ASTRONOMY FROM WIDE-FIELD IMAGING

Part Three:

PHOTOGRAPHY IN WIDE-FIELD IMAGING

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PHOTOGRAPHY IN WIDE-FIELD ASTRONOMY

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1. Introduction

It is an honour for me to be able to present this review of photography in wide-field astronomy. Let me begin by assuring this distinguished audience that this talk is not some sort of sentimental tribute to a redundant technology. Although photography may be the oldest way of accurately recording images of stars and galaxies it is still the most powerful tool which we possess for surveying the sky on the world's large Schmidt telescopes. Indeed, if the full promise of Tech Pan film is realised (and there will be more on that subject from Dr. Parker later today), photography in its 'old' age may extend in its usefulness well into the next century. So, far from being on its last legs, photography is just reaching its maturity, though not without something of a mid-life crisis.

2. A Brief History

Photography has been used in wide-field imaging for over 100 years. One of the first 'deep' photographs made possible by the introduction of the new 'dry gelatin' emulsions in the late 1870s was that of the great comet of 1882. The potential which wide-field photography revealed for recording literally thousands of stellar images was appreciated at once from this photograph and its promise of providing a most powerful tool for carrying out astrometry was immediately apparent.

This photograph led directly to the convening of the International Astrographic Conference of 1887 at the Paris Observatory, when the Carte du Ciel survey was initiated. This huge undertaking was to be the first all-sky photographic survey and was carried out on standard astrographic refracting telescopes mostly during the first one third of this century. The Survey involved an international cooperation of 18 observatories worldwide and used 160 mm plates on fields 2.7 degrees in diameter and reached a limiting magnitude of approximately 15 in the blue, a passband defined by the technology then available.

The Carte du Ciel distracted many observatories from other advances that were made possible by photography, mainly in recording spectra and in the detection of myriads of faint objects that were found to be distant galaxies. The combination of deep imagery and spectroscopy led to the most profound discovery of all, that the Universe is apparently both limitless and expanding. At

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the same time, photographic photometry laid the foundations for the new science of astrophysics. Photography made astrophysics possible.

3. The Schmidt Telescope

By this time, reflecting telescopes had proved their worth. However, in 1930 Bernhard Schmidt, a member of staff of the Hamburg Observatory, designed a telescope which combined a spherical mirror with a refractive corrector. This soon became known as a Schmidt camera, because its restricted focal surface was really only suitable for photographic image recording. These instruments combined excellent image quality over a wide field-of-view with very small plate scale and unprecedentedly fast focal ratios.

Walter Baade was also a staff member of the Hamburg Observatory at that time, and when he left to join the Mount Wilson Observatory in 1931 he took with him a number of photographs of the night sky which had been taken by Schmidt and himself. Astronomers in California were greatly impressed by these results and largely at the insistence of Fritz Zwicky, who realised that such a telescope would be perfect in a search for supernovae, an 18 inch (46 cm) Schmidt telescope was built and went into operation in 1936.

This Schmidt was the first telescope on Palomar Mountain. The potential of an even larger Schmidt to complement the 200 inch telescope, construction of which was then underway, was obvious and Walter Baade supervised construction of the venerable 48 inch (1.22 m) Schmidt which saw first light in 1947.

4. The First Schmidt Survey

The first Palomar Sky Surveys with the 1.2 m telescope consisted of pairs of plates in the blue and red passbands and were carried out between 1950 and 1958 using 103a-O and 103a-E emulsions respectively. These fast but coarse-grained photographic emulsions, with relatively little low light level reciprocity failure, were produced by the Eastman Kodak Research labs specially for astronomy at the insistence of the then Director of Research, C.E. Kenneth Mees, who was interested in astronomy and in the photographic challenges presented by long exposures. Many of the advances incorporated into these extremely sensitive emulsions eventually found more commercial (and more profitable) application. But these emulsions were less than ideal for the finely-detailed images produced by Schmidt-type telescopes.

