Introduction of near-infrared (NIR) spectroscopy

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Near-infrared in astronomy

- wavelength range of 1-5 um
- observable windows are limited (J, H, K, L', M')

absorption by terrestrial atmosphere

Transmittance vs. Wavelength [μm]
Science case 1 in near-infrared astronomy

- high-redshift galaxies
e.g. Hα emission line at z>1, Lyα at z>7

Hα emission line in the rest-frame (z=0)
-> \( \lambda_{\text{rest}} = 0.6563 \text{ um} \) (optical)

Hα emission line at z=2.35
-> \( \lambda_{\text{obs}} = \lambda_{\text{rest}}(1+z) \)
   = 2.2 um (near-infrared)

Yoshikawa et al. 2010
Science case 2 in near-infrared astronomy

- dust obscured objects
e.g. Galactic center, star-forming regions

created by Ichi Tanaka
Science case 3 in near-infrared astronomy

- cool objects
  e.g. brown dwarfs, young gas planet

Kuzuhara et al. 2013

Credit: SEEDS project

Adaptive optics at 8m-class telescopes works very well at near-infrared wavelengths.

NGC1333 SVS13 with Keck/OSIRIS

Integral Field Spectroscopy

QMBOFU

Kuzuhara et al. 2013
- Subaru telescope has three NIR instruments.
- MOIRCS is mounted on the Cassegrain focus.
- MOIRCS has two detectors, providing a FoV of 4′×7′
- imaging mode and spectroscopy mode
Multi-object spectroscopy mode

MOIRCS raw image (4′×4′)→

many stripes!
-> Target spectra are hidden behind OH lines

spatial direction

OH lines

slit

diffracted spectrum by grism

wavelength direction
2D spectra and 1D spectra

2D spectra

spatial direction

wavelength direction

1D spectra
Sky is bright in near-infrared

\[ \lambda < 2.2 \mu m : \]
OH lines dominate (green line)

\[ \lambda > 2.2 \mu m : \]
thermal radiation from telescope dominate (pink line)

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

- sky emission should be subtracted
A-B sky subtraction

- sky emission is roughly subtracted
- but sky emission is time variable
signal to noise ratio (S/N)

\[
S/N = \frac{\text{object} \times t}{\sqrt{\text{object} + \text{sky}} \times t + \text{readout noise}}
\]

- if \( \text{sky} \times t \ll \text{readout noise} \)
  \( S/N \propto \frac{1}{t} \)

- if \( \text{sky} \times t \gg \text{readout noise} \)
  \( S/N \propto \frac{1}{\sqrt{t}} \)

\( \rightarrow \) background limit

- integration time should be longer than the background limit

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**from MOIRCS website**

<table>
<thead>
<tr>
<th>Grism</th>
<th>Saturation magnitude</th>
<th>Max exposure time (s) (^{(2),(3)})</th>
<th>Min BLIP time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>zJ500-J</td>
<td>9.8 11.3 13.0 13.8</td>
<td>800</td>
<td>300</td>
</tr>
<tr>
<td>HK500-H</td>
<td>9.4 10.9 12.9 13.9</td>
<td>600</td>
<td>50</td>
</tr>
<tr>
<td>HK500-K</td>
<td>8.4 9.9 11.7 12.5</td>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>R1300-J</td>
<td>6.8 8.3 10.1 10.8</td>
<td>TBD</td>
<td>4200</td>
</tr>
<tr>
<td>R1300-H</td>
<td>7.3 8.8 10.6 11.3</td>
<td>2800</td>
<td>300</td>
</tr>
<tr>
<td>R1300-K</td>
<td>7.3 8.8 10.5 11.3</td>
<td>2500</td>
<td>500</td>
</tr>
</tbody>
</table>
MOIRCS Grisms

<table>
<thead>
<tr>
<th>Grism name</th>
<th>Operating range [um]</th>
<th>Resolution (0.5'' 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>HK500</td>
<td>1.3-2.5 (*4)</td>
<td>640 @ H, 820 @ Ks</td>
<td>7.72</td>
<td>H=17.8, 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 \( \Delta \lambda = 22000\text{Å}/820 \sim 27\text{Å} \)

- use the appropriate grism for your science case
- resolution depends on the slit width
Procedures of data reduction

0. raw data
1. flat fielding
2. Interpolation of cosmic ray and bad pixel
3. A-B sky subtraction
4. distortion correction
5. slit extraction
6. wavelength calibration
7. residual sky subtraction
8. combine frames
9. telluric correction and flux calibration
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)

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

②. **interpolation of cosmicray and bad pixel**

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

③. **sky subtraction**

  ② - **sky** = **object**
1. flat fielding

\[
\text{rawdata} \div \text{domeflat} = \text{after flat fielding}
\]

correct the inequity of sensitivity between detector pixels

\[
\text{rawdata} / \text{gain(x,y)} = \text{object} + \text{sky} + \text{cosmicray} + \text{bad pixel}
\]
2. interpolation of cosmic rays/bad pixel

Before cosmic ray interpolation:

After cosmic ray interpolation:

Interpolate the pixel value along spatial direction.

\[ - \text{cosmicray} - \text{bad pixel} = \text{object} + \text{skynoise} \]
3. A-B sky subtraction

A position - B position = after sky subtraction

signal at A position

signal at B position
9. telluric correction and flux calibration

telluric absorption

spectra of object

\[ \frac{N_{\text{obs}}(\lambda)}{R(\lambda)} \]

spectra of standard star (A0V)

\[ \frac{\text{spectra of object (after correction)}}{F_{\lambda,\text{int}}} = \frac{N_{\text{obs}}(\lambda)}{R(\lambda)} \times F_{\lambda,\text{int}} \]

model spectra (A0V)

spectra of object (after correction)

\[ \lambda [\mu\text{m}] \]

\[ N_{\text{obs}}(\lambda): \text{observed count} \]

\[ R(\lambda): \text{efficiency of atmosphere/telescope/instrument} \]

\[ F_{\lambda,\text{int}}: \text{intrinsic flux} \]
From raw image to reduced spectra

**raw data**

**reduced spectrum**

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