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Technical Aspects of the New AAO/UKST Hα Interference Filter

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Abstract: We briefly describe technical aspects and specifications of the new UKST Hα interference filter, which is probably the largest of its kind available in astronomy. Preliminary exposures show that the filter gives excellent imaging with high overall transmission and uniformity at Hα wavelengths. This is achieved over a circular area of about 305 mm diameter or about 5·7 degrees (the so called 'clear aperture'). The prospects for the new UKST Hα survey of the southern Milky Way with this new filter are excellent.

Keywords: instrumentation: miscellaneous — methods: laboratory — techniques: photometric

1 Introduction

A major UK/Australian consortium (including the authors) have just commenced a new Hα survey of the Galactic plane and selected regions on the UKST to take advantage of the enhanced sensitivity of Tech Pan film at Hα along with other beneficial emulsion properties such as high DQE ($\sim$10%), low noise and improved imaging (e.g. Phillipps & Parker 1993; Parker et al. 1994). A survey with an unprecedented combination of resolution, coverage and depth should result, superior to any other survey of Galactic line emission at high resolution. The strong science drivers behind this new AAO/UKST survey are described elsewhere (e.g. Parker & Phillipps 1997) and in this issue (e.g. Masheder, Phillipps & Parker 1998, p. 5; Parker & Phillipps 1998, p. 28). Here we concentrate on the design, specification and testing of the new, ultra-high specification single-element interference filter purchased for this purpose. The excellent quality of the filter is demonstrated.

2 UKST Hα Survey and Need for a New Filter

With the successful introduction of Tech Pan film at the UKST in 1992, a series of experiments with narrowband Hα imaging was performed using existing Hα filters. This was because Tech Pan has a sensitivity peak around Hα, lending itself to the possibilities of a new Hα survey. However, serious defocusing/imaging defects were seen.The old 254×254 mm AAO656 filter (FWHM 190 Å, central wavelength 6560 Å) had become locally delaminated, giving gross defocusing over large areas. Other remaining UKST Hα filter mosaics (e.g. as used by Meaburn & Rovithis 1977) generally had fields of view too small for survey work, were very old and suffered from cosmetic defects, blemishes and poor image quality. Such effects are expected due to the nature of narrowband interference filters used in fast converging beams, especially if they are mosaics and not of extremely tight specification. Imaging imperfections are also more noticeable with Tech Pan's high resolution compared to that of the coarse-grained 098–04 emulsion used for most previous UKST Hα exposures. Existing full-field 4 and 16 element Hα mosaics also gave stripey cosmetic defects and defocused areas due to small filter component alignment problems, as well as having quite broad passbands (80–200 Å).

Clearly, if we wished to properly exploit the excellent imaging qualities of Tech Pan to obtain deep, wide-field, UKST Hα imaging then we needed an interference filter of exceptional specification and quality, and one that could image a substantial fraction of the UKST's large field. We thus sought an unusually large custom-made, narrowband interference filter that would give the best achievable imaging over the widest area. This was necessarily coupled with a choice of filter central wavelength and bandpass that would work effectively under the constraints imposed by use in the UKST's fast $f/2\cdot48$ converging beam.

3 Basic Filter Options Considered

The chosen filter design and quality must preserve the improved resolution benefits of Tech Pan film for the best possible wide-field imaging, while also satisfying the scientific criteria of the new survey; namely to be able to properly sample the full range

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of likely velocities of gaseous Hα emission in our Galaxy of -400 to $+600$ km s^{-1}. We also wish to sample Hα emission from our nearest major external galaxies, groups and clusters, such as the SMC, LMC, South Polar group and the rich Virgo and Fornax clusters at ~1200 km s^{-1}.

Satisfying these requirements necessitates careful selection of the optical and physical filter specifications, including choice of bandpass (which has to incorporate the effects of use in a converging beam), central wavelength and stringent manufacturing tolerances of thickness, flatness, rigidity etc.

3.1 A Full-aperture Objective Filter

The ideal Hα filter is one where the incoming beam is normal to the filter surface. In this case we would need to place the filter across the entrance aperture of the UKST in front of the corrector, where the $3\cdot3°$ deviations from the optical axis (which define the $6\cdot6°$ field of view of the UKST) have a negligible effect on the filter bandpass (~3 Å). We could also choose the minimum filter bandpass necessary to satisfy our scientific requirements for sampling Galactic Hα emission. Due to the size of the entrance aperture (1·2 m), the filter would have to be a mosaic. In principle we could also tilt the individual filter elements to tune the filter blueward within a limited wavelength range (equation 1). Unfortunately this solution proved impractical, being technically difficult and very expensive, so after initial experiments with a mosaic mask it was not considered further.

