Photonic OH suppression: the next wave in observational cosmology

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The Problem

The sky is bright and highly variable

2MASS airglow experiment
## The Problem

Typical night sky brightness at a good observing site

<table>
<thead>
<tr>
<th>Band</th>
<th>Surface brightness mag arcsec$^{-2}$</th>
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<tbody>
<tr>
<td>U</td>
<td>21.5</td>
</tr>
<tr>
<td>B</td>
<td>22.4</td>
</tr>
<tr>
<td>V</td>
<td>21.7</td>
</tr>
<tr>
<td>R</td>
<td>20.8</td>
</tr>
<tr>
<td>I</td>
<td>19.9</td>
</tr>
<tr>
<td>J</td>
<td>16.0</td>
</tr>
<tr>
<td>H</td>
<td>14.0</td>
</tr>
<tr>
<td>K</td>
<td>13.0</td>
</tr>
</tbody>
</table>

![Graph showing surface brightness vs. wavelength](graph.png)
OH emission lines:

\[ H + O_3 \rightarrow OH^* + O_2 \]

Extremely bright
Extremely variable

99% of J and H band background
AAOmega
VPH spectrograph (optical)

IRIS2
Grism spectrograph (IR)
The Photonic Solution

• Suppress OH lines before light enters spectrograph
• Knock out lines at high resolution (R~10,000)
• Maintain high overall throughput (>80%)
Fibre Bragg Gratings

- Optical fibres with periodicity in refractive index
- Fresnel reflections at each boundary
- Small but in phase with each other
- Strong reflection at a single wavelength
Single mode fibres

First device FBG takes out 96% of OH background by suppressing 18 doublets over 70nm

JBH et al, Optics Express, 2004
Fig. 4. First broadband FBG from our initial attempt at an optimized design. The inter-line transmission loss is <5% over the full 120nm band. The red dots show the 36 target wavelengths (42 doublets) and notch depths; the varying depths follow the OH line strengths (see Fig. 3).
Multimode Fibres

Number of modes, $M$

$$M = \frac{V^2}{4} \quad V = \frac{\pi D}{\lambda} NA$$

80 µm core, $NA=0.10 \Rightarrow M = 61$

Midwinter, 1979
Multi-mode fibres

Photonic lantern

Leon-Saval, Birks & Bland-Hawthorn (2005)

Fig. 1 The first ever demonstration of a fibre Bragg grating in a multimode fibre using a taper technology shown in A (see page 3), a device we call a tapered multimode fibre grating device comprises an input multimode fibre (MMF) which transforms via a taper (see...
Next Steps

• To perform single-fibre on-sky demonstration
  – 80 µm core fibre tapering to 61 SMF FBGs
    (170nm band, 75 notches) feeding IRIS-2

• To demonstrate 350nm FBG for J, H bands
  (150 OH lines in each band, <5% loss)

• To develop fibre feed for existing IR spectrograph — FLEX
Multimode hexabundles

1x19 (fully fused)  1x61 (not fully fused)

We are now making 1x127 and beyond…
Hexabundle facts:

No need for microlens array

Conventional fibre positioner (low tension)

If needed, macro lens to change plate scale

Fused region ~ 3 cm in length

Core sizes ~ 50-150... microns

Cross talk < 0.05 dB

Cladding loss ~ 25% down to 5%

NA ~ 0.05 to 0.25

Format ~ 1×91, 1×127 done; 1×397 possible
Spectroscopic modes

Single object or Multi-object
Single IFU (up to 400 elements) or Multi-IFU
Wide-field, conventional robotic positioners
GLAO or better preferred, but natural seeing possible

Further reading:
Science case for GSMT in progress (first draft done)
## Science case

<table>
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<th>Description</th>
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<td>Lyα luminosity function in early universe</td>
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<td>4 – 10</td>
<td>Wind diagnostics in high-z galaxies</td>
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<tr>
<td>1 – 4</td>
<td>Star formation history of galaxies</td>
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<td></td>
<td>Gas dynamics in galaxies</td>
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<tr>
<td>0.9 – 2.5</td>
<td>Velocity d</td>
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<tr>
<td>0.2 – 1.5</td>
<td>Stellar dyr</td>
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<tr>
<td>0 – 0.2</td>
<td>Abundance</td>
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<tr>
<td>0</td>
<td>Activity in</td>
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<tr>
<td></td>
<td>Galactic as</td>
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Science case

Redshift

7 – 13  Lyα luminosity function in early universe
4 – 10
1 – 4
0.9 – 2
0.2 – 1
0 – 0.2
0
Simulations