5. Palomar I Survey Uses

Nevertheless, the Surveys were very much deeper than any previous all-sky surveys and they provided an immense amount of material for further investigation on the new 200 inch (5.08 m) telescope. Copies of the surveys were used extensively to search for the optical counterparts of newly identified radio sources; catalogues of galaxies were compiled and classified and literally hundreds of new clusters of galaxies discovered. The Surveys were in far greater demand than had ever been expected, for research activities that were completely unexpected when the plates were taken.

Before the 48 inch Schmidt had come into general use, our knowledge of what was actually there to observe with the large reflectors was totally inadequate. Prior to Palomar I for example, using the 15 arcmin field of the 200 inch, Hubble could only sample small patches of the northern sky and from 1283 such samples was only able to cover a total area of only 300 square degrees, equivalent to eight 48 inch Schmidt plates. However, the samples were distributed over the sky uniformly and did give a valid picture of the distribution of galaxies brighter than 20th magnitude.

On the basis of 20 known great clusters of galaxies (ones as rich or richer than the Coma Cluster) in a survey to 20th magnitude, Hubble estimated that there would be one such cluster per 50 square degrees. The conclusion seemed to agree well with Abell's catalogue of rich clusters, compiled from the surveys which indicated one such cluster per 40 square degrees. The difference was that Abell's catalogue contained 462 such clusters compared to the 20 of which Hubble was aware.

The Palomar I surveys reached magnitude 20-21 in B and approximately 20 in R and mapped the entire sky north of declination -30 (over 70% of the entire sky) in less than 10 years. They used plates as received from the manufacturer on non-overlapping 6 degree centres. No systematic sky surveys of the southern hemisphere existed at magnitudes approaching those of Palomar I until the advent of the ESO and UK Schmidts in the 1970s. These Schmidts were built to complement large reflectors which were being constructed at their respective sites, at La Silla in Chile and Siding Spring in Australia, an arrangement which was justified by the success of having the Palomar Schmidt next to the 200 inch in California.

6. Southern Schmidt Surveys

After discussing strategies for surveying the southern sky, an agreement was eventually signed between ESO and the British Science Research Council (later to become SERC) in May 1972. Under the agreement ESO and SRC were to share the task of surveying the southern skies and both organisations would pool the results of their surveys. ESO planned a survey in the blue (IIa-O emulsion) and red wavebands, corresponding to Johnson B and Palomar Sky Survey R, while the UK Schmidt would survey with the IIIa-J blue-green sensitive emulsion to reach the faintest possible magnitudes — using field centres at 5 degree intervals south of -20 degrees declination. In addition, it was later decided at the UK Schmidt to continue the J Survey to the equator (making a grand total of 894 fields from declination 0 degrees to declination -90) as various RA ranges of the original southern survey were completed and to pursue this equatorial survey in the red as and when the J plates were obtained.

It is salutary to note (especially for those intent on future wide-field surveys, perhaps with CCD mosaics) that at that time, the ESO B survey was expected to be complete in 1 year, ESO R in 2 and SRC J also in 2. In the event, the B spanned 1973-78, the R 1978-1990 and the J 1974-87. Learning how to effectively hypersensitise and process the IIIa emulsion took much longer than was at first expected and in the early days of the surveys, Kodak produced a number of plate batches which included numerous unacceptable plate defects. The exposure times were longer than for Palomar I but the main reason for the surveys taking so long was the quest for uniformly high quality. This meant that survey plates were attempted only in the best conditions and strict quality control criteria led to the rejection of as many as half of the plates taken. The southern J and R surveys used much finer-grained photographic emulsions than Palomar I and reached 2-3 magnitudes fainter than the earlier survey. Although these new emulsions were inherently slower than the 103 or IIa materials, techniques of hypersensitisation (hypering) were developed whereby the speeds of these emulsions reached or surpassed the speeds of the earlier unhypered coarse-grained products.

