Tutorial 3: AO Gemini/NIFS Observations of NGC 1277

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1 Overview

This Tutorial will walk through the data reduction of Gemini Near-Infrared Integral-Field Spectrograph (NIFS) observations. NIFS is an image slicer and provides three-dimensional imaging spectroscopy in the z through K-band wavelength range(0.95-2.40 μm).

The NIFS data that we will reduce is that of a S0 galaxy, NGC1277 at a distance of 71 Mpc. This is a local compact galaxy, much like the objects we observed in Tutorial 2. This data was obtained over four nights in 2012: Oct 30, Oct 31, Nov 25, and Dec 27. The table below is a more in-depth log of observations for each of the files we will be observing:

file number	object	exposure time (s)
255 – 260	NGC 1277 and sky (following O-S-O-O-S-O)	600
261	Ar-Xe lamps	30
267 – 272	HIP 20063 and sky (following O-S-O-O-S-O)	10
334 – 338	flat lamps on	5
339 – 343	flat lamps off	5
344 – 345	Ar-Xe lamps off	30
346 – 347	Ronchi lamps on	5
348	Ronchi lamps off	5

Note. — The first column provides the end of the file number and all files begin with N20121030S0.

2 Results

Below we summarize our work for each section of the tutorial and address the questions posed in the manual.

2.1 Sorting Files and Examining the Raw Data

We begin this tutorial by running the nifs_main_LP.py pipeline, to receive the files listed in the table above. To do this we will set the "reduce_sortfiles" parameter to 'yes' and all other pipeline steps to 'no'. We must also activate the iraf27 environment to run the pipeline, using the code:

pyexecute("∼/nifs_reduction/py_pipeline/nifs_main_Lp.py")

This will give us a directory located in ∼/nifs_ngc1277/reduced_data/ that holds all of our files in.

2.1.1 Daycals

After running the nifs_main_LP.py pipeline. We wanted to begin by observing file 261 to determine a mapping between pixel number and wavelength. The bright vertical lines seen throughout the image are the emission lines from argon and xenon lamps. We then used DS9 to open the file and plotted a row cut for y = 871 which can be seen on the next page.

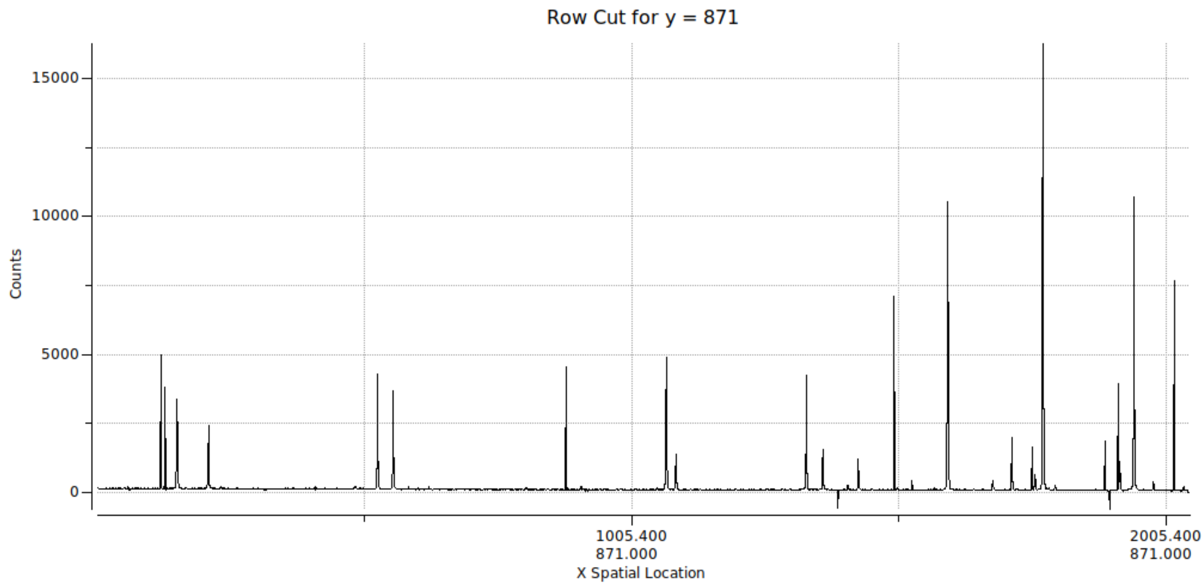

Figure 1: A row cut of file 261 at y = 871 with xenon and argon lamps on.

2.1.2 Telluric Standard Stars

We observed one of the telluric star raw frames, specifically file 267 in DS9 to try and better understand the horizontal and vertical lines that populate the Daycal files.

We first noticed that file 267 has a bright line listed at around row 1016, this is the telluric star. There are more copies of other bright horizontal lines that extend throughout the image yet they get dimmer as we move further away from row 1016. This is likely due to the sky moving while the telescope is taking data where row 1016 just so happens to be the row where the star is viewed straight on, giving the brightest observation.

