Tunable Filters and Large Telescopes

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Introduction

Traditionally, astronomy has relied upon filters with a fixed bandpass to select the wavelengths of the light allowed to reach the detector, thus allowing the astronomer to derive some colour information about the objects under study. In the optical, these filters are most often classical broadband UBVRI, or narrow passbands centred at the wavelengths of the common emission-line features, either at rest-frame or redshifted wavelengths.

Examples of the latter are becoming numerous, especially on the 8–10-m-class telescopes that make it possible to detect very faint, distant emission-line objects, even through narrow passbands. In this vein, Kurk et al. (2000) used FORS1 at the VLT with a 65-Å-wide filter at 3814 Å to image a $z = 2.2$ radio galaxy, searching for nearby Ly-alpha detections at the same redshift. They detected around 50 such objects, collectively suggestive of strong clustering around the dominant radio galaxy. Moreover, they also found extended Ly-alpha emission (~ 100 kpc in extent) centred on the galaxy, adding further evidence to the possible scenario of protocluster formation.

Steidel et al. (2000) used an 80-Å-wide filter on Keck to search for Ly-alpha emitters at $z = 3.09$, the redshift of a prominent peak in the redshift distribution of their original sample of broad-band selected Lyman-break galaxies. This took the number of galaxies associated with the peak from 24 to 162, a gain of almost a factor of 7, thereby demonstrating the power of narrow-band observations in the detailed mapping of large-scale structures at high redshift. They also found extended (~ 100 kpc) Ly-alpha emitting "blobs'', that again may point to incipient cluster formation at these redshifts.

Kudritzki et al. (2000) used FORS1 at the VLT for the spectroscopic follow-up to a sample of emission-line objects, identified by narrow-band imaging in the field of the Virgo cluster. The expectation was to confirm them as intra-cluster planetary nebulae, given their detection with a [OII] (lambda = 5007 Å) filter. As it turned out, however, the narrow passband was equally good at revealing Ly-alpha-emitting objects at $z \sim 3.1$, and nine were found.

In some of the above examples, a filter with the desired passband luckily matched the project requirements; in others, one had to be designed with a specific target in mind. However, studies of this kind (as well as many others in the local universe), would clearly benefit given the use of a passband that can be easily tuned both in its width and central wavelength, over the full optical range. The use of (Wide-band) Tunable Filter (WTF) instruments at the Anglo-Australian and William Herschel Telescopes (Bland-Hawthorn & Jones 1998a,b) in the past five years has indeed seen a very broad range of astrophysical applications. At low redshifts, science undertaken with these instruments includes studies of brown dwarf atmospheric variability (Tinney & Tolley 1999), and the identification of optical counterparts to Galactic X-ray sources (Deutsch, Margon & Bland-Hawthorn 1998). High-redshift science has included estimates of the cosmic star-formation history (Jones & Bland-Hawthorn 2001), identification of galaxy clustering around high-redshift QSOs (Baker et al. 2001), deep imaging of jet-cloud interactions in powerful radio galaxies (Tadhunter et al. 2000), and the detection of a large ionised nebula around a nearby QSO (Shopbell et al. 2000). Figure 1 shows a section of field from a tunable filter survey on the Anglo-Australian Telescope (Jones & Bland-Hawthorn 2001), for distant emission-line galaxies. Figure 2 shows example scans and scanning narrow-band "spectra" obtained with the tunable filter for some of the same objects.

Understandably, there is growing interest in the role that tunable filters can play in the instruments currently under design and construction for the new generation of large telescopes. These include tunable filters in instruments for the GranTeCan (OSIRIS: Cepa et al. 2000) and SOAR telescopes (Cecil 2000), among others under consideration. The technique is all the more powerful when the focal reducing instruments in which they are placed have the capability for both tunable imaging and multi-object spectroscopy, since the two modes are complementary. In this article we review tunable imaging and the future role it could potentially play at the VLT. We also briefly mention the wide range of science, both Galactic and extragalactic, that could be undertaken with a tunable filter on an 8-m-class telescope.

