MACHINE-PROCESSING OF OBJECTIVE-PRISM PLATES AT THE ROYAL OBSERVATORY, EDINBURGH

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ABSTRACT

This paper reviews the methods and early results of work in progress at the Royal Observatory, Edinburgh that involves the machine-processing of objective-prism plates. This work is in two categories: (i) semi-automated galaxy redshifts, and (ii) automated quasar detection. The galaxy redshifts are used, for example, to determine the radial velocities of clusters, to test cluster membership, to reveal superimposed clusters, and to reveal connecting bridges between clusters. Automated quasar detection uses selection criteria that are known, pre-defined and rigidly maintained to select complete samples of quasars. Unlike the earlier visual samples of optically-selected quasars these new samples are well suited to work in cosmology and the collective properties of quasars.

INTRODUCTION

At the Royal Observatory, Edinburgh (ROE) an extensive library of high-quality photographic plates has accumulated from its operation of the UK 1.2m Schmidt Telescope (UKST) near Coonabarabran in Australia. Supposing the plates to be digitised with 256 transmission levels and 16μm square pixels the library represents, at present, ∿ 2TByte of image information and sky background. In order to manage and analyse objectively even a small fraction of this quantity of data fast plate-measuring machines and excellent computing facilities are essential. In the UK there are two such measuring machines: COSMOS at ROE and APM at the Institute of Astronomy, Cambridge (IOA). Both ROE and IOA are nodes of the STARLINK network of computers dedicated to astronomical image and data processing.

In general, the machine processing of Schmidt plates divides into two classes, corresponding to direct plates and objective-prism plates. Normal requirements for direct plates are a set of parameters

M. Capaccioli (ed.), Astronomy with Schmidt-Type Telescopes, 107–120.

describing each image (e.g. magnitude, x-y coordinates, ellipticity and orientation) whereas normal requirements for objective-prism plates are pixel data for each spectrum. This paper reviews the work being done with objective-prism plates at ROE using COSMOS and STARLINK (the work with direct plates is reviewed at this Colloquium by Gilmore). This work is in two categories: (i) semi-automated galaxy redshifts, and (ii) automated quasar detection (AQD). Note that the techniques for obtaining galaxy redshifts could be adapted to provide a third category, stellar classification. The galaxy redshifts have been used, for example, to reveal the constituent clusters, connecting bridges, and diffuse components of superclusters, and to show that particular instances of rich clusters actually consist of two clusters aligned along the line of sight. AQD selects quasars from objective-prism plates according to selection criteria that are known, pre-defined and rigidly maintained. Unlike the earlier visual searches which it has replaced, AQD yields complete samples, and their selection effects are known.

UKST OBJECTIVE-PRISM PLATES

The UK Schmidt Telescope possesses two full-aperture objective-prisms. The low-dispersion prism (reciprocal dispersion: 2480Åmm^{-1} at 4340Å, resolution for 2 arcsec seeing: 74Å at 4340Å, apex angle: 44 arcmin) has been in use since 1975 and has made valuable contributions to surveys for quasars, intergalactic HII regions, Wolf-Rayet stars, and to stellar classification and the determination of galaxy redshifts. Probably the most well known contribution is that to the quasar surveys, in which many hundreds of new candidates have been discovered, including many of the instances of rare types. In general, the low-dispersion prism is used with Kodak emulsion IIIa-J, giving a wavelength coverage from the atmospheric cut-off at ∼3200Å to the sharp emulsion cut-off at ∼5400Å. At longer wavelengths the dispersion of this prism is too low to be very useful and so a high-dispersion prism (reciprocal dispersion: 830Åmm^{-1} at 4340Å and 2750Åmm^{-1} at 6560Å, resolution for 2 arcsec seeing: 25Å at 4340Å and 82Å at 6560Å, apex angle: 130.8 arcmin) was acquired in 1982 (Cannon et al. 1982). With Kodak emulsion IIIa-F the wavelength coverage can extend from ∼3200Å to the sharp emulsion cut-off at ∼6850Å, but it is usually restricted by a filter to ∼4950-6850Å in order to obtain fainter limiting magnitudes by suppression of the sky background at short wavelengths and also to reduce the number of overlapped spectra.

