IV

OTHER TECHNICAL DEVELOPMENTS

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Multi-fibre Spectroscopy with Schmidt Telescopes

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Abstract. Large Schmidt telescopes are peculiarly well-suited to multi-fibre spectroscopy. The extent to which the small aperture is compensated by the wide field is illustrated by the fact that the total photon throughput of the 1.2 m UK Schmidt Telescope (UKST) is almost identical to that of the 3.9 m Anglo-Australian Telescope (AAT) in its new 2-degree field (2dF) mode. In the implementation of the technique, Schmidt telescopes have a number of practical advantages, while there is no shortage of scientific problems that can be addressed. However, the instrumentation required to capitalize fully on this potential is costly and, because Schmidts are perceived as "small" telescopes with a specialist following, the required funding is likely to remain elusive.

1. Introduction

The technique of multi-fibre spectroscopy, in which low-loss optical fibres are used to re-format the random distribution of target objects for entry into a wide-field spectrograph, is now part of the standard repertoire of the world's major observatories. It provides the most efficient method of gathering statistically-significant amounts of spectroscopic data on all the commonest classes of astronomical objects, so long as they are brighter than a rather significant fraction of the night sky (see Parry & Carrasco 1990; Barden et al. 1993).

Technologically, the method has spawned a number of ingenious solutions to the problem of accurately positioning fibres in the telescope focal surface. Manual plug-plate systems like the original "Medusa" and FOCAP (Hill et al. 1982; Gray 1984) have largely given way to robotic positioners in the MX and Autofib classes (Hill & Lesser 1986; Parry & Gray 1986). Prime focus correctors for 4 m class telescopes have been designed with the express purpose of feeding multi-fibre systems (e.g. Jenkins et al. 1993; Gray et al. 1993). Fibres have been made long enough to remove the spectrograph from the telescope altogether, resulting in very high stability.

2. Why Schmidt telescopes?

It is more than a decade since the astronomical potential of fibre-coupled multi-object spectroscopy with Schmidt telescopes was first rehearsed by Dawe and Watson (1984). A figure of merit derived by these authors for comparing the efficiency of different telescopes was the "effective aperture", a, and it remains a

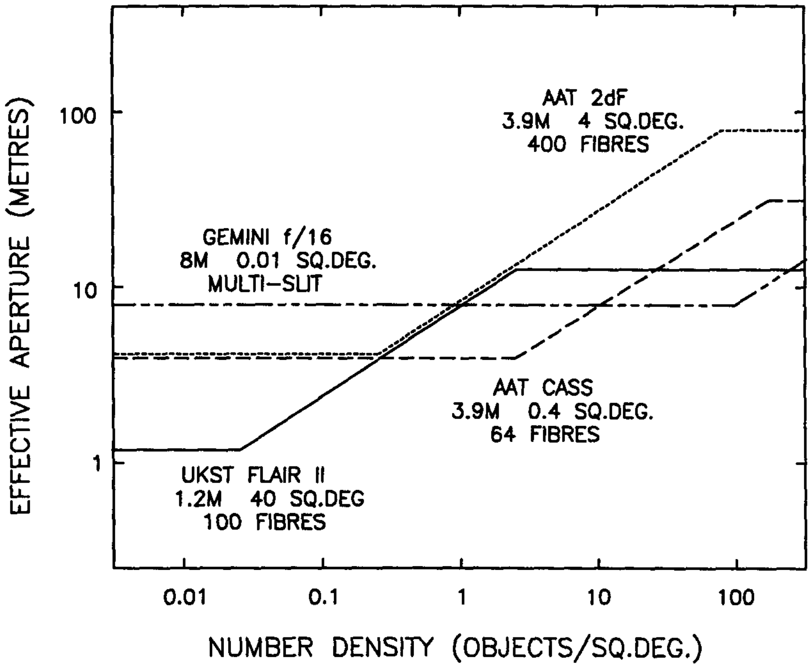

Figure 1. Effective aperture of four multi-object spectroscopy systems plotted against target object number-density.

useful indicator of the performance of a spatially-multiplexed (e.g. multi-fibre) telescope.