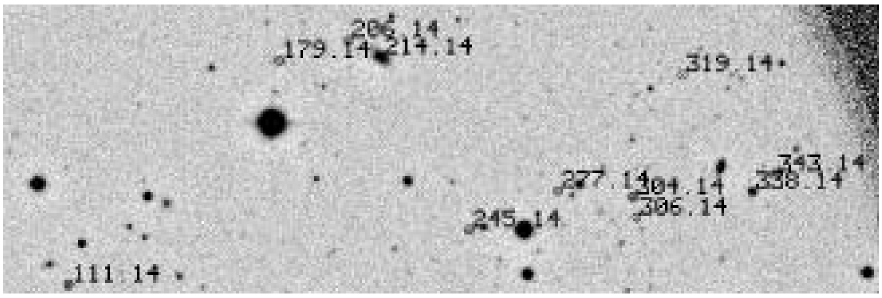

Figure 1: A section of field (approximately 6 × 2 arcmin with north up, east left) from the emission-line galaxy survey of Jones & Bland-Hawthorn (2001). The numbers next to each emission-line candidate are object identifications.

Making a Filter Tunable

There are many ways of making a filter with tuning capability, and consequently, many types of tunable filter. These include those using birefringent materials (such as the Lyot, Solc and acousto-optic tunable filters), more traditional interferometers such as the Michelson and Fabry-Perot, and even liquid crystal tunable filters. We will not describe details of each technology here, but instead refer the interested reader to Bland-Hawthorn (2000), who discusses the merits of each for tunable imaging. While all have advantages and limitations, in the end it is the stringent demands of night-time astronomy that dictate which are feasible. For astronomical applications, the ideal filter should have high peak transmission, a broad (rectangular) profile, and should be large enough to admit a generous beam size. It should also be of good imaging quality, produce a stable and reproducible passband, and cover a large range of wavelengths, to name just the major requirements.

Of all the possibilities, it is the Fabry-Perot interferometer that has been the popular choice of astronomers for three-dimensional spectral imaging. This is because they are readily available on a commercial basis and make use of well-established technology. Astronomical applications of these instruments have included studies of extended diffuse nebulae (e.g. Haffner, Reynolds & Tufte 1999) and obtaining kinematic information (such as line widths and radial velocities) on nearby disk galaxies (e.g. Amram and Östlin in this issue, p. 31; Laval et al. 1987; Cecil 1989; Veilleux, Bland-Hawthorn & Cecil 1997; Shopbell & Bland-Hawthorn 1998). The Fabry-Perot systems employed have traditionally used narrow wavelength coverage and high spectral resolutions (resolving powers R 1500).

There are two problems to be overcome in the adaptation of a Fabry-Perot interferometer to tunable imaging. First, it must work at sufficiently low spectral resolution (in other words, narrow plate spacing) that scanning in spectral steps over larger ranges of wavelength is feasible. Second, the filter coatings must be optimised over a large range of wavelengths. Traditionally, Fabry-Perots have had neither the wavelength coverage nor the ability to work at such small plate spacing.

Fabry-Perot Tunable Filters

It is a little more than one hundred years since Charles Fabry and Alfred Perot first highlighted the potential of an interference device producing fringes from two parallel silvered plates (Perot & Fabry 1899; Fabry & Perot 1901). Modern Fabry-Perot interferometers consist of two parallel glass plates held a small distance apart, such that constructive interference of light between the plates causes only specific wavelengths to be transmitted. However, with typical plate spacings in the range 20 to 500 microns, Fabry-Perots for astronomical work have been confined to high orders of interference (50 to 2000), thereby giving rise to the high resolving powers mentioned earlier.