3.2 Focal Surface Filter

The adopted solution was to obtain a single-element 'monolithic' interference filter of the largest size possible. This would have no edge defects, unlike a mosaiced filter where stripes of slightly lower background density would be apparent on any exposures (Elliot & Meaburn 1976) due to shadowing by the thin opaque joins between the filter components. Matching each element of a mosaic to the same optical flatness is also difficult.

After initial groundwork by David Malin, one of us (QAP) identified Barr Associates as the only company able to accept our order for a full-field single-element filter and come close to satisfying the stringent specifications set by the authors. A suitably large RG610 glass substrate was obtained with some difficulty and cut to the full 356 × 356 mm size of standard UKST glass filters. Their largest available thin-film coating plant was used to coat the multilayer dielectric stack to form a circular 'clear aperture' of about 305 mm diameter. Since it is this circular aperture coating which forms the interference filter on the RG610 glass substrate, the corners of the square substrate do not form part of the Hα filter. This does not quite permit standard UKST survey field overlap on 5° field centres. We thus adopted a conservative 4° field centre separation for the survey to ensure proper Hα coverage in each field. A filter bandpass of ~70 Å was necessary not only to ensure proper sampling of the extreme velocities of the Hα emitting gas in our Galaxy but also to meet the requirement to cover HII regions in nearby galaxy groups such as Virgo and Fornax (at ~1200 km s^{-1}) while also accounting for the blueward shifts in central filter wavelength caused principally by the UKST's $f/2\cdot48$ cone-angle variations (see Section 4·1).

Interference filters placed at the focal surface of a fast telescope must be carefully specified if optical aberrations and other imaging problems are to be kept within acceptable limits. Given Tech Pan's fine grain, such effects would be more noticeable than with coarser-grained emulsions previously used for Hα work, such as 098–04 and 103aE. Elliot & Meaburn (1976) detailed the aberrations expected and attempted to quantify the effects on resultant image size. Many of these aberrations can be minimised by achieving tight tolerances on thickness and flatness. The final filter choice was dictated mainly by the desire to provide a filter that yields the best possible imaging so that the resolution advantages of Tech Pan are properly exploited for maximum scientific gain.

4 Practical Considerations with Interference Filters

Specification of a narrowband interference filter mounted at the telescope focal surface is complicated by environmental and optical considerations which have implications for the chosen filter design. If used in converging beams, the inherent properties of interference filters lead to significant blueward shifts in the measured wavelength of the transmitted beam on- and off-axis while also affecting the filter bandpass shape. Comprehensive details of the main effects were given by Elliot & Meaburn (1976), Miller (1978) and filter manufacturers (e.g. the *Photonics Design and Applications Handbook* 1994). A brief description is included here.

Temperature effects: Thermal variations cause changes in the refractive indices of the spacer layers in any interference filter, which lead to small central wavelength shifts in converging beams. The design temperature of interference filters is typically ~20°C while night-time temperatures at the UKST are ~10–20°C less. Small blueward shifts in the filter's central wavelength occur whose magnitude depends on the number of filter cavities and the refractive indices of the dielectric layers of the multilayer stack defining the interference filter. When combined with other effects, the resultant blueward shifts could have implications for the intended scientific use. For example, if too narrow a bandpass is selected it may not be possible to fully cover the adjacent [NII] 6548·1 Å, Hα 6562·8 Å, [NII] 6583·6 Å emission lines for low-redshift extragalactic projects over the expected operating temperature range. These effects have been accounted for in the final specifications adopted for the filter.

Humidity effects: Narrowband interference filters have a finite lifetime due to the effects of constant thermal variations and changing humidity. Moisture eventually penetrates the hygroscopic dielectric layers causing localised delamination and gross image defocusing. A process known as scribing at the filter edges offers a degree of protection but interference filters should still be protected from prolonged exposure to large temperature variations and high humidity. The new UKST filter is stored in a specially constructed container purged with dry nitrogen when not in use to minimise these problems.

4.1 Effects with Collimated or Uncollimated Incident Flux

Collimated flux: Ideally an interference filter should be illuminated with collimated flux. If the flux is not normal to the filters surface then the central wavelength of the filter passband is shifted to the blue. For angles $\leq 10°$ the shift is given by the formula

$$\lambda_\theta = \lambda_0 (1 - \sin^2\theta / n_e^2)^{\frac{1}{2}} \,, \qquad (1)$$

where λ_θ is the shift with incident angle θ, λ_0 is the chosen central wavelength of the filter bandpass and n_e is the refractive index of the spacer layers (generally ~ 2).