For the galaxy redshifts and for AQD the typical plate requirements are deep (B>20), unwidened plates taken through the low-dispersion prism on emulsion IIIa-J. In addition, AQD uses second plates with the direction of dispersion rotated by 90° in order to minimise the number of overlapped spectra. Clowes (1983a) gives details of the variation with wavelength of the response of emulsion IIIa-J.

Each plate covers an area of 6.4°x6.4° at a scale of 67.12 arcsec mm^{-1}. Vignetting is $\Delta m \sim 0.1$ at a radius from the plate centre of 200mm (3.73°) (Dawe and Metcalfe 1982).

Most UK Schmidt plates (those with numbers exceeding 3148) were taken through the achromatic doublet corrector. This corrector introduces an image spread that is approximately constant with wavelength, at 1.50 arcsec, for wavelengths greater than ∿3300Å. Earlier plates, however, including those used for Savage and Bolton's (1979) visual search for quasars, were taken through the singlet corrector. The singlet corrector introduces an image spread that descends steeply from 4.75 arcsec at 3200Å to a minimum at the corrected wavelength of 4200Å and then rises slowly to 2.75 arcsec at 5400Å and 4.15 arcsec at 6850Å; only at wavelengths close to 4200Å is the image spread of the singlet less than that of the achromat. Savage's (1983) Figure 1 plots manufacturers' data for the dependence of image spread on wavelength for both correctors. Only objective-prism plates taken through the achromat should be used for quantititive work.

Plates taken in excellent seeing (< 2 arcsec) with the low-dispersion prism have limiting continuum magnitudes $m_\lambda \sim 20.5$. With the high-dispersion prism (emulsion IIIa-F + GG495 filter), however, the higher dispersions and the brighter sky background cause a loss in limiting magnitude. No precise values of this loss are available at present but Savage (private communcation) estimates that quasars fainter than $m_\lambda \sim 18$, discovered using the low-dispersion prism, are not visible. One of the main reasons for having a high-dispersion prism is to discover quasars with redshifts greater than ∿ 3.5; only ∿ 0-2 such quasars are expected per plate.

COSMOS

For the work on galaxy redshifts and AQD the COSMOS measuring machine is used in its mapping mode (MacGillivray 1981; Stobie 1982 - COSMOS user manual). It then becomes simply a fast densitometer which outputs the transmission values and, implicitly, the x-y coordinates of each pixel: it does not threshold or otherwise process the data. Digitisation is presently to eight bits (due to change to 14 bits in December 1983), which gives 256 transmission levels in the range 0-255. COSMOS, a flying spot scanner, has nominal spot-size options of 8,16,32μm (actual FWHMs = 13.9,25.5,31.1μm) and independent pixel-size options of 8,16,32μm. The "standard" selections for measurement of objective-prism plates are the nominal 16μm spot and 16μm pixels. Measurement of the maximum area that can be measured in one session - 287x287 mm^2 - then takes ∿ 6 hours and, with eight bits, the 306.8Mbyte of data occupy 12 magnetic tapes.

From ∿ March 1984 COSMOS should acquire a dedicated computer with a 1.2Gbyte capacity. Then, the mapping mode data with 14-bit digiti-

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sation for entire 287x287mm^2 areas will be written directly to the COSMOS disk, whereas at present the data are written to tape and then dumped in halves onto two 300Mbyte disks on the ROE STARLINK VAX 11/780. Ideally, the galaxy redshift software and the AQD software (both written on STARLINK) will be compatible with the COSMOS computer so that, because of the dedicated CPU time, processing in real time will be considerably faster.

STARLINK

The processing of objective-prism plates requires moderate processing power, large disk capacity, and excellent graphics facilities. These three requirements are provided at ROE by the STARLINK node, a VAX 11/780 and its peripherals.

STARLINK comprises six full-sized VAX 11/780 nodes and two smaller VAX 11/750 nodes, which are linked together by one or both of two networks. ROE has a full-sized node. The VAX 11/780 has 4Mbyte of memory, a floating-point accelerator (FPA), 1Gbyte disk capacity (of which 300Mbyte are non-STARLINK), graphics terminals, and high-resolution hard-copy devices. In particular, the node possesses two ARGS graphic monitors which can display 512x512-pixel images in colour or monochrome. For inspection, the appearance of objective-prism plates can be reconstructed (in monochrome, of course) on the ARGS monitors from the COSMOS data (see Figure 1).