Tunable filters differ from conventional Fabry-Perot devices in two novel but important ways. First, the plates are operated at much smaller plate spacings than the Fabry-Perot instruments so far used for astronomy. The effect of this is to widen the central interference region of the chosen wavelength. A conventional Fabry-Perot, with a plate spacing of many tens or even hundreds of microns, presents an interference region as a narrow ring on the sky, with very small area (Fig. 3a). A tunable filter, with a plate spacing of no more than a few microns, aims to provide a broadened central interference region, known as the Jacquinot spot (Fig. 3b). The latter is more useful for survey work, where one seeks a common wavelength transmitted across the full field and where lower spectral resolutions are desired.

The second way in which a tunable filter differs from a conventional Fabry-Perot is in its ability to access a much wider range of plate spacings. Conventional devices are most commonly used to scan through a relatively small range of wavelengths around a single spectral feature. However, a tunable filter, aiming to access as broad a tunable range as is possible, needs to access a much wider range of plate settings. This is made possible by having a stack of piezo-electric transducers (PZTs) to control plate spacing, instead of the usual single-layer. These structural differences between a tunable filter and a conventional Fabry-Perot contribute to the different types of data that are obtained with each instrument:

(i) conventional Fabry-Perots can be used to obtain a high-resolution narrow-range spectrum at each pixel position over a wide field (Fig. 3i),

(ii) conventional Fabry-Perots can also be used to obtain a single spectrum of a diffuse source which fills a large fraction of the aperture (from one or more deep frames at the same etalon spacing, Fig 3ii), and,

(iii) tunable filters can obtain a sequence of monochromatic images within a field defined by the Jacquinot spot, (Fig. 3iii).

Atherton & Reay (1981) were the first to suggest the possibilities of a Fabry-Perot as a tunable imager. However, the technology available at the time was not sufficient for precise control of the plates over a such wide range of spacings, and suitable coatings were not very good by the standards of today (see Pietraszewski 2000 for descriptions of the current state of the art in Fabry-Perot technology). In the mid-1990s, J. Bland-Hawthorn (AAO) revisited the tunable filter concept by