Effective aperture is simply $i^{1/2}A$, where A is the aperture of the telescope and i is the number of fibres in use (out of a total, j, available). By considering the behaviour of a with N, the number-density of objects of a particular class, the effect of the area of field, F, of the telescope, can be demonstrated. Three cases arise depending on the value of N; they are: (1) $N < 1/F$, when one object only is observed and $a = A$; (2) $1/F < N < j/F$, so that i fibres can be used and $a = (FN)^{1/2}A$; (3) $N > j/F$, when all the fibres can be used and $a = j^{1/2}A$.

In practice, classes of target objects for multi-fibre systems can be mixed, so that it is not usually the number density of a particular class that determines how many fibres are used. (It is more likely to be the number of fibres required to sample the sky.) Also, of course, the effective aperture makes no difference to the magnitude of the faintest objects that can be observed. Nevertheless, the relative merits of widely differing systems can be compared by plotting a against N. Fig. 1 shows such plots for some existing and forthcoming facilities.

It is apparent that the existing FLAIR II multi-fibre system on the UKST does better than its counterpart at AAT Cassegrain in the range $1 < N < 10$ deg^{-2} (irrespective of the number of fibre channels on the latter). FLAIR II and 2dF are comparable at $N \sim 1$ deg^{-2}, and are complementary in as much as the

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brighter objects at this density are more likely to be FLAIR targets than 2dF targets.

Although the f/16 foci of the proposed Gemini telescopes do not pretend to offer wide-field capability, instruments for multi-object spectroscopy *are* envisaged, and Fig. 1 includes a line representing these. It would be naive to suppose that a 1.2 m Schmidt could out-perform an 8 m telescope, but the greater effective aperture of the UKST in the range $1 < N < 100$ deg^{-2} at least inspires some confidence that we are still dealing with a world-class facility. The argument is even more applicable to the AAT.

Not depicted in Fig. 1 is the monotonically-increasing dependence of N (taken as *integrated* number-density) on magnitude. Thus, for a particular class of objects, there will be a value of N that corresponds to the limiting magnitude of the telescope, so that the maximum useful number of fibres will be FN_{lim}. In the case of the UKST carrying out galaxy redshift surveys, for example, the limiting magnitude of $B \sim 17$ corresponds to ~200 objects per field, so the 92-fibre capability of FLAIR II is well-chosen for 1-in-3 surveys (e.g. Broadbent et al. 1992).

3. Practical aspects

In the practical implementation of the multi-fibre method for spectroscopy, Schmidt telescopes have particular attributes that have to be considered. Some are advantages and some are disadvantages; some are both.

3.1. Advantages of Schmidts

1. Field of view is vastly in excess of most other types of telescope.

2. Even the largest Schmidts allow fibre coupling to stable, floor mounted spectrographs with only modest fibre lengths (~10 metres). This is important from the point of view of wide spectral coverage; the blue performance of all fibre types is compromised by excessive length, though the high-OH^- type ("wet") fibres suffer less in this regard than fibres optimised for the near-IR. However, long "wet" fibres will have deep OH^- absorption bands redward of about 8500 Å.

3. The classical Schmidt optical system is perfectly telecentric, so that the converging beam is everywhere axially symmetric about the normal to the focal surface (within the unvignetted area of the field). Thus, there is no dependence of emergent-beam focal ratio on input-end field position, as there is in multi-fibre systems on most other types of telescope (see Wynne 1993).

4. The fast focal ratio of most Schmidts is well-matched to fibre numerical aperture, and reduces the detrimental effects of focal-ratio degradation (FRD). The all-silica fibres used in multi-object spectroscopy will propagate beams almost up to f/2 in speed, and the best ones have good FRD characteristics at ~ f/2.5.

3.2. Disdvantages of Schmidts

1. The limited aperture of Schmidt telescopes means that sensitivity will always be a problem; they are small telescopes, no matter how great the multiplex advantage. In general, spectra will be dominated by CCD read-out noise rather than sky noise at all but the lowest dispersions. Lengthy integration times will be required.