Uncollimated flux—converging beams: With an uncollimated beam the situation is more complicated, as rays can enter the filter through a range of angles leading to angle-dependent wavelength shifts and, to a lesser extent, a broadening of the bandwidth and depression of peak transmittance. Near the UKST's focal surface the situation with the uncollimated $f/2{\cdot}48$ cone encountering the flat filter at different angles from the field centre was given by Elliot & Meaburn (1976). The values for wavelength shifts depend on the precise filter specification. Choosing a high value for n_e leads to much lower sensitivity to such shifts.

In Figure 1 we simulate how the bandpass varies for the UKST $f/2{\cdot}48$ beam with a 1% filter (i.e. a filter whose bandpass is about 1% of the value of the central wavelength) both for the on-axis case (solid curve) and at an off-axis position (thin curve) at the edge of a 356 mm square filter (a full-sized UKST filter). Note the trend in broadening (particularly the full-width zero intensity), skewing and the loss in mean transmission. The ideal filter is shown as a dotted line and is assumed to have a mean refractive index $n_e = 1{\cdot}9$. The maximum centroid shift from centre to edge is 38 Å. This necessitates a redward shift of the central wavelength from Hα to minimise the beam effect. The resulting bandpass is slightly asymmetric. On-axis broadening is, however, <10%.

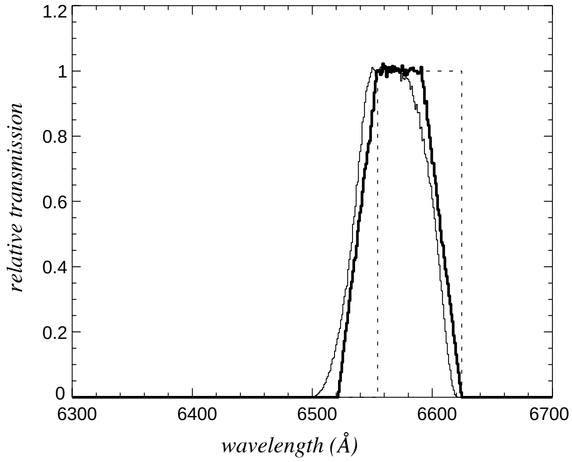

Figure 1—UKST bandpass simulation for a 1% filter both on-axis (solid curve) and off-axis (thin curve) cf. an ideal filter (dotted line). Note that the transmission extends to 1·2 for the purposes of clarity of the underlying curve.

Below we present the basic specifications and features of the filter. Many of these details were independently confirmed by the CSIRO National Measurement Laboratory.

5 Basic Features of UKST Hα Interference Filter

Basic design: A three-cavity design of ion-assisted deposition (IAD) of refractory oxide material on both sides of a Schott RG610 R-band filter.

Filter size: 356 × 356 mm. A single-element 'monolithic' Hα interference filter.

Clear aperture: Approximately 305 mm diameter. Coatings were deposited within a circular aperture to ~20 mm of the edges of the square blank.

Measured filter thickness: 5·53 mm. The filter was easily accommodated inside an existing UKST plateholder with only minor modification. The filter is actually 1 mm closer to the focal surface than existing filters, maximising image quality.

Central wavelength: 6590 ± 25 Å. The central wavelength variations incorporate the effects of the $f/2{\cdot}48$ beam.

FWHM of filter bandpass: 70 ± 3 Å achieved, i.e. a 1% filter.

Blocking: 0·01% of peak out-of-band transmission over the range 2000–6990 Å.

Transmitted wavefront: Better than $\lambda/4$ achieved. Confirmed by interferogram (see Figure 2). Peak-to-valley range of only 0·193 waves with an rms of 0·040 waves. Results integrated from 2732 points measured over the clear aperture using a HeNe laser at 6330 Å with aperture size of 51 mm.

Peak transmission: ≥85% across the clear aperture with 5% maximum variations (see Figure 3).

Temperature effects: Central wavelength temperature shift 0·035 Å/°C. An extreme operating range of -5°C to 30°C corresponds to a blueward shift of 1·23 Å.