The processing power of the VAX 11/780+FPA may be assessed using the Central Computer and Telecommunications Agency (CCTA) synthetic benchmarks for single-precision Fortran, which give VAX 11/780+FPA: 0.24, to be compared with, for example, PDP 11/45: 0.04, GEC 4080: 0.05, IBM 360/195: 1.00, and CRAY1 (scalar): 3.52.

THE TECHNIQUE OF SEMI-AUTOMATED GALAXY REDSHIFTS

Cooke et al. (1977) and Cooke (1980) began the work on galaxy redshifts from objective-prism plates using measurements with a Joyce-Loebl microdensitometer of Curtis Schmidt and UKST plates. The emulsion cut-off of emulsion IIIa-J was found to provide an adequate and convenient reference point for wavelengths (see Nandy et al. 1977). Redshifts could then be obtained by measuring the position with respect to the cut-off of the 3990Å continuum break - "the 4000Å feature". This continuum break corresponds to the sharp red edge of a general depression in the spectrum that begins with the strong CaII H & K absorption lines and extends shortwards, because of a multitude of other metal lines, to the atmospheric cut-off. The 4000Å feature is generally detectable in the UKST objective-prism spectra of ellipticals and nuclear bulges of spirals for $16 < B < 19$. Secondary absorption features might also be present. Using this method Cooke et al. (1981) found rms errors of $\sim$1800Kms^{-1} compared with slit spec-