- 8m telescope
- AO corrected (Strehl=0.3) feed to FLEX IFU
- 30dB max suppression, 150 lines in both J and H
- Background model includes variability
- Background subtraction includes systematic calibration errors

Ellis & JBH (2008)
First stop: $z > 7$ candidates

Stark et al. 2007
For permission to reuse, contact journalpermissions@press.uchicago.edu.
GSMT, J=25 AB mag, 4 hr, R=1000, 30 dB max
QSO simulation \((z=11)\)

GSMT
H=26 AB mag
R=1000
70 hrs
OH-suppressed hexabundles are ideal for wide-field ELT science
Velocity dispersion functions

M. Pierce talk (VDDF):

Hierarchical vs. anti-hierarchical evolution

Major study:

Multiplicity of absorption lines tracked out to z~1.5 (CaT) or z~2 (weaker lines)

\[ \sigma = 88.8 \text{ km/s} \]

\[ \alpha = 6.5 \]

\[ \beta = 1.93 \]

Fig. 1.—Velocity dispersion function in the SDSS. Error bars show \( \phi(\sigma) \)
for the early-type galaxy sample, estimated using the \( 1/r_{\text{max}} \) method.

Sheth et al 2003
Coma cluster abundance gradients

Figure 1. Sky distribution of the line-strength sample (black). The filled points are galaxies used in the fits of Section 3. Open symbols are either bright \( M_r < -19 \) comparison galaxies, have emission lines, or no measured age. Small points show other SDSS galaxies within the Hectospec survey region in red (confirmed members), yellow (confirmed background galaxies) or grey (no redshift information). The redshifts are from our Hectospec survey and literature sources. Pale-blue squares indicate the regions.

Figure 2. The \( g-r \) colour magnitude diagram for the galaxies in Figure 1 from SDSS photometry. For comparison, we note the position of the LF break, \( r^* \), and the magnitude range for "giant" early-type galaxies, having velocity dispersions \( \sigma \geq 75 \text{ km s}^{-1} \). Symbols are as in Figure 1.

galaxies, we observed 79 known cluster members with luminosities \( 3 - 4 \text{ mag below } M^* \), plus ten brighter galaxies for overlap with previous studies (e.g. Sánchez-Blázquez et al. 2006). The target galaxies were selected to lie close to the red sequence of non-star-forming galaxies (Figure 2). The 270 line mm\(^{-1}\) grating was used, resulting in a wide wavelength coverage (3700–9000 Å) at a spectral resolution of 4.5 Å, FWHM. The median total integration time for the faint galaxies was \( \sim 7 \) hours, yielding typical signal-to-noise ratio of \( \sim 40 \text{ Å}^{-1} \) (at \( \sim 5000 \text{ Å} \)). The brighter galaxies were observed for 0.7–2.0 hours. Relative flux calibration was imposed using F stars with photometry from Sloan Digital Sky
Combining to cf. chemodynamical evolution with CDM prediction

Figure 5. Quenching redshift, defined here as the redshift for which the look-back time is equal to the Balmer age, as a function of projected distance from the cluster centre. Although the most recent burst will generally be superposed on an older population, the Balmer age is strongly weighted toward the youngest stars present. If the mass-fraction of the most recent burst is very small, the quenching redshifts plotted here are upper limits. The assumed cosmology has parameters \((\Omega_M, \Omega_k, h) = (0.3, 0.7, 0.7)\).

Figure 6. Comparison of our index gradient pattern (yellow) with previous work. For clarity, the results for each index have been normalised by its age response. Thus if age was the only variable changing with radius, all indices should give the same gradient. Yellow boxes show the 1σ range from this work. For Carter et al. (2002, green) we compare their (Fe) with our Fe5335; their Mg2 gradient has been converted to an equivalent gradient in Mgb5177. For Smith et al. (2006, red), we have converted their gradients in \(R_{200}\) to degrees assuming \(R_{200} \approx 80\) arcmin for Coma. The bottom row shows the age gradients derived for the three studies, including a new estimate for Carter et al., based on their published index gradients.

Smith+ 2005; 2007
Reionization and Lyα damping wings

Figure 6. The Ly transmission through line profile taken at surrounding medias complete absorbptive modification of the 1Mpc, 5Mpc or 50 Strömgren sphere, reaches sufficiently...
Summary

• We must suppress OH lines before they are dispersed
• OH suppression is close to being solved using fibre Bragg gratings and photonic lanterns
• Sky becomes ~4 mag fainter with huge potential gains in signal to noise
• Ultra-deep NIR observations must be achieved if ELTs are to compete with or surpass JWST