2. The wide field brings with it significant distortion due to differential atmospheric refraction (Watson 1984). This dictates against the use of fibres subtending "conventional" angles on the sky (1–3 arcsec), which would reduce the duration of satisfactory registration of the fibre field with the telescope image. Because of disadvantage (1), such a limitation on integration times would be unwelcome, so larger fibres are required.

3. The focal surface of the telescope is large compared with the incoming light beam, so bulky fibre-positioning equipment will cause vignetting of the beam or the field, or both. Furthermore, the focal surface is steeply curved, so a means has to be found of positioning the fibres in three dimensions. A field-flattener will negate advantage (3).

3.3. Other considerations

The fine plate-scale demands high fibre-positioning accuracy. The technology required to achieve this is costly, but no more so than on larger telescopes. Most of the world's large Schmidts, having been built solely for photography, lack suitable means of field acquisition. Photography has no need for rotation of the plate, nor of aligning it with arc-second accuracy on the sky; these facilities must be provided . Finally, some of the considerations above lead to the conclusion that Schmidt multi-fibre spectroscopy could be successful at poor observing sites.

4. Implementation of the technique.

4.1. FLAIR II

Multi-fibre systems have been built at a handful of large Schmidts, perhaps nowhere more successfully than at the Anglo-Australian Observatory's 1.2 m UKST. Here, three generations of multi-fibre systems have built up a service that now yields up to 5000 spectra per year alongside the telescope's conventional photographic work. The current version of the system, FLAIR II, has been described in detail elsewhere (Watson et al. 1993a,b; Bedding, Gray & Watson 1993), and a critical review of its performance has recently appeared (Watson & Parker 1994).

Briefly, FLAIR II consists of two interchangeable plateholders feeding fibres from the 6.5×6.5 deg^2 (356×356 mm^2) field of the telescope to an intermediate-dispersion CCD spectrograph in the dome. Each plateholder can hold up to 152 fibres, which can be retracted into the plateholder body so that a minimum length of each crosses the focal surface (Fig. 2). Externally, the plateholders resemble their photographic counterparts, and they are loaded into the telescope in the same way. The fibre input-ends are equipped with 90-deg microprisms, and are aligned manually on a copy plate of the target field (supported flat) using

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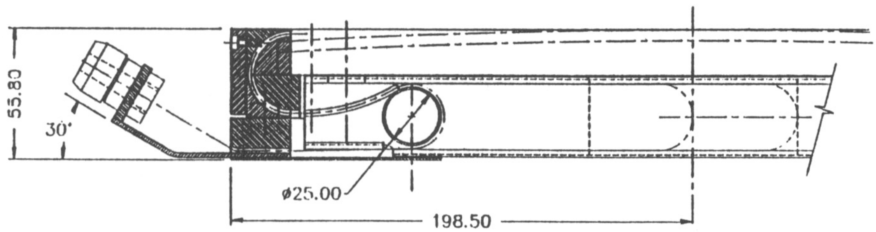

Figure 2. Cross-section of the southern half of one of the FLAIR II compact fibre plateholders, showing the fibre route around the edge of the field plate (uppermost in diagram) to the retraction storage loops behind. Dimensions are in mm.

a robot-assisted positioning table ("AutoFred"). The copy plate is deformed to the focal curvature over a spherical mandrel prior to loading. This preparation method involves no bulky equipment round the telescope focal surface, but the manual set-up process is labour-intensive and time-consuming. The number of fibres that can be used simultaneously is limited by the spectrograph; with the current feeds, the maximum is 92.

The fibres are 11 m long, and run to an all-Schmidt reflection-grating spectrograph ("FISCH") mounted on an optical table next to the telescope. The CCD detector is operated from the first-floor common-room, and it is linked by Ethernet to both a MicroVax and a Sparcstation, so that spectral data frames can be sent by FTP for immediate reduction.

FLAIR II is a common-user instrument scheduled on the telescope for approximately 5 nights per lunation. The programmes being carried out cover a very wide variety of object types, including galaxies to $B \sim 17$ for large-scale redshift surveys (e.g. Broadbent et al. 1992; Parker 1992), LMC objects, galactic planetary nebulae and bright ($R \sim 18$) quasars.