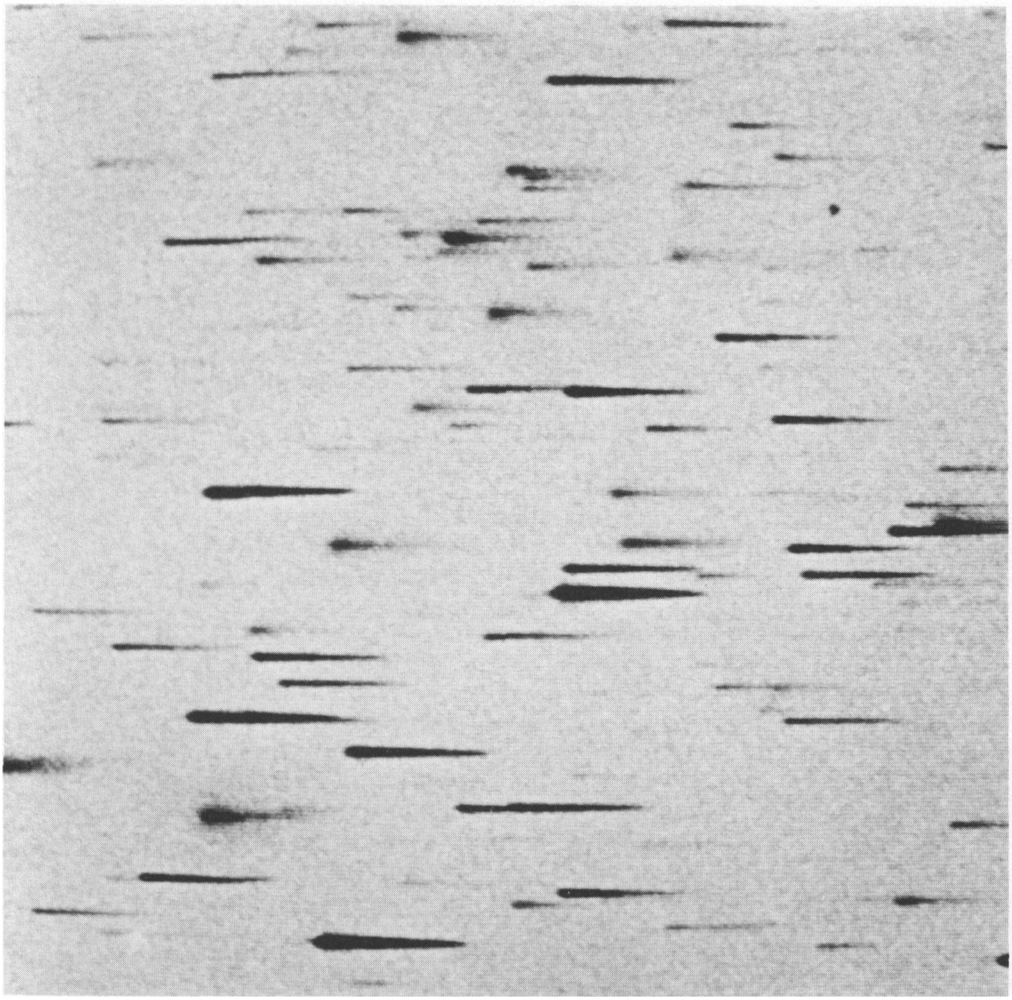

Figure 1 is a photograph of a STARLINK ARGS graphic monitor displaying a small area (512x512 16μm pixels) of an image on disk that was formed from COSMOS measurements of an objective-prism plate. The image is of the cluster 2143-5732 in Indus (Corwin, 1981).

troscopy for the objective-prism redshifts of bright (B $\sim$ 17) ellipticals in the cluster Abell 2670. Similar velocities were measured for the cluster Abell 140 but the wider dispersion suggested a superimposition of clusters. Cooke et al. (1981) concluded that the technique is useful for determining the radial velocities of clusters, for testing the cluster membership of ellipticals, and for resolving superimposed clusters.

During the early work the attempts to extract spectra from COSMOS mapping-mode data were essentially abandoned because the available processing power and disk capacity were too small. However, when ROE became a STARLINK node this approach was revived. Cooke et al. (1984) and Cooke et al. (1983) have now written software for the recognition and extraction of spectra from digital images on disk of the objective-prism plates. The software is not, of course, restricted to galaxy spectra, and it has already acquired another application in the AQD process.

The recognition and extraction of spectra begins with the formation of a compressed image on a 300Mbyte disk (one byte per pixel) of the measured area. Large areas required splitting over two disks. Figure 1 is a photograph of an ARGS graphics monitor displaying a 512x512-pixel area of such an image - the cluster 2143-5732 in Indus (Corwin, 1981). From this image an array representing the smoothed sky background is generated by smoothing with a median filter the weighted means from transmission histograms of 256x256-pixel areas (Cooke et al. 1984). Spectra are then recognised using the threshold criterion that N connected pixels should have transmissions that are at least T% brighter than the local sky background. The effects of particular values of N and T may be tested interactively on a small part of the image. Recognised spectra are extracted, and unrecognised spectra and empty areas of sky background are discarded. Each spectrum is extracted as a block of 8x128 pixels, located by the emulsion cut-off in the dispersion direction and by the centroid in the perpendicular direction. This block size is generally large enough to contain substantial areas of the local sky background. The recognition and extraction of spectra from the maximum COSMOS area of $287x287mm^2$ requires $\sim$ 24 hours of CPU time using present software (but it is known that this time can be reduced).

There is an alterantive approach (Clowes et al. 1980) to the recognition and extraction of spectra. It uses coordinate transformations from direct plate to prism plate to locate on the prism plate a separate raster scan for each required object on the direct plate. The "little image mode" of COSMOS is not well suited to a large number of objects and so the same effect, if required, is then better obtained from software and mapping mode data. Work is in progress on this approach, which gives more accurate definition of the reference point for wavelength (the emulsion cut-off).

Beard et al. (1984) (see also Beard 1983, Cooke et al. 1983) have obtained galaxy redshifts in a segment of the Indus supercluster that was proposed by Corwin (1981). In the automated part of their technique Beard et al. (1984) used their recognition and extraction software to extract 50324 spectra of all types from an area of 255x281mm^2, and converted them to one-dimensional approximate-intensity spectra. Then, in the interactive part of their technique, they used plots of these one-dimensional intensity spectra to separate galaxies from stars, and to obtain redshifts for 2294 of the galaxies by locating the emulsion cut-off and the 4000Å feature of each. Repeat measurements of the same plots gave rms errors of $\sim$3000 kms^{-1}. The early work concentrated on bright (B $\sim$ 17) ellipticals whereas this recent work includes the types E-Sb (16 < B < 19), the extension to spirals and fainter magnitudes being responsible for the increase in random errors. An excess of "redshifts" in the range 0.10-0.12 was found to be caused by misclassification of stars with misleading features as galaxies. Figure 2 shows the approximate-intensity plots of a representative set of nine galaxies. In each case the 4000Å feature appears as a sharp discontinuity. The deduced redshifts are, reading from left to right and downwards, 0.051, 0.109, 0.056, 0.176, 0.058, 0.055, 0.085, 0.049, 0.041.