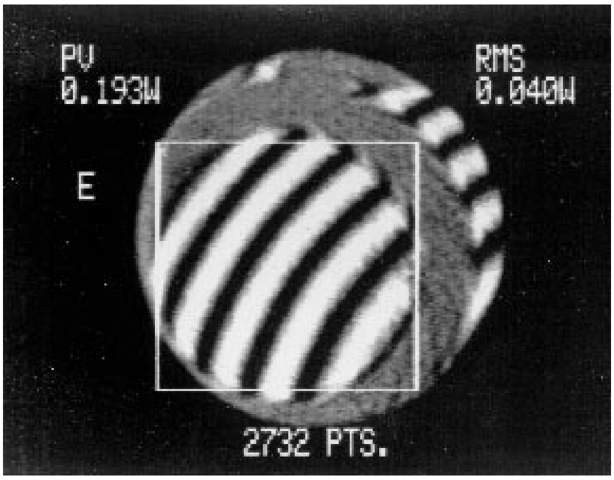

Figure 2—Interferogram of the full uncoated RG610 filter substrate taken in transmitted light, as provided by Barr Associates. The interference lines are quite parallel with little distortion. The interferogram confirms that the transmitted wavefront is better than 1/4 wave per 25 mm.

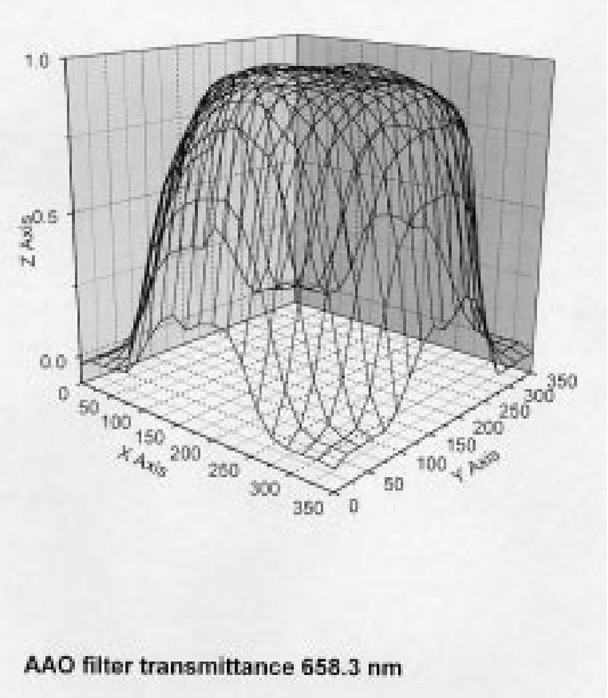

Figure 3—Transmission map of the coated Hα filter as provide by CSIRO National Measurement Laboratory as part of the independent filter acceptance tests, reproduced with their permission. Note the very high and uniform levels of filter transmission (>85%) over much of the circular aperture.

Coating refractive index: 1·973.

Surface quality: S/D (scratch/dig) = 80/50 a measure of the number of minor surface imperfections per unit area.

Humidity tolerance: The filter meets or exceeds the US military standard for protection against humidity.

Polarisation effects for off-axis rays: At large incident angles the filter peak will broaden and split into two peaks whose polarisations are 90° apart. Plots provided by Barr Associates reveal that with 10·64° angle-of-incidence in collimated light the s- and p-planes of polarisation have bandpass shifts of only 1·8 Å with respect to each other.

Physical filter deformation: The filter is quite heavy, such that some physical deformation of the filter under gravity might be expected when in the telescope. Any sag is in the same sense as the existing curvature of the focal surface. Barr Associates have not provided any details but indicate that any minor sagging present will not create any problems. Certainly the image quality across the entire filter surface is excellent.

Coating toughness: The filter surfaces can be cleaned with a lint-free soft cloth soaked in methanol, acetone or ethanol. The coatings also meet or exceed military standards for moderate abrasion resistance.

5.1 *Environmental Issues*

The Hα focal surface filter mounted in a dedicated plateholder only becomes uncovered inside the protected telescope tube of the UKST, and is thus less prone to external environmental effects such as high humidity since dry nitrogen is purged over both emulsion *and filter* at the focal surface. Off the telescope the filter is stored in a dry inert atmosphere which affords further protection, ensuring filter longevity. Such a filter can be interchanged with any other during the night so no observational flexibility is lost.

5.2 *Operation over Bright of Moon*

Because of the narrow bandwidth of the filter, deep exposures can be taken in brighter sky conditions. Initial tests indicate that the Hα survey could be undertaken during currently unscheduled bright of moon nights when the UKST is otherwise idle. This offers the potential for making more effective use of the telescope.

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