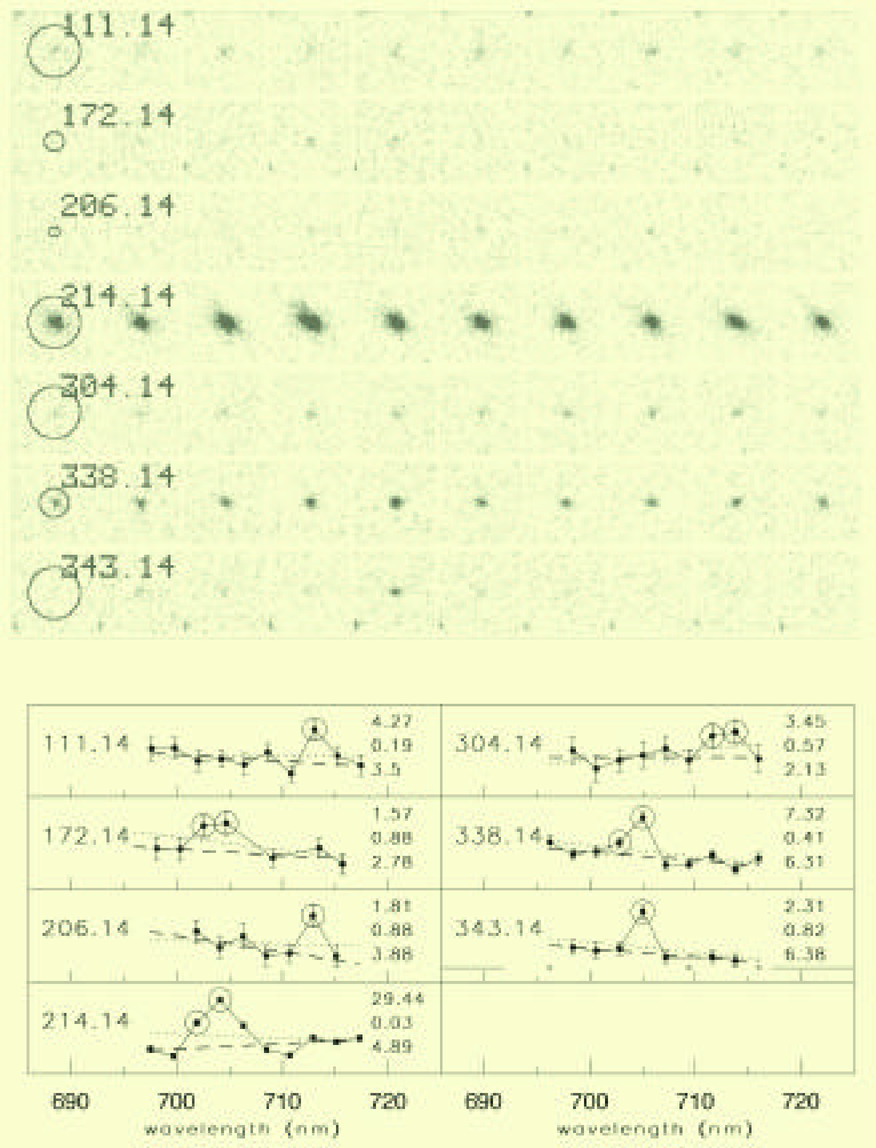

Figure 2: (Top) Individual object scans for some of the same candidates as in Figure 1. Individual images are 9 arcsec on a side with north at top, east to the left. Circles denote aperture size.
(Bottom) Spectral flux measurement for the same galaxies. Both preliminary (dotted line) and final (solid line) continuum fits are shown. Numbers shown on the right are flux (× 10^{-16} ergs/s/cm^2, a star-galaxy classification parameter and deviation of the line detection in sigma. Deviant points (excluded from the final continuum fit) are indicated by circles. The zero flux level is shown by the horizontal tickmarks (where present) and non-detections are represented on this level by crosses. Galaxy 214.14 has independently been found to have emission in [OII] by Ellis et al. (1996); the emission we see here is H-alpha and [NII].