Direct plates will, in future work, be used to assist the separation of galaxies from stars, and to reduce magnitude-dependent errors in locating the emulsion cut-off of each galaxy by defining coordinate transformations from the direct plates to the objective-prism plates. Furthermore, new software being developed by Cooke, Kelly, Beard and Emerson (initial tests of it are reported in their poster paper presented at this Colloquium) should replace visual location of the 4000Å feature by automated pattern-matching of the galaxy spectra with standard references. They expect that this new software could be adapted to provide classification of stellar spectra.

Corwin found, using visual counts of galaxies on UKST direct plates, that the Indus supercluster comprised an approximately elliptical ring (major and minor axes of ten and eight degrees respectively) of clusters at a mean redshift of 0.076. Beard et al. (1984) found that the redshifts of 325 of their 2294 galaxies were within ± 0.01 of Corwin's mean redshift. They have shown that there is a 7h^{-1} Mpc bridge between two constituent clusters, 2151-5805 and 2143-5732, of the supercluster, and have shown that some galaxies which, with two-dimensional information only, apparently belong to 2151-5805 are distinctly members of a more distant, unrelated cluster.

Parker et al. (1983) used the technique to obtain approximate radial velocities for the rich clusters that were found in the deep (B < 22) galaxy survey of MacGillivray and Dodd (1983). Their results suggest a supercluster, at a mean redshift of $\sim$ 0.12, that comprises not only clusters but also a large dispersed component of galaxies. Parker, MacGillivray, Dodd, Beard, Cooke and Kelly are presenting their latest results in a poster paper at this Colloquium.

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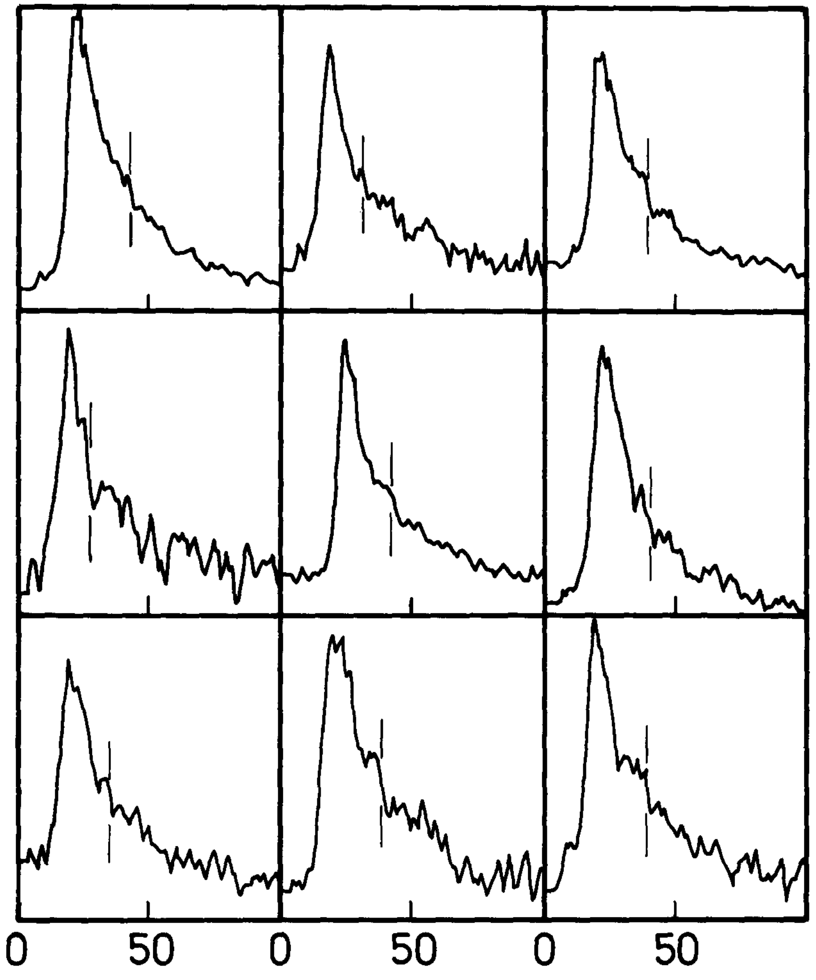

Figure 2 shows the approximate-intensity plots of a representative set of nine galaxies. The y-axis is relative approximate-intensity and the x-axis is pixel number (increasing pixel number corresponds to decreasing wavelength). In each case the 4000Å feature appears as a sharp discontinuity. The deduced redshifts are, reading from left to right and downwards, 0.051, 0.109, 0.056, 0.176, 0.058, 0.055, 0.085, 0.049, 0.041.

