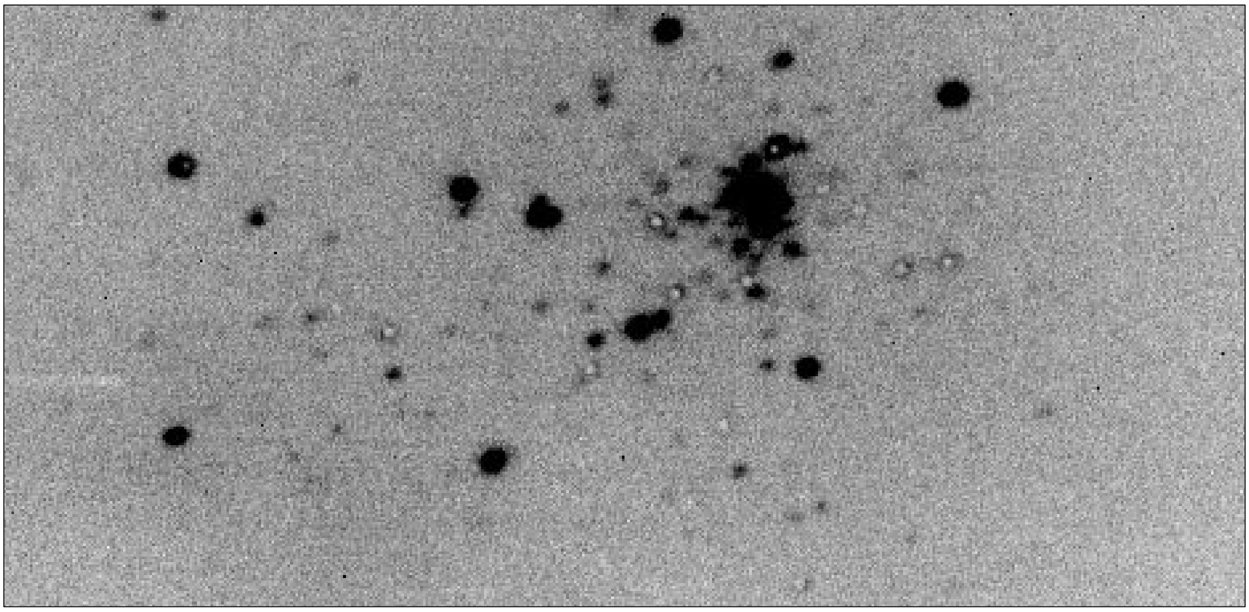

Figure 4—Image of the young LMC star cluster NGC 2004 reflected from the back of a DBS aperture plate. Objects recorded by the spectrograph are seen only in light reflected from the edges of the circular apertures, and consequently appear as doughnuts.

This also served to further increase the field-of-view. The DBS slit jaws then illuminate approximately one third of the AP7 CCD. By suitably windowing the guide region, it is possible to reduce the guide frame readout time to ∼3 s. While not real-time, the implementation of a 'move' command (Section 4.2) has minimised observer frustration with this 3 s frame update time. There is also currently ∼1·8 s dead time between the acquisition of successive autoguiding sub-frames.

4.1 Slit Viewing Optics

The new camera required new DBS slit viewing optics. After testing many catalog lens combinations with the Zemax[3] ray tracing program, we chose a simple two doublet focal reducer consisting of a 50 mm diameter Edmund Scientific doublet collimator and a Melles Griot doublet camera lens. Figure 2 shows the slit viewing camera assembly. On the right of the figure, f/18 cones from the telescope reflect off the tilted DBS slit, then off a folding mirror, and into the focal reducer. The focal reducer carries the six position filter wheel and the focus mechanism. The first lens acts as a field lens reimaging the telescope exit pupil. The second lens which acts as a camera is deliberately placed at this pupil. This lens images the slit into the Apogee camera at f/4·2. To cover the whole length of the DBS slit at a scale of 0·5″/pixel would have required a 100 mm diameter collimator lens as the f/18 cones pivot about the secondary exit pupil and the collimator optics would have to capture the entire beam envelope. We considered this to be impractical.

[3] http://www.focus-software.com

Standard $BVRI$ filters and a NG5 neutral density filter are provided in the DBS acquisition filter wheel so photometric imaging frames can be recorded to disk in FITS format.

4.2 Software Modifications

The MaxIm CCD software runs under Windows NT4 on a 266 MHz Pentium computer. Several aspects of the basic MaxIm CCD software package were modified by Diffraction Ltd to allow it to interface in a convenient way to the 2·3 m telescope control system and to provide additional functionality. All of these changes have been incorporated into the standard product for general sale. We required the guiding commands to be output to the computer RS-232 port as ASCII strings of the form *AUTOGUIDE ra dec*, where *ra* and *dec* are the require RA and DEC offsets in arcseconds in the instrument rotator reference frame. This offset command is input directly to the 2·3 m telescope computer control system.

The need to move objects from anywhere in an acquired CCD frame to the preset CCD coordinates of the slit centre meant that a new 'Move' command was added to the 'Guide' mode in MaxIm CCD. With this command, the user selects the science object of interest using the cursor, and MaxIm CCD initiates a blind offset of the telescope to move the object to slit centre. Extremely accurate telescope offsetting is not required because this is accomplished with the 'Guide' function once the object is within the guide box. The response time of the 'Move' command is limited by the telescope; 2 s is required for the telescope to respond to the 'Move' command and a further 6 s delay is needed for a typical 1 arcminute offset to complete the move and ensure that the telescope has settled.

The issue of shutter lifetime has been addressed by modifying MaxIm CCD to allow the shutter function optionally to be disabled during autoguiding. For short integrations on faint guide stars, this causes only an insignificant smearing of the image and should greatly extend the shutter life.

4.3 Heat Management

The AP7 operates at 50–55°C below ambient temperature in order to achieve low dark current. It was originally felt that the standard fan cooling may be inefficient, and this form of cooling is in any case undesirable near the telescope. An optional cooling plate is offered by Apogee Instruments Inc. to allow water cooling of the camera head. This option has not yet been implemented on the DBS camera, but the camera easily maintained a steady −37°C throughout the last very hot summer.

5 Camera Performance

The AP7 camera and MaxIm CCD software have been in use with the DBS at the 2·3 m telescope since September 1998. The system performs as well as we predicted. Acquisition of objects as faint as $B = 21{\cdot}5$ mag in $1{\cdot}4''$ seeing has been reported using 30 s integrations. This, and the autoguiding capability, have enabled several new science programs to commence on the telescope (see Figure 3). Most recently, aperture plates with small holes have been successfully used with the DBS for the first time (see Figure 4).

The AP7 camera has been so successful that the acquisition system on the Nasmyth B Imager has now been modified to also allow its use with this instrument.

6 Conclusions

The sensitivity of the AP7 camera has allowed greatly improved acquisition of the faintest objects measured with the DBS on the ANU 2·3 m telescope. Reliable on-slit autoguiding and offset autoguiding are now also possible using the MaxIm CCD camera control software. This removes the main barrier which in the past has limited the quality of DBS spectra of the faintest objects. A User's Manual for the camera is available on the web.[4]

Acknowledgments

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[4] http://msowww.anu.edu.au/~conroy