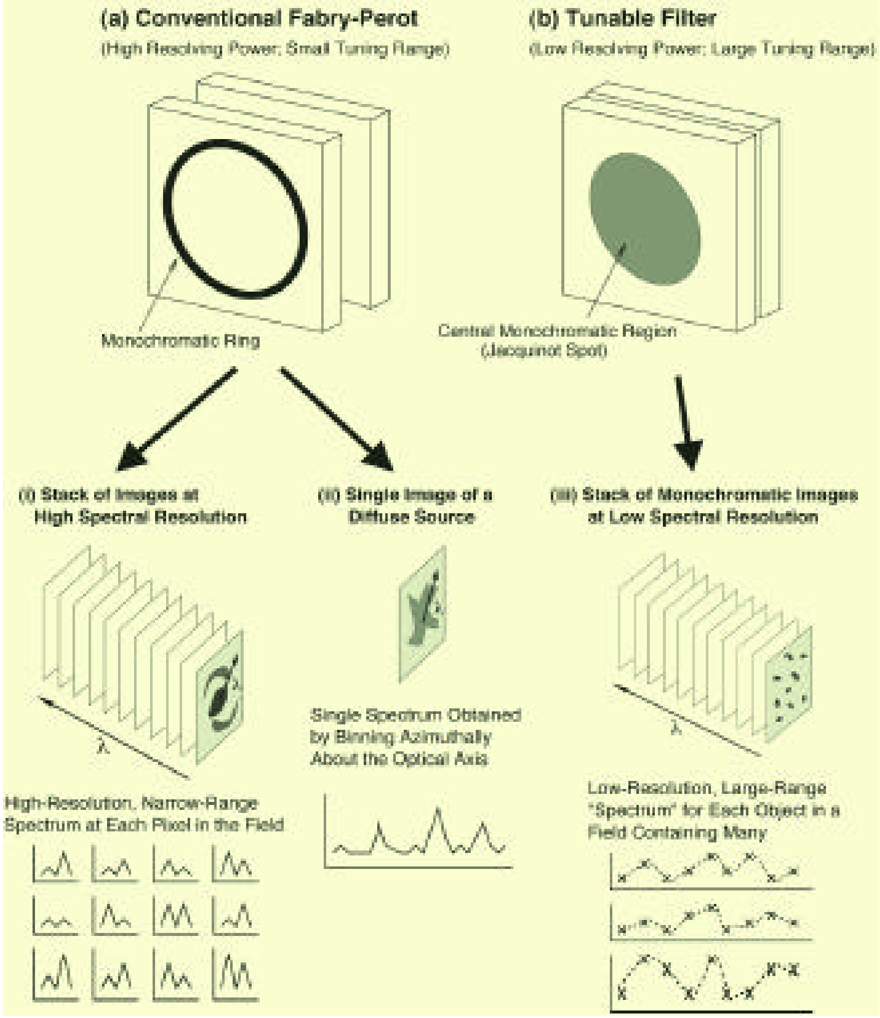

Figure 3: Different modes of Fabry-Perot use in the case of both (a) conventional instruments, and (b) tunable filters.

having an old, disused conventional Fabry-Perot, refitted with stacked PZTs, then repolished and recoated for the range 6500 Å to 1 micron. The result was the first TAURUS Tunable Filter (TTF; Bland-Hawthorn & Jones 1998a,b) implemented at the Anglo-Australian Telescope (AAT). Two years later, an instrument coated for the blue (3700 to 6500 Å) was commissioned. These instruments are operated at the Cassegrain focus of the AAT, and together have been used extensively. The instruments can also be used in conjunction with a CCD charge-shuffling mode, that allows repeated multi-band imaging on different parts of the CCD frame, before it is read out (Bland-Hawthorn & Jones 1998a, b). More details of the different features of TTF can be found at http://www.aao.gov.au/local/www/jbh/ttf/ . The advantages of using a Fabry-Perot for tunable imaging has also been recognised by other groups (e.g. Thimm et al 1994, Meisenheimer et al. 1997).

How does one set about tuning a passband to a specific width and placement, when all one is changing is the spacing between the plates? As Figure 4 shows, the answer lies in the nature of the transmission profile of the Fabry-Perot, and the different effect of making small and large adjustments. Figure 4a shows the set of blocking filters used with the red TTF. These are necessary to block the light of unwanted orders and make excellent intermediate-band filters in their own right, given their placement between the brightest parts of the night-sky background. Suppose we wanted to scan around H-alpha at 6563 Å. First we would put the R_0 blocking filter in place (Fig. 4a, solid line). Then we would set the spacing of the plates according to the desired width of our passband. Figure 4b shows that if we set the plates to 8 or 10 microns, we get a very narrow profile (at orders 24 or 30 respectively); if we set the plates to just 2 or 4 microns we get a much wider band (orders 6 or 12). If we then wanted to scan the passband, we would adjust the spacing between the plates by small amounts, thereby shifting the chosen order one way or the other in wavelength. The dotted profiles in the lower panel of Figure 4b show the effect of changing 2 microns slightly to 1.98, 1.96 and 1.94 microns. Note that the images delivered by a tunable filter are not strictly monochromatic, but shift slightly to the blue as one moves from the location of the optical axis on the image, to the edge. This phase effect is a natural consequence of interference between two surfaces and easily characterised through the cosine of the off-axis angle (at the etalon). The red TTF shifts about 18 Å at a distance of about 5 arcmin from the optical axis, as measured on the sky. The phase effect is not normally a problem for most applications, especially if the objects of interest are compact sources such as distant galaxies and stars.

A Tunable Filter versus Many Narrow-band Filters

Is a tunable filter any better than simply having a large set of filters? With a Fabry-Perot tunable filter it is possible to control both the width and placement of the bandpass. The only restriction on placement is that it must lie within one of the order-sorting filters. For example, the red TTF on the AAT can select a bandpass of between 6 to 60 Å in any of the 7 order-sorting filters that collectively cover 2300 Å in the 6500 Å to 1 micron range of the device.