These were the first emulsions to adequately sample the excellent images produced by large Schmidt telescopes. It is a pity that we had to wait until 40 years after the invention of the Schmidt design for them to appear. Hypersensitization made these materials usable, and most of the development of hypering methods came from the astronomical community, though the major breakthrough, reduction sensitisation with hydrogen gas, came from the Kodak Research labs.

Hypering increased the detective quantum efficiency of these emulsions from less than 1% to 4% or so. This, coupled of course to their superior resolving power, was the reason for the remarkable gain in depth of the southern surveys. It needs emphasising that without the great effort which went into developing the techniques for hypersensitising the new emulsions the new surveys would not have been feasible.

Glass and film negative contact copies were made of the B, R and J Surveys at the ESO Sky Atlas Laboratories and became readily available to the astronomical community. Photographic Laboratories were also established at the Royal Observatory Edinburgh, where the southern galactic plane (infrared — to 900 mm) I/SR survey was copied onto film and issued as an atlas and where currently, the EJ and ER surveys are also being produced as film atlases. As with Palomar I, the southern sky surveys were put to enormous use and led to many new discoveries.

7. Research Highlights with the Southern Sky Surveys and the UKST

I would briefly like to mention just a few of the research programmes carried out with plates from the UKST because that is the one with which I am most familiar, although of course similar programmes have been carried out on the other large Schmidts.

The UK Schmidt Telescope has supplied data for over 1000 special 'non-survey' research projects since it began operations in 1973. Probably at least as many projects will have made significant use of data from the sky surveys, quite apart from the many which have used the surveys for ancillary purposes such as making finding charts or simply looking at objects. These projects cover the whole range of modern astronomy; the main areas of research and examples of some key projects are mentioned below.

7.1 QUASARS

The UKST has probably been the most successful single telescope in the world for discovering quasars, both in terms of finding large, well-defined samples and for discovering interesting individual objects. A variety of techniques have been used, sometimes in combination, for example multi-colour photometry, objective prism spectroscopy, variability and the identification of radio and X-ray sources. Since the late 1970s the UKST has repeatedly held the record for the most distant known quasar, but more importantly various systematic samples have set new limits on the distribution and evolution of quasars in different redshift and magnitude ranges.

7.2 DISTRIBUTION OF GALAXIES AND OBSERVATIONAL COSMOLOGY

COSMOS (Edinburgh) and the Automated Plate Measuring machine (APM, Cambridge) scans of survey plates have been used to generate two-dimensional maps of the distribution of galaxies over the entire southern sky. Clustering and nearest neighbour analyses of these data have set important constraints on permissible cosmological models. FLAIR on the UKST and Autofib on the AAT are now being used to obtain large samples of radial velocities so that the full 3-D structure can be mapped. Other cosmological studies have depended on identifying samples of galaxies from radio, infrared (IRAS) and X-ray surveys.

7.3 PECULIAR AND INTERACTING GALAXIES

The Schmidt sky survey plates have proved a goldmine for discovering interesting individual galaxies. Samples of interacting galaxies have led to an understanding of their dynamics and mechanisms of star formation; the discovery of very faint 'shells' around many elliptical galaxies is evidence for past mergers. Searches for very low surface brightness galaxies have greatly extended the range of known types of galaxies. Numerous individual galaxies have been found to have anomalous very faint extensions, for example the extensions of NGC 5128 which is the radio source Centaurus A and the still unexplained jets of NGC 1097.

7.4 LOCAL GROUP GALAXIES

Multicolour photometry of huge samples of stars in the Magellanic Clouds, involving the measurement of many Schmidt plates in COSMOS and APM, have led to a new and much more complete understanding of the structure and evolution of our nearest companions. Samples of special objects including star clusters, planetary nebulae, carbon stars and variable stars such as RR-Lyraes and long period variables, have been used to derive kinematic and population models of the Clouds. The Carina dwarf spheroidal galaxy was discovered on a Schmidt plate in 1977, and subsequent Schmidt studies have determined the true shape and extent of this and other dwarf galaxies, the eighth of which, the dwarf spheroidal in Sextans, was discovered on a UK Schmidt plate from APM scans in 1990.

