The Tunable Filter Imager – TFI

David Lafrenière, René Doyon (U. Montréal) & the TFI science team

JWST and the ELTs: An Ideal Combination
ESO Garching, April 13, 2010
The Fine Guidance Sensor (FGS) – Tunable Filter Imager (TFI) module

- TFI is a science instrument packaged within the FGS module
  - Canadian Space Agency (CSA) contribution to JWST
    - Prime contractor is COM DEV Canada
  - PI of TFI: René Doyon (U Montreal)
  - PI of FGS: John Hutchings (HIA)

- TFI provides narrow band imaging between 1.5 μm and 5.0 μm
  - Based on a Fabry-Perot etalon
TFI at a glance

- FOV: 2.2’x2.2’
  - 65 mas pixel sampling (Nyquist at 4.0 µm)
  - 2048x2048 pixels (Hawaii 2RG)
- Wavelength range: 1.6-2.6 µm and 3.2-4.9 µm
  - (actually 1.5-2.7 µm and 3.1-5.0 µm)
- Resolving power of ~100 (80-120)
- Sensitivity, 10σ 10x1000 s

<table>
<thead>
<tr>
<th>Wavelength μm</th>
<th>Sensitivity nJy</th>
<th>Sensitivity mag</th>
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<tbody>
<tr>
<td>1.5</td>
<td>149</td>
<td>24.8</td>
</tr>
<tr>
<td>2.0</td>
<td>139</td>
<td>24.3</td>
</tr>
<tr>
<td>2.5</td>
<td>119</td>
<td>24.1</td>
</tr>
<tr>
<td>3.5</td>
<td>110</td>
<td>23.5</td>
</tr>
<tr>
<td>4.0</td>
<td>136</td>
<td>23.1</td>
</tr>
<tr>
<td>4.5</td>
<td>142</td>
<td>22.8</td>
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- Operating modes
  - Normal imaging
  - Lyot coronagraphy
    - 4 occulting spots, 3 lyot masks
  - Non-Redundant Masking interferometry (NRM)
Spectral Resolution

[Graph showing spectral resolution as a function of wavelength (nm). The x-axis represents wavelength in nanometers ranging from 1500 to 5000. The y-axis represents resolution (in increments of 10). The graph includes a red line indicating the gap (nm) and a blue line representing the resolution.]
Coronagraphy

- 4 occulting spots engraved on pick-off mirror
  - Diameters of 0.58”, 0.75”, 1.5” and 2.0”
- 3 lyot masks
  - Transmissions of 71%, 66% and 21%
  - Robust against pupil shear of up to 4%

C71
0.58” and 0.75”
<1”

C66
1.5”
1”-2”

C21
1.5” and 2.0”
>2”
Coronagraphy contrast limits (3% pupil shear)

- **Small separations**
  - C71N + 0.58", 0.75"

- **Medium separations**
  - C66N + 1.5"

- **Large separations**
  - C21N + 1.5" (orange), 2" (blue)

These contrasts can be improved further with PSF subtraction.
Multi-Wavelength PSF subtraction

- Image of the target itself at a different wavelength is used as a reference PSF image
- Uses sharp spectral feature in companion spectrum
  - Image 1: companion bright
  - Image 2: companion faint
- Demonstrated in the lab using the TFI etalon prototype P0

Achieved speckle noise attenuation of 10
Non-Redundant Masking interferometry

- Insert a mask containing multiple small apertures at a pupil plane
  - No line joining any two sub-aperture has the same length and PA as another one
- From FT of interferogram, amplitude & phase of interference fringe coming from each pair can be measured “easily”
- Fit a model to measured phases and amplitudes

- Two advantages:
  - **Better resolution** - two sources can be resolved for a separation of $0.5 \lambda / D$
  - **Better contrast at small separations** - Wave front phase errors have little effect on closure phase
TFI Non-Redundant Mask

- 7 apertures
  - 5.28 m longest baseline
  - 1.32 m shortest baseline
- Throughput
  - 15%
- Resolution ($\lambda/2B_L$)
  - $\approx 75$ mas at 4.6 $\mu$m
- Nominal FOV ($\lambda/2B_S$)
  - $\approx 0.4$” at 4.6 $\mu$m
- Contrast sensitivity
  - $\approx 10$ mag
TFI/NRM occupies a unique niche