With a set of fixed filters one is stuck with a predetermined width and placement for the bandpass. Tilt-tuning might be considered an option but this quickly broadens and degrades the passband, in the sense that peak transmission is lowered and the profile skewed. Furthermore, such tilt tuning only allows adjustment to the blue. The inability to set the bandpass means one cannot optimise spectral resolution, nor background level, nor central wavelength nor sampling (in the case of scans). The ability to tune and optimise is critical to projects with (i) objects at arbitrary redshift, (ii) background-limited observations, and (iii) objects with a specific spectral feature in mind. These make up the majority of front-line narrow-band observing, since much has already been done in the way of imaging bright objects at common spectral features. Furthermore, the exact optical characteristics of individual filters will vary slightly from filter to filter, implying inhomogeneities which will need to be dealt with on a filter-by-filter basis. This limits the ability to do precise differential imaging between two bands – a common application in both stellar and extragalactic work.

Reducing Tunable Filter Data

There is often the perception that Fabry-Perot interferometers produce data sets that are difficult for first-time users to understand and reduce. This is not true in the special case of tunable filters, as the variety of published results from the AAT and WHT

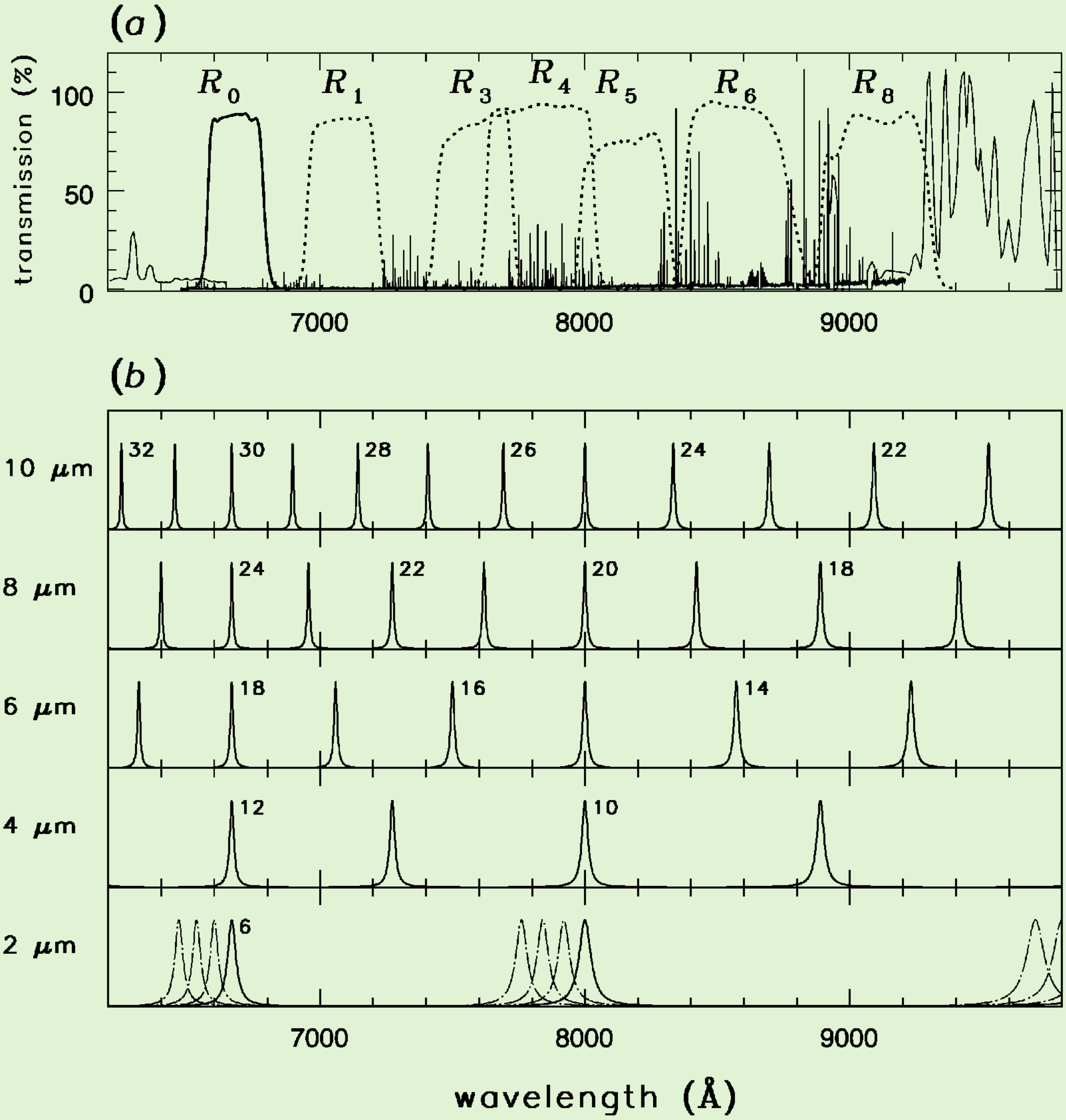

Figure 4:
(a) Wavelength region covered by the red TTF at the AAT, showing the location of the intermediate blocking filters with respect to bands of OH night-sky emission.
(b) Transmission profile of the tunable filter plotted on the same scale, as a function of changing plate separation (left). Even-numbered orders are indicated. The dotted lines in the lower panel show the effect of changing the plate spacing to 1.98, 1.96 and 1.94 µm.

show. Conventional Fabry-Perots work at much higher resolving powers and so when they are used to map kinematics in nearby galaxies, it requires precise mapping of the wavelength change across the field, so that a 3D-spectral cube can be constructed and subsequently transformed into a 2D map of velocities. However, tunable filter data are typically concerned only with scanning surveys of small point-like