7.5 STRUCTURE OF THE GALAXY

Similar studies of large samples of stars in our own Galaxy, particularly distant stars at high galactic latitudes, have been used to determine the structure of the Galaxy in terms of the disk, halo and a variety of thick disks. Objective prism plates have been used to find samples of extremely metal-poor stars. Dedicated astrometric studies of a couple of selected fields have led to the discovery of large numbers of faint, nearby stars with high proper motions and measurable parallaxes, but so far have done no more than demonstrate the feasibility of this type of study. Similarly, comparison of long series of plates of one or two fields have resulted in a systematic inventory of their variable star content to unprecedentedly faint limits. Hα interference filter photographs of the Milky Way (and the Magellanic Clouds) have resulted in new catalogues of young HII regions and old supernova remnants; infrared surveys have generated lists of dark dust clouds; and the deep sky survey plates taken in blue light revealed the extent of the interstellar 'cirrus' which was subsequently also mapped by the IRAS satellite. Spectacular colour photographs have been created by combining plates taken through different filters and have revealed new features in many areas of Galactic nebulosity.

7.6 SOLAR SYSTEM STUDIES

Many serendipitous discoveries of asteroids and comets have been made. Several systematic searches have greatly improved our statistical knowledge of various classes of asteroids. Large scale photographs of comet tails, notably Comet Halley in 1985 and 1986, provide information on the processes of outgassing and on interactions with the solar wind.

8. Measuring Machines

As always with photography, the raw results are analogue and non-quantitative. As computers became widely used, it was obvious that computer-readable forms of the sky surveys would be necessary to exploit the huge amount of information they contain. Thus appeared the need for fast, accurate measuring machines. In the UK, at first with GALAXY and then with COSMOS and the APM, digitisation of Schmidt plates was pursued exhaustively in the 1970s and 1980s for a multitude of research projects. New measuring machines have been constructed in the USA, in Europe and Japan, and at the Royal Observatory Edinburgh, COSMOS has evolved into SuperCOSMOS. At the Space Telescope Science Institute, the Guide Star Catalogue was derived by measuring the Sky Survey plates in two specially built PDS 2020 microdensitometers and has been issued on two CD ROMs. Exabyte tapes of digitised data from the measuring machines now exist in profusion.

The projects to construct these high speed digitising microdensitometers are in themselves massive undertakings, involving many years of effort in engineering and analysis software. Ultimately all the sky surveys should be digitised and this data made available to astronomers. Providing them with the tools to exploit this mass of data is every bit as important as obtaining the photographic plate in the first plate.

9. Palomar II Surveys

The second epoch Palomar Sky Surveys which commenced in 1987 were initiated in order to redress the balance in depth of the SERC J and the Palomar I B surveys. Before the new surveys began, the Palomar Schmidt was substantially refurbished, with the introduction of an achromatic corrector in 1984 and facilities for hypersensitising the IIIa and near infra-red 4N emulsions.

This time, 5 degree field centres were used from the equator to the pole to provide the same field overlap as the UKST had in the south. The northern and southern surveys have the zero declination zone in common and so depth comparisons can be readily made. Analysis of the 17 issued POSS II B film copies in this zone with corresponding SERC J currently indicates that for stellar objects 4 fields have identical limits, 7 are marginally deeper from POSS II and 6 are marginally deeper from SERC J and so, essentially, there is nothing in it. This may not be the case in the red and the near infra-red however where the Palomar sky suffers from greater light pollution and exposure times will thus be limited, nor will it be the case for extended objects in the B band because of the greater sky brightness at Palomar.

