Introduction to near-infrared spectroscopy with MOIRCS

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originally created by Ken-ichi Tadaki (NAOJ) for 2013 Subaru winter school
updated by Masao Hayashi (NAOJ) for 2014 Subaru autumn school
Near-infrared in astronomy

- absorption by terrestrial atmosphere \((\text{H}_2\text{O} \text{ and } \text{CO}_2)\)
- wavelength range of 1-5 \(\mu\text{m}\)
- observable windows are limited \((J, \text{H}, \text{K}, \text{L}', \text{M}')\)
**Features of NIR observations (1)**

- **Detector**
  - Optical ($\lambda < \sim 1\mu m$) - silicon CCD (Charge Coupled Device)
  - NIR ($\lambda > \sim 1\mu m$) - semiconductor crystals

  MOIRCS: HgCdTe arrays named HAWAII-2 (sensitivity: 0.9-2.5\mu m)

- **Multi-Object InfraRed Camera and Spectrograph**
  - Inhomogeneous sensitivity
  - Non-sensible pixels (bad/hot pixels)
  - Notable differences among arrays

- MOIRCS has two detectors, providing a FoV of 4’ x 7’
- Imaging mode and spectroscopy mode

Suzuki et al. 2008
Features of NIR observations (2)

- High sky background $\rightarrow$ short exposure
  - Strong emission by night airglow line (OH and O$_3$)
  - Variation in short time scale (several minutes $\sim$ upwards of ten minutes)

<table>
<thead>
<tr>
<th>Sky is bright in near-infrared</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="http://www.kusastro.kyoto-u.ac.jp/iwamuro/LECTURE/OBS/" alt="Graph" /></td>
</tr>
</tbody>
</table>

- Ground-Based Telescope
- Atmospheric Emission
- OH airglow

- $\lambda < 2.2\mu$m:
  - OH lines dominate (green line)
- $\lambda > 2.2\mu$m:
  - Thermal radiation from telescope dominate (pink line)

- Zodiacal Emission
- Zodiacal Scattered Light

- Sky emission should be subtracted

Reference: lecture note by Iwamuro-san (http://www.kusastro.kyoto-u.ac.jp/iwamuro/LECTURE/OBS/)
Features of NIR observations (2)

- High sky background → short exposure
  ✓ Strong emission by night airglow line (OH and O$_3$)
  ✓ Variation in short time scale (several minutes ~ upwards of ten minutes)

![Graph showing intensity vs wavelength](http://ww)
### MOIRCS Grisms

<table>
<thead>
<tr>
<th>Grism name</th>
<th>Operating range [um]</th>
<th>Resolution (0.5&quot; slit)</th>
<th>Dispersion [Å/pixel]</th>
<th>Sensitivity (Vega magnitude) [mag/arcsec²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>zJ500</td>
<td>0.9-1.78 (*3)</td>
<td>700 @ J</td>
<td>5.57</td>
<td>J=19.2</td>
</tr>
<tr>
<td><strong>HK500</strong></td>
<td>1.3-2.5 (*4)</td>
<td><strong>640 @ H</strong></td>
<td>7.72</td>
<td><strong>H=17.8</strong> K=17.6</td>
</tr>
<tr>
<td>R1300 (*1)</td>
<td>1-2.5 (*5)</td>
<td>1300 @ ch1 ~1100 @ ch2 (*2)</td>
<td>1.91 @ J 2.61 @ H 3.88 @ K</td>
<td>J=17.8 H=16.7 K=17.1</td>
</tr>
</tbody>
</table>

spectral resolving power: \( R = \frac{\lambda}{\Delta\lambda} \)

in the case of the HK500 grism
\( R=820 \) and \( \lambda=22000\text{Å} \) -> spectral resolution \( \Delta\lambda=22000\text{Å}/820\sim27\text{Å} \)

- use the appropriate grism for your science case
- resolution depends on the slit width
Grisms for MOIRCS

Which grim should be used?

- Required resolution ($\Delta \lambda$) for your science
- Wavelength coverage
  ✓ spec-z is available or not
- Grism efficiency
- Brightness of targets

Figures from MOIRCS web page
signal to noise ratio (S/N)

$$S/N = \frac{\text{object} \times t}{\sqrt{(\text{object} + \text{sky}) \times t + \text{readout noise}}}$$

If sky $\times t >>$ readout noise, $S/N \propto \sqrt{t}$ (background limited).

- Integration time should be longer than the background limit.
Multi-object spectroscopy mode

**Alignment Star**
- **Spectroscopic Target**
- **Mask Design**
  - `.mdp`: the file where information of mask design is described

**Spectra**
- **Hole for Alignment**
- **Slit for Spectroscopy**

Tokoku 2006, PhD thesis
Multi-object spectroscopy mode

MOIRCS raw image (4′×4′)→

many stripes!
-> Target spectra are hidden behind OH lines
Two-point dithering on the slit

frame at A position

frame at B position

A-B frame

OH lines

slit

spectra of star

spectra in frame A

spectra in frame B
From raw image to reduced image

extract the **object** information from **raw data including noises**

raw data = \( \text{gain}(x,y) \times (\text{object} + \text{sky} + \text{cosmicray} + \text{bad pixel}) \)

①. flat fielding (=gain map)

\[
\text{rawdata} / \text{gain}(x,y) = \text{object} + \text{sky} + \text{cosmicray} + \text{bad pixel}
\]

②. interpolation of cosmicray and bad pixel

① - cosmicray - bad pixel = **object** + sky

③. sky subtraction

② - **sky** = **object**
Procedure of data reduction

1. Raw data
2. Flat fielding
3. Interpolation of bad pixels
4. Removal of cosmic rays
5. A-B sky subtraction
6. Distortion correction
7. Extraction of individual 2-D spectra
8. Wavelength calibration
9. Removal of residual sky emission
10. Combining all of the spectra
11. Reduction of spectrum of a standard star
12. Flux calibration and telluric correction
1. flat fielding

rawdata / gain(x,y) = object + sky + cosmicray + bad pixel

correct the inequity of sensitivity between detector pixels
2. interpolation of cosmic rays/bad pixel

interpolate the pixel value along spatial direction

① - cosmicray - bad pixel = object + skynoise
3. A-B sky subtraction

A position - B position = after sky subtraction

signal at A position

signal at B position
Procedure of data reduction

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Wavelength calibration using OH airglow lines

2D spectra and 1D spectra

2D spectra

wavelength direction

spatial direction

1D spectra
Procedure of data reduction

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12. Flux calibration and telluric correction
9. telluric correction and flux calibration

Telluric absorption

$N_{\text{obs}}(\lambda)$: observed count
$R(\lambda)$: efficiency of atmosphere/telescope/instrument
$F_{\lambda,\text{int}}$: intrinsic flux

$N_{\text{obs}}(\lambda) = R(\lambda) \times F_{\lambda,\text{int}}$
From raw image to reduced spectra

raw data

reduced spectrum

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