The dark vertical streaks that fall throughout the stars continuum are likely absorption lines of either the star on an object between the star and telescope. The bright vertical lines that appear when looking at the sky exposure are likely emission lines of certain elements found throughout this region of the sky.

2.1.3 Galaxy Observations

When further observing the raw frames of galaxy NGC 1277, we were able to notice some distinctions between files 225 (the galaxy exposure)and 256 (the sky exposure). For example, the bright vertical lines in the galaxy exposure are likely the emission lines from objects found throughout the region that was observed. When comparing the sky exposure of the galaxy to the sky exposure of the star, the vertical lines are much brighter in the sky exposure for the galaxy, this is likely due to the star having a much brighter magnitude than the galaxy. This increased brightness likely “drowned out" the emission lines of the objects found in the region of sky that was observed.

2.2 Reducing the Daycals

We now are going to run the pipeline again changing the parameters “reduce_sortfiles" to ‘no’, “reduce_daycals to ‘yes’, “flinter_arc to" ‘no’ and “flinter_sdist" to ‘no’. This would give us a Ronchi calibration image. We can use this image to create a Ronchi mask data cube, by summing the extensions in output file:

cube_tfrgnN20121030S0346.fits. Below is a sample of code we wrote that sums the extensions of these files and the resulting image displayed in DS9.

```
import numpy as np
import os
from astropy.io import fits

#Pulling from the correct directory
os.chdir("/home/student/nifs_ngc1277/reduced_data/daycals/20121030/hk_2.20/")
Path = os.getcwd()

#Summing the cube
data_cube = fits.open("cube_tfrgnN20121030S0346.fits")[1].data
summed_cube = np.sum(data_cube, axis=0)

#Saving a fits file
hdu = fits.PrimaryHDU(summed_cube)
hdul = fits.HDUList([hdu])
hdul.writeto(Path + '/summed_cube.fits')

```

Figure 2: The code we used to sum the Ronchi Mask calibration image.

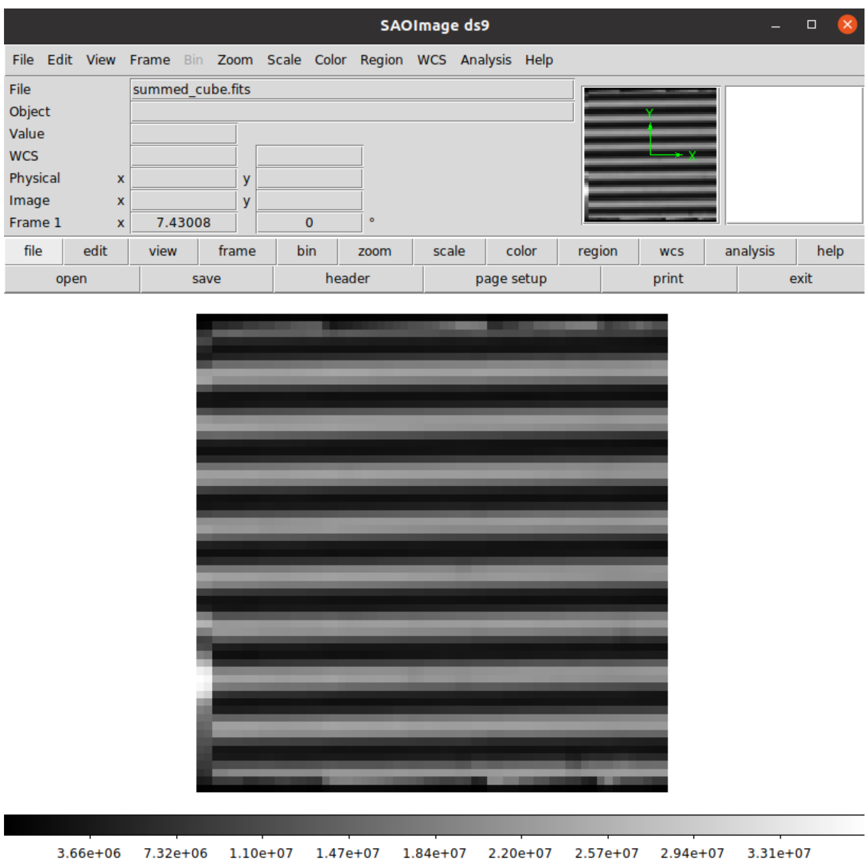

Figure 3: The resulting fits file displayed in DS9.