4.2. Other systems

Schmidt multi-fibre systems have been tested at a number of other observatories. FLAIR-type systems, using manual positioning, have been built at the Kvistaberg 1.0 m Schmidt (Pettersson 1988), and at the 0.6 m Schmidt of the Beijing Astronomical Observatory (Wang 1988) in preparation for the proposed Chinese large Schmidt. The latter system resembles a manual version of Autofib, using magnetic fibre buttons (fitted with microprisms) and a metal field plate.

More recently, work has been undertaken on the "Feldspinne" fibre positioner for the 1.33 m Tautenburg Schmidt telescope (Pitz, Lorenz & Elsässer 1993). This novel instrument utilizes a computer-controlled positioning system developed for the 3.5 m telescope at Calar Alto (Pitz 1993). An actuator with (r, θ) movement manipulates magnetic buttons attached to pivoted rods whose other ends hold the fibres. Thus, the "field plate" supporting the magnets has a large central hole (surrounded by a circle of pivots), which corresponds to the telescope field. The concept of the instrument owes as much to the MX "fishermen round the pond" technique as it does to Autofib. "Feldspinne" has a diameter of 600 mm, obstructing a significant portion of the incoming beam, and a field diameter of 2.3 deg (160 mm). A field flattener is used, and there are 36 fibre rods, two of which are used for acquisition. The remaining rods hold the science fibres in pairs (object and sky).

5. Future prospects

5.1. Fibre positioners

Probably the most serious drawback of the "Feldspinne" is the limited number of object fibres it provides. Without doubt, the most significant difficulty with FLAIR II is its manual positioning system. To keep up with an observing run taking data on two fields per night (common in winter months), large amounts of effort are required.

When FLAIR II was first envisaged, a fully-automated version of the existing off-telescope fibre positioning system was costed and found to be well beyond the budget of the project. If significantly higher funding for a new instrument on the UKST were available now, this would still be the preferred option. It is just conceivable that an Autofib-type system (using miniaturised components and addressing a reduced area of the field) could be mounted at the focal surface. However, such a device would be advantageous only in the situation where the fibre field is reconfigured at frequent intervals during the night.

Given typical FLAIR II exposure times (9,000 s to 18,000 s), this is the exception rather than the rule. So long as two fibre plateholders can be exchanged in the telescope in a matter of a few minutes, little more flexibility is necessary. Thus, the ideal "FLAIR III" would use interchangeable plateholders similar to the current ones (but with deformable metal field plates), and an intelligent robotic positioner capable of reconfiguring the fibres in less than, say, an hour.

This argument is probably true for most existing large Schmidts. For a completely new telescope, particularly one significantly bigger than the current generation, an *in situ* Autofib might well be a more desirable solution.

5.2. Spectrograph design

The "large" fibres mentioned in disadvantage (2) above (Section 3.2) are still relatively small compared with those used on larger telescopes. For example, at the UKST, 55 μm and 100 μm fibres (subtending 3.7 and 6.7 arcsec) are used. In order to match these to conventional CCD pixel sizes, a spectrograph with magnification near unity is required, resulting in a slow camera.

In fact, the FISCH spectrograph has a magnification of 0.4, so while the camera works at $\sim$ f/1, the smaller diameter FLAIR II fibres are undersampled by the 22 μm pixels of the CCD. Such undersampling is not confined to the smaller fibres. While the 100 μm fibres are intended for 17th magnitude galaxies (to which they are well-matched), they are also frequently used for observing point objects for the reasons outlined in Section 3.2. Fibres with good FRD characteristics are very poor at radial scrambling when illuminated with a fast