sources such as stars or distant galaxies. This requires nothing more than the detection, matching and photometry of each object on each frame – routine steps in any imaging survey, with or without a tunable filter. There is still a change in wavelength across the field of the tunable filter, but the lower resolving power makes this a less dramatic effect in terms of the broader width of the transmitting bandpass.

Tunable filter data from the AAT have been reduced with scripts utilising both the FOCAS (Valdes 1993) and SExtractor (Bertin & Arnouts 1996) packages for the object detection. One of us (Jones) has written a collection of IRAF tasks (TFred) offering a range of tools to treat tunable filter data in IRAF. A more comprehensive treatment is given in Jones, Shopbell & Bland-Hawthorn (2001), where approaches to the reduction of Fabry-Perot tunable filter photometry are described.

Tunable Filters and the VLT

There is currently no tunable filter capability on the VLT, and (in the short-term at least), neither on 8–10-m-class telescopes elsewhere. It is therefore worthwhile to contemplate if and how it might be possible to implement a tunable filter at the VLT. While a detailed technical, cost and manpower study remains to be done, we have investigated the main parameters of a possible incorporation of a tunable filter into the FORS2 focal reducer.

The largest commercially available tunable filter which could be fitted into either of the FORS instruments has a free aperture of 116 mm. The mechanical size of such a unit (sealed to minimise thermal/environmental influences) is 200 mm in diameter and about 135 mm in height (as measured along the optical axis). This space could be accommodated in the collimated beam of FORS2 if the upper of the two grism wheels were dismounted. Nevertheless, the full spectroscopic capability of FORS2 is preserved, albeit with more frequent grism exchanges. The FORS2 echelle mode would be lost, although it would be possible to reinstall the corresponding grisms in FORS1. Most importantly, no major mechanical hardware modifications would be necessary to effect the implementation. The control electronics needed to operate the tunable filter are delivered by industry. However, to allow for efficient use of the filter by the observer, a full integration into the GUI of the instrument would be needed.