10. UKST II Survey

A second epoch survey of the southern sky also commenced at the UKST in 1990 which gave a 15 year baseline between fields which formed part of the first J survey. It is however in red light and uses the IIIa-F emulsion. There were two principal reasons for commencing this survey:
1) to provide a database of HST guide stars at a recent epoch, and
2) a desire to study southern hemisphere proper motions and more importantly, to search for nearby low luminosity stars with anomalously high proper motions.

This survey is due for completion in 1996/7 and is currently on track.

11. Photographic Amplification, Analogue and Digital Addition

In general, the plates (and films) which are produced by the large Schmidts are extremely uniform. This makes possible a high contrast copying technique ('photographic amplification') that is ideally suited for the detection of extended features that are less than 1% as bright as the night sky. At Siding Spring, this can often imply a limiting magnitude of about 28 mag arcsec^2, and several discoveries have flowed from this, such as the huge but very faint galaxy Malin 1 which lies far beyond the Virgo cluster.

Another by-product of only accepting the best plates was a growing collection of less-than-perfect, but still useful plates of identical fields. Photo-amplified derivatives from these can be combined to yield ever fainter limiting magnitudes. By combining the data from several exposures, the signal is effectively strengthened while the random noise inherent in the emulsion layer is 'smoothed out'.

There are, however, drawbacks with photographic addition. For example, there is distortion between plates taken at different hour angles and so the whole field must be cut up into relatively small pieces and these added, one at a time, but the technique is ideal for small objects and is rapid in operation. Digital addition does not suffer from the same problem although it was delayed in implementation until the advent of cheap mass storage at the several Gbyte level. Software is able to compensate for rotation and translation and the better alignment causes less image degradation. Work by Marston, Kemp and Hawkins has established the reliability of the technique and its suitability for investigations which require great depth and wide area coverage such as the galaxy correlation function, galaxy cluster distribution, searches for high redshift quasars and studies of the galactic halo, brown dwarfs and cool white dwarfs. An increasing number of the already large set of 'non-survey' requests at UKST are for sets of 4 to 6 tech pan films with the express intention of digitally adding them (combining 6 images should in theory lead to a 1 magnitude increase in depth).

12. Tech Pan Discussion

Having just mentioned Tech Pan, I would briefly like to say why we believe that we are reaching DQEs of the order of 10% with this emulsion on film. The DQE of an emulsion is related to its speed, the gradient of the D-logE curve and the rms granularity of the emulsion at the density where the gradient is measured by the formula:

$$\mathrm{DQE} = (K \times \gamma^2 \times S) / (A \times \sigma^2)$$

where K is a constant, γ is the gradient of the D-logE curve, S = 1/nt where n is the number of

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photons incident per unit per second and t is the exposure time in seconds, and σ is the rms granularity measured with a scanning aperture of area A.

Our hypersensitising and development renders gammas for IIIa-F and 4415 equal to within 3%. Exposure times to reach similar sky densities on identical fields are also comparable and so the relative DQEs for the 2 emulsions vary as

$$\mathrm{DQE}(4415) \,/\, \mathrm{DQE}(\mathrm{IIIa\text{-}F}) = (\sigma\ \mathrm{IIIa\text{-}F} \,/\, \sigma\ 4415)^2$$

$$\text{i.e. } \mathrm{DQE}(4415) = \mathrm{DQE}(\mathrm{IIIa\text{-}F}) \times 3.2$$

(using quoted values at a background density of 1 from Eccles, Sim & Tritton [1983]) and if we accept a DQE(IIIa-F) of the order of 3%, then

$$\mathrm{DQE}(4415) = 9.6\%.$$

Alternatively, CCD imaging at prime focus (f/3.3) at the AAT reaches 24 in R in 5 minutes. The loss in magnitude by having the CCD at the Schmidt would amount to

$$2.5\log(3.9/1.22)$$
$$= 1.26$$

and so in 5 minutes at the Schmidt it should reach 22.74.