NIRCam & MIRI contrast from Beichman et al. 2010

TFI curve assumes only a modest PSF subtraction performance
The HR 8799 planetary system

- Three 7-10 M\textsubscript{Jup} planets imaged
- A dusty disk with three components
  - Warm (150 K) dust belt at 6-15 AU – inside planet d
  - Cold (45 K) planetesimal belt just outside planet b
  - A surrounding halo of dust out to ~1000 AU


- Is there a planet inside the inner belt?
  - ~5 AU, separation of 0.13” → NRM

Marois et al. 2008
TFI/NRM simulation of “HR 8799 e”

- Simulation
  - 10 $M_{\text{Jup}}$ planet at 5 AU
  - age of 50 Myr assumed
  - 20 min total integration over 9 dithers
  - Includes realistic noise sources

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<tr>
<th>Input</th>
<th>Measured</th>
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<tr>
<td>Sep (mas)</td>
<td>132</td>
</tr>
<tr>
<td>PA (deg)</td>
<td>50.7</td>
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<tr>
<td>Contrast (mag)</td>
<td>8.0</td>
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TFI/NRM exoplanet science

- (molten) proto-Earths around nearby young stars (1-100 Myr)
  - Following collisions, planets could stay at >1000 K for several Myr
  - Region of interest <0.5"
  - Contrast of <10 mag for late-type stars

- Long-λ characterization of GPI/SPHERE planets
  - At 4 μm, GPI/SPHERE planets at 0.1”-0.4” and contrasts of 8-10 mag will be accessible only with TFI/NRM

- Planets in star-forming regions (1-5 Myr age)
  - 75-400 mas is 10-60 AU at 150 pc
  - 10 mag contrast sufficient to see gas giants

Miller-Ricci et al. 2009
**Exoplanet characterization**

- TFI can extract spectral information at $R \sim 100$, at high contrast, and at any $\lambda$
  - For highest contrast planets, TFI could be the only option

- Lots of structure in spectrum at $R \sim 100$
  - Probe molecular content of atmosphere
  - Constrain $T_{\text{eff}}$ & $\log g$
  - Test models

- Follow-up planets found by NIRCam, GPI, SPHERE, etc.

Burrows et al. (2003) models for a 5 $M_{\text{Jup}}$ planet binned to $R=100$
High-Redshift Science with TFI

- TFI wins by detecting line emission in faint objects.
- Lyman Alpha Emission can be up to 20x as bright as the continuum for a Lyman Alpha Emitting (LAE) galaxy.
- Lyα is redshifted into the TFI λ range for z~10-30, covering the era from the dark ages to first light where the universe becomes reionized.

- Its relatively small bandpass yields higher S/N than NIRCam broadband filters, reaching fainter flux sensitivity for line emission.

Slides by E. Mentuch, representing the TFI High-z Tiger Team.

High-Redshift Science with TFI

* Predictions of Lyman Alpha emitting galaxies at $z=12, 15, 30$ are highly speculative
* Can make a guess by using the parameters (IMF, metallicity, photon escape fraction) defined by population of LAEs at $z=6.5$ Kashikawa et al. (2006)
* However, **THIS IS EXPLORATORY SCIENCE**, TFI is the best and if the sources of *First Light* are very faint, it may be the only option

* A single 2.7 hour pointing is sufficient to detect an LAE in the more optimistic, but plausible scenarios. Multiple pointings probe more volume and lead to higher possible detections.

* Can ‘tune’ TFI to redshifts of suspected galaxy overdensities soon to be predicted from high-z 21 cm mapping of neutral hydrogen, increasing chances even more.

Slides by E. Mentuch, representing the TFI High-z Tiger Team
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<th>Name</th>
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<tr>
<td>R. Doyon</td>
<td>PI of TFI, U. Montréal</td>
<td>Here all week</td>
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<tr>
<td>J. Hutchings</td>
<td>PI of FGS, HIA</td>
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