MULTI-OBJECT SPECTROSCOPY USING FIBRE-OPTICS SYSTEMS

Redshifts obtained with large telescopes would, of course, be preferred, and the recent development of multi-object spectroscopy using fibre-optics systems on telescopes such as the Anglo-Australian Telescope (AAT) provides the means, in principle (the field of the AAT system is soon to increase from 12x12 $arcmin^2$ to 40x40 $arcmin^2$). In practice, for galaxy redshifts, the large numbers of galaxies covering relatively large areas of sky together with their unavoidably non-stellar appearance cause multi-object spectroscopy to be impracticable at present, except for establishing wavelength references in small areas. For quasars, however, although the areas of sky remain relatively large the numbers are very much smaller and multi-object spectroscopy becomes more practicable: indeed, objective-prism redshifts, with random errors slightly larger than desired and $\sim$ 20% incorrect redshifts because of misidentified single lines, would be an unnecessary contaminant of the samples discovered by AQD.

THE TECHNIQUE OF AUTOMATED QUASAR DETECTION AQD

AQD was developed in order to combine the inherent sensitivity of objective-prism (and grism and grens) plates for detecting quasars with an objective detection procedure. Previously, this sensitivity was used inefficiently by visual searches because of their subjective selection criteria that varied systematically, and the resulting samples were properly useful only as sources of individually interesting objects and not for work on cosmology and the collective properties of quasars. With AQD, however, the selection criteria and consequently the selection effects are known, pre-defined and rigidly maintained; large, complete samples can be assembled from many plates. AQD is an extension of earlier work on objective-prism spectrophotometry (Clowes et al, 1980) and on the selection effects that operate in spectral searches for quasars (Clowes, 1981).

The AQD samples are well suited to studies of anisotropy on scales greater than $350h^{-1}$Mpc (q_o = 0), self-clustering in two and three dimensions, cross-clustering with faint galaxies, the density contrast with sensitivity to values greater than 10% on scales of $150h^{-1}$Mpc at z $\sim$ 2.3 (but not its evolution), the luminosity function and its evolution.

AQD (Clowes et al. 1983a,b; see also Clowes, 1983b) uses the galaxy-redshift software (Cooke et al. 1984) for the recognition and extraction of spectra of all types from images on disk. At this recognition and extraction stage there is no testing of the quality of the spectra so the output blocks may contain, for example, overlapped, saturated and spurious spectra. Quality testing is performed by the AQD software. In future work quality testing will be assisted by the use of direct plates when coordinate transformations from direct plate to prism plate are used at the recognition and extraction stage. All spectra that survive quality testing, regardless of type, are converted to intensity (Clowes et al. 1980).

AQD can select quasars by emission lines (intended to be the primary method), absorption lines, spectral discontinuities, ultraviolet excess, and red excess. For selection by either emission or absorption lines a continuum spectrum is derived from the intensity spectrum and a noise spectrum is generated to represent the expected noise fluctuations of the intensity spectrum about the continuum spectrum. The criterion for recognising a spectral line is that its peak exceeds the specified signal-to-noise ratio with respect to the continuum. For selection by spectral discontinuities the ratio (B-G)/G is formed for each element of the intensity spectrum, where B is the average of the next M elements to shorter wavelengths and G is the average of the next M elements to longer wavelengths. If this ratio is negative and it exceeds the specified limit then a discontinuity is recognised. For selection by ultraviolet or red excess two broad-band filters are defined for each case and corresponding magnitudes are derived from the intensity spectrum. Spectra are selected when the colours exceed the specified limits. Full details of the AQD process are given in Clowes et al. (1983b).

Figure 3 is a photograph of the ARGS monitor displaying the 8x128-pixel blocks of a representative set of AQD quasars selected by emission lines and spectral discontinuities from a field centred close to the South Galactic Pole. Using the same objective-prism plate as the visual search (Clowes and Savage 1983) of that field, AQD discovered (subject to confirmation) $\sim$ 50-100% more quasars brighter than B = 19.5 (Clowes et al. 1983b).