From Phillipps & Parker (1993), Tech Pan film has a reported gain of 1.5 mag over IIIa-F.

Accepting that the limit in R at the Schmidt using IIIa-F is 22, that implies a limit with Tech Pan of 23.5 (in 60 minutes). To reach 23.5 the CCD exposure would need to be for 10 minutes. Thus, the CCD is 6 x faster, and with a reported peak DQE in the red of 68% this implies a DQE for Tech Pan of the order of 11% (if we conservatively estimate the limit in R(IIIa-F) at the Schmidt to be 21.7 this would in turn result in a DQE for the film of 8.7%.

A Tech Pan 14-inch film contains some 5 billion 5 micron pixels, with say, 10% DQE. The largest currently available CCDs (and even they aren't all that available, as we have discovered to our cost) contain 4 million pixels and have say 80% QE. Thus you need about 100 large CCDs to get the same actual observing efficiency in terms of telescope time, and you need to mount them in a telescope with a large enough plate scale that their 24 micron pixels are not undersampling the images. You also have to be able to handle horrendous amounts of data in real time. Of course the CCD data have the advantage that they are already digitised and calibrated. Working with smaller arrays of CCDs on a larger aperture telescope, and scanning the sky, is probably a more practical way to go, but in that case you have to somehow maintain uniformity during varying observing conditions and you have to tie all the exposures together on a positional grid if you want to do astrometry.

13. The Future of Large Schmidt Telescopes

Until we have a totally adequate digital substitute, as astronomers we must not abandon the photographic layer as a recording medium. But equally, we must not be side-tracked into believing that photographic surveys are useful for their own sake, otherwise our science will peter out, just as the Carte du Ciel did. Note however that even the old Carte du Ciel data have recently found a new application, being used to determine first epoch positions for new southern astrometric reference star catalogues which incorporate proper motions and hence are more accurate than any previously available, particularly in the south (as reported at the recent Cambridge Workshop on Astrometry, June 1993). We must focus our attention on the science that can be done with the promising new materials that are here or on the horizon.

As we have heard this morning, CCDs, either singly or in the form of mosaics are already in use in some Schmidt telescopes. At the Beijing 0.6 m Schmidt in China; at the Kiso Observatory in Japan; on the Burrell Schmidt at KPNO in the United States (one degree field, heavily used and very productive); on the Curtis Schmidt at CTIO in Chile (0.5 degree field); and on the OCA Schmidt in France and it seems clear that the trend will continue (as long as funds are available). At the UKST there is a proposal for a 2 degree field CCD mosaic facility (Shanks, University of Durham) and in the future one could conceive of a continuing programme of observations with the telescope alternating between photographic and CCD imaging in much the same way as the telescope now operates between photography and FLAIR spectroscopy (roughly 3:1).

We believe that the demise of photography in wide-field astronomy has been arrested by the current success of the extremely fine-grained tech pan emulsion in the red (currently 65% of all new non-survey programmes request the use of this emulsion) and we hope very much that Kodak are able to produce an equivalent in the blue spectral region (which is where the sky is darkest) to supersede IIIa-J. If this eventuates, a new blue survey at high galactic latitudes would be of great value especially as the very large new reflectors come into service in the N and S and since Tech Pan is optimised for Hα, this could be accompanied by a new Hα survey of the galactic plane, using narrow band full aperture Hα interference filters located by the Schmidt corrector.

All these activities would complement each other perfectly, both from a scientific and a practical perspective and give us an unprecedentedly deep, wide-field view of the Universe as we enter the next century.

References

Eccles, M.J., Sim, M.E. and Tritton, K.P., 1983. 'Low light level detectors in astronomy', Oxford University Press.

Phillipps, S. and Parker, Q.A., 1993. 'Galaxy Surface Photometry with Kodak Technical Pan Film', *Mon. Not. R. astron. Soc.*, **265**, 385.