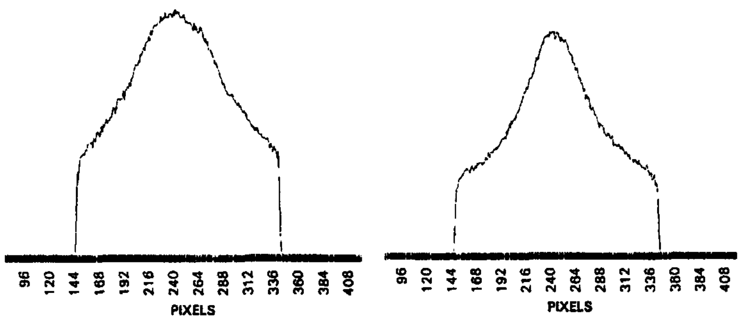

Figure 3. Output end intensity patterns when a 153 μm diameter fibre is centrally illuminated at its input end by a spot of about 1/3 its diameter (left) and 1/10 its diameter (right), showing highly-incomplete scrambling. Beam focal ratio f/2.8.

beam, and a centrally-placed point image on the input face will give rise to an output-face illumination pattern of the kind shown in Fig. 3 (Watson & Terry 1993). Thus the effective image-size seen by the spectrograph may frequently be less than the fibre diameter. This situation is likely to arise in other fibre-coupled spectrographs; rescue seems to be approaching in the form of CCD chips of astronomical quality with significantly smaller pixel sizes.

The design of fibre-fed spectrographs for use with fast ($\sim$ f/2.5) telescopes can also benefit from the use of microlenses to tailor the emergent beam from each fibre to the focal ratio of the collimator. For example, on the WYFFOS spectrograph for the 4.2 m William Herschel Telescope (Jenkins et al. 1993), these are used in the "reverse Fabry" mode suggested by Hill, Angel & Richardson (1984), thus providing good throughput stability (but not resolution stability) with focal ratio degradation. WYFFOS uses the white-pupil configuration of Baranne (1988), and employs a relay-mirror to transfer the pupil from the grating to the camera. The pupil imaging is effective at controlling vignetting, and significantly eases the camera design. The Baranne configuration would offer similar advantages if adapted for use with Schmidt telescopes.

General-purpose fibre spectrographs for use with large numbers of fibres must, themselves, be large (e.g. FISCH has a beam-diameter of 150 mm). At the other end of the scale, it is possible to imagine a very efficient multi-fibre spectrograph made from a stack of waveguide spectrometers of the type proposed by Lang (1992). One possible application of such an instrument with high multiplex-advantage and $\sim$ 20 Å resolution is in quasar follow-up spectroscopy with a wide-field telescope (Watson, in preparation).

6. Conclusion

It has been shown that Schmidt telescopes are generally well-suited to multi-fibre spectroscopy. Useful science is there to be carried out, mostly in large-scale surveys of intermediate brightness objects. Implementation of the technique brings interesting challenges to the instrument designer. Why, then, have only two of the world's eight Schmidt telescopes with apertures of 1 m or more taken serious steps to develop multi-fibre spectroscopy systems?

Some would argue that a large Schmidt on a good site should be doing what it was built for—deep, wide-field imaging. It is true that the uniqueness of the Schmidt's capability is less evident in multi-fibre spectroscopy than it is here. The real reason, though, is related to capital cost. While experimental work can be carried out with very low levels of spending, achieving the full potential of the technique demands fibre positioners and spectrographs comparable to those on much larger telescopes. Astronomers involved with Schmidt-type survey work are in a minority—more so than the potential users of 2dF. Thus, while the cost per spectrum of a Schmidt multi-fibre system is low, the cost per astronomer is high. In the light of this, it is perhaps remarkable that FLAIR II and Feldspinne have been developed at all.

Acknowledgments

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Discussion

Armandroff: Could you tell us about the relative use of, and demand for Flair II versus other uses of the AAO Schmidt.

Watson: The time allocation with FLAIR II is currently 5–7 nights per lunation. This has been established in response to user demand, by the time allocation panels.

Ward Moody: You mentioned the trail rates being 5″/hour. Isn't the real problem the displacement of an object's position across a Schmidt plate as the hour angle increases?

Watson: Trail rates are just a convenient way of plotting the differential atmospheric refraction data. You have to integrate the trail rate along a line of constant declination to get the total trail in a given exposure.

Ward Moody: When you take an exposure do you then aim for the mean position and leave it there for the whole exposure?

Watson: The plates used as templates to set up the fibres were obtained close to the meridian where the refraction effects are minimised.