Figure 4 shows the intensity and superimposed continuum spectra of the top nine blocks of Figure 3. The y-axis is relative intensity and the x-axis is pixel number (increasing pixel number corresponds to decreasing wavelength). All except the fifth (counting from left to right and downwards) were selected by emission lines. The fifth was selected by a continuum discontinuity and it illustrates one algorithm by which very high redshift quasars might be selected when Ly-α is beyond the emulsion cut-off (however, high stellar contamination is expected).

The CPU time required for the maximum area is $\sim$ 24 hours for the recognition of extraction of spectra and $\sim$ 8 hours for selection of the quasars.

AQD, is intended for statistical work on defined samples of quasars, and, therefore, it requires calibration of the plate noise, the emulsion response, and the absolute flux scale. Such calibration is, as usual, difficult and time-consuming. For non-statistical work (eg the searching of many plates for close pairs) AQD can, of course, be used more crudely with only an invented calibration; the samples will then be similar to the undefined visual samples but will be spatially consistent on a single plate.

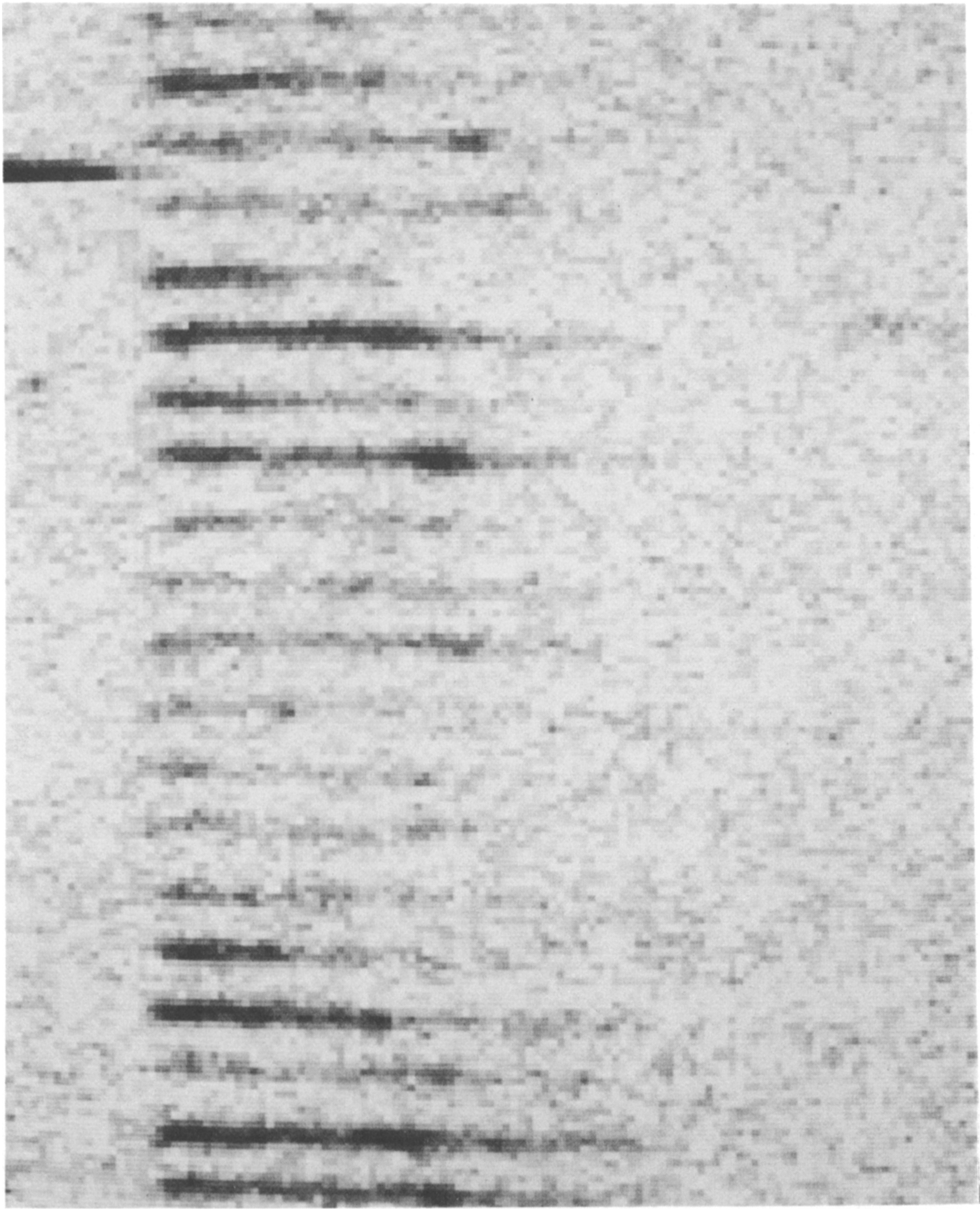