As the free aperture of the tunable filters is slightly smaller than that needed to cover the full FORS field of view, a vignetting of 7.5 % occurs at the corners of the detector, preserving an unvignetted central field of 4.8 arcmin diameter. The blue shift of the filter transmission at the edge of the unvignetted field is only a fraction of the transmission profile width and therefore not a problem for most applications. For the lowest resolution, ordinary broad-band filters could be used as blocking filters. Additional filters needed to work at higher orders could be placed in the two interference filter wheels in front of the detector. The optimum passband for such filters is slightly less than the free spectral range at the highest resolving powers envisaged for use.

The useful wavelength range of the tunable filter is largely arbitrary but needs to be decided at the time of manufacture, as it is governed by the design (and resulting performance) of the etalon coating. For example, the two tunable filters in use at the AAT individually cover 3700–6500 Å and 6500 Å–1 micron. With a device in FORS, spectral resolutions achievable at 370 nm for example, would range from 330 to 1350, while at 650 nm would encompass 180 to 720. Such resolutions assume a variation of the spacing between the etalon plates from 2 to 8 micron, which can be achieved through stacked piezo-electric transducers. The tunable filter has a high efficiency comparable or even superior to common narrow-band filters.

The approach of using FORS2 to furnish the VLT with a tunable filter carries both pros and cons. On the one hand there is the relatively small effort compared to that of building an entirely new instrument, and the extension of the scientific uses of FORS2 following the commencement of VIMOS. On the other there is the need to remove one of the grism wheels to make the space. Eliminating one grism wheel will make for increased manual intervention in the exchange of grisms if one wants to preserve all the filter/grism combinations presently available. Clearly, the relative weight of these different arguments needs to be evaluated before deciding how to proceed.

Potential Science on 8-m-class Telescopes

Scientific applications of a tunable filter at an 8-m telescope span an extremely wide range, potentially satisfying the needs of what is a very diverse user community. Several such applications were described at the beginning of this article. Here, we mention a few more possibilities. At the high limit of spectral resolution (R ~ 1500) it may be possible to probe the internal dynamics of most kinds of emission-line nebulae and relatively nearby galaxies, along with that of QSO and radio galaxy environments. At lower resolutions (R ~ 150), most (but not all) applications will concern the distant universe. For example, high-redshift clusters of galaxies are usually found either in deep X-ray or infrared surveys, with cluster members being identified relatively easily through association with the 'red sequence' of passively evolving ellipticals. With such methods, however, spirals and star-forming galaxies that may also be cluster members are much more difficult to identify, given their broad range of colours, which can sometimes act to make them indistinguishable from foreground or background galaxies. However, tuning the tunable filter to a suitable emission line at the cluster redshift easily permits identification of these late-type galaxies.

Mapping the large-scale structure out to *z* ~ 5 is one of the main goals within reach of the current generation of large telescopes and their instruments. The pilot experiment by Steidel et al. (2000) clearly demonstrates the advantages of narrow-band detection for this kind of work. Indeed, tuning the filter to the redshift peaks found through future Lyman-break galaxy surveys will expand the number of galaxies associated with these large-scale features many times over. Multi-object spectroscopy will further complement this, by determining the dynamics of sheets, filaments, and proto-clusters.

As the new VLT instrument VIMOS comes into operation, it becomes necessary to re-assess the role of the two FORS instruments, since the former will outperfom the FORSes in many of their current applications. An upgrade plan for the two FORS instruments is therefore under study at ESO, including the red-optimisation of the CCDs on FORS2, which is planned for later in the year. Installing a tunable filter on FORS2 is another possibility for consideration, and in this article we have illustrated some of the scientific advantages and a possible technical implementation. The VLT also currently lacks an efficient UV imager, and indeed another upgrade under consideration concerns the UV optimisation of FORS1, all the way to the atmospheric cutoff. Together, these upgrades would restitute new scientific utility to the FORS instruments, while significantly expanding the capabilities of the VLT overall.

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