Figure 3 is a photograph of the ARGS monitor displaying the 8x128-pixel blocks of a representative set of AQD quasars. Wavelength increases to the left.

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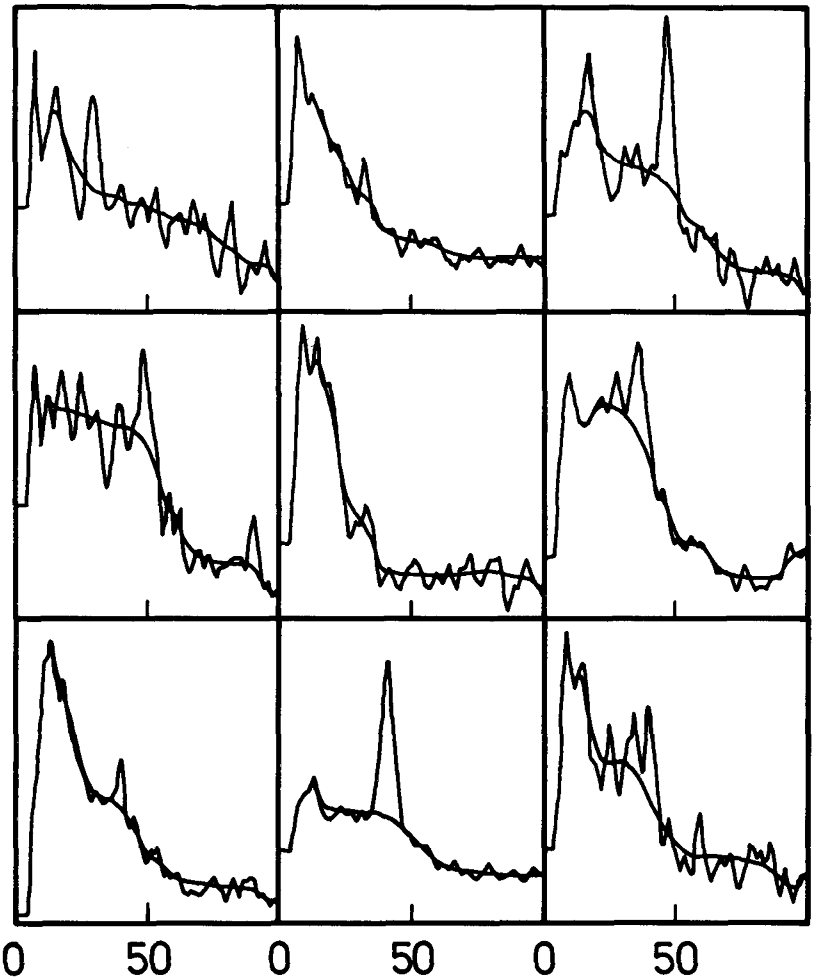

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Unfortunately, AQD is presently restricted by the quality of the COSMOS data and of the calibration data. Noise in COSMOS data is correlated from pixel to pixel, and the degree of correlation is a function of transmission because the ratio of machine noise to plate noise is a function of transmission. However, the electronics of COSMOS have recently been rebuilt, and preliminary noise tests suggest that, in future measurements, the machine noise will be reduced to insignificance and that the degree of correlation will consequently be constant with transmission. The difficulty with the calibration data is that, for the emulsion responses at wavelengths shorter than ∿3950Å (see Clowes 1983a), they do not exist because of attenuation caused by glass in the UKST calibraton spectrograph. Ideally, the emulsion response should be obtained from on-plate exposures rather than separate exposures in a calibration spectrograph.

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