2.3 Reducing the Telluric Standard Star

We are going to modify the pipeline again by changing the parameter "reduce_tellurics" to 'yes', and all other pipeline steps to 'no'. The main output of doing this step would be a 1D telluric correction spectrum called **cgxtfbrsnN20121030S0267_final.fits** and a 1D telluric star spectrum for HIP 20063 called **gxtfbrsnN20121030S0267.fits**. Below we plotted the spectra of both of these files and show the code we used to calculated the wavelength array of their raw data.

```python
import numpy as np
import matplotlib.pyplot as plt
import os
from astropy.io import fits

#Pulling from the correct directory
os.chdir("/home/student/nifs_ngc1277/reduced_data/tellurics/20121030/hk_2.20/hip20063")
Path = os.getcwd()

#Loading the fits files
tell_corr = fits.open("cgxtfbrsnN20121030S0267_final.fits")
tell_star = fits.open("gxtfbrsnN20121030S0267.fits")

#Opening the data files
corr_data = tell_corr[1].data
star_data = tell_star[1].data

#Reference pixel
star_ref = tell_star[1].header['CRPIX1']
corr_ref = tell_corr[1].header['CRPIX1']

#Wavelength of the reference pixel
star_wav_ref = tell_star[1].header['CRVAL1']
corr_wav_ref = tell_corr[1].header['CRVAL1']

#Wavelength step size between pixels
star_wav = tell_star[1].header['CD1_1']
corr_wav = tell_corr[1].header['CD1_1']

#Calculating the wavelength
wavelength_star = []
wavelength_corr = []

for i in range(len(corr_data)):
    wavelength_corr.append(corr_ref * (i+1) * corr_wav_ref + corr_wav)
    wavelength_star.append(star_ref * (i+1) * star_wav_ref + star_wav)
```

Figure 4: The code we used to calculate the wavelength array.

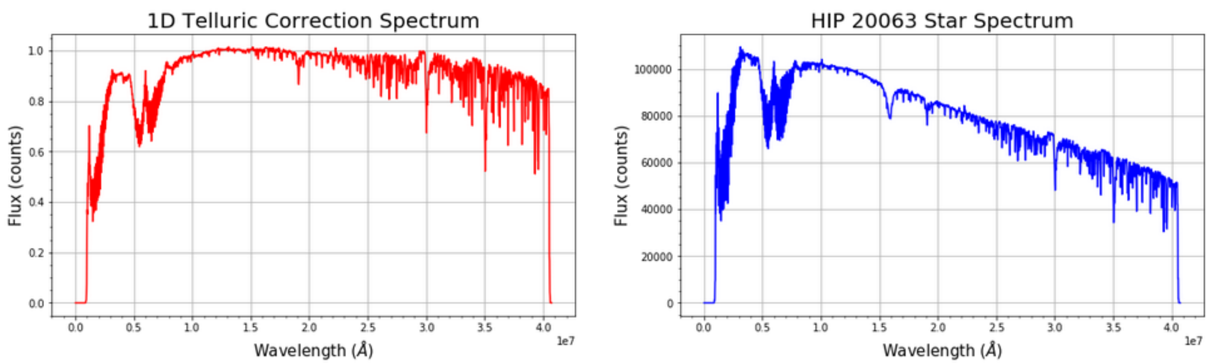

Figure 5: The Spectrum images observed side-by-side.

When looking at the differences in the correction and star spectrum, we immediately notice that the star spectrum follows the same general relationship of a black body with divots populating the curve. These downward bumps are likely the absorption lines we observed when looking at the 1D stellar spectrum in DS9.

When observing the correction spectrum, we also notice the same absorption line pattern but the curve is now flat instead. Moreover, the curve seems in a sense “Normalized" where the spectrum doesn’t seem to increase above 1 count. Furthermore, when observing the CRPIX1, CRVAL1, and CD1_1 values, in these fits files headers, we can say that they are identical.

The telluric star should be observed close in airmass and in time to the main science target to be a sort of “control". We want this observation to take place in a similar environment to that of our science target to help us try and remove any errors that could have taken place when making our observations.

We are using star HIP 20063 to make these corrections, this star is better than a K2 III star as the K2 III star has a lot more fluctuations in the stars intrinsic features. As we are using this star for corrections, we want to find a star that has less intrinsic features.

There is another file, **rsnN20121030S0267.fits**, that is one of the telluric star exposures after extracting each slice. This file has 88 total extensions, we believe extensions 2 - 88 are the individual slices of a larger daycal image, plotting all of these slices together would hopefully give us an file similar to that of 267.

2.4 Reducing the Galaxy Exposures

For this next section we want to adjust our pipeline parameters again, changing “reduce_galaxies" to ‘yes’ and all other pipeline steps to ‘no’, we need to ensure that before we run the pipeline again, we need to have a DS9 window open by typing **ds9** & into the terminal window. Now, after running the pipeline, an interactive prompt should appear asking us to check some files. After approving everything to the same standards as the tutorial manual, an interactive telluric correction window should appear where we would then input a scale and shift parameter for one of the exposures using DS9. Unfortunately, when conducting this step the pipeline continued past the section where the telluric correction window should have appeared, setting its own automated values. A screenshot of the terminal at this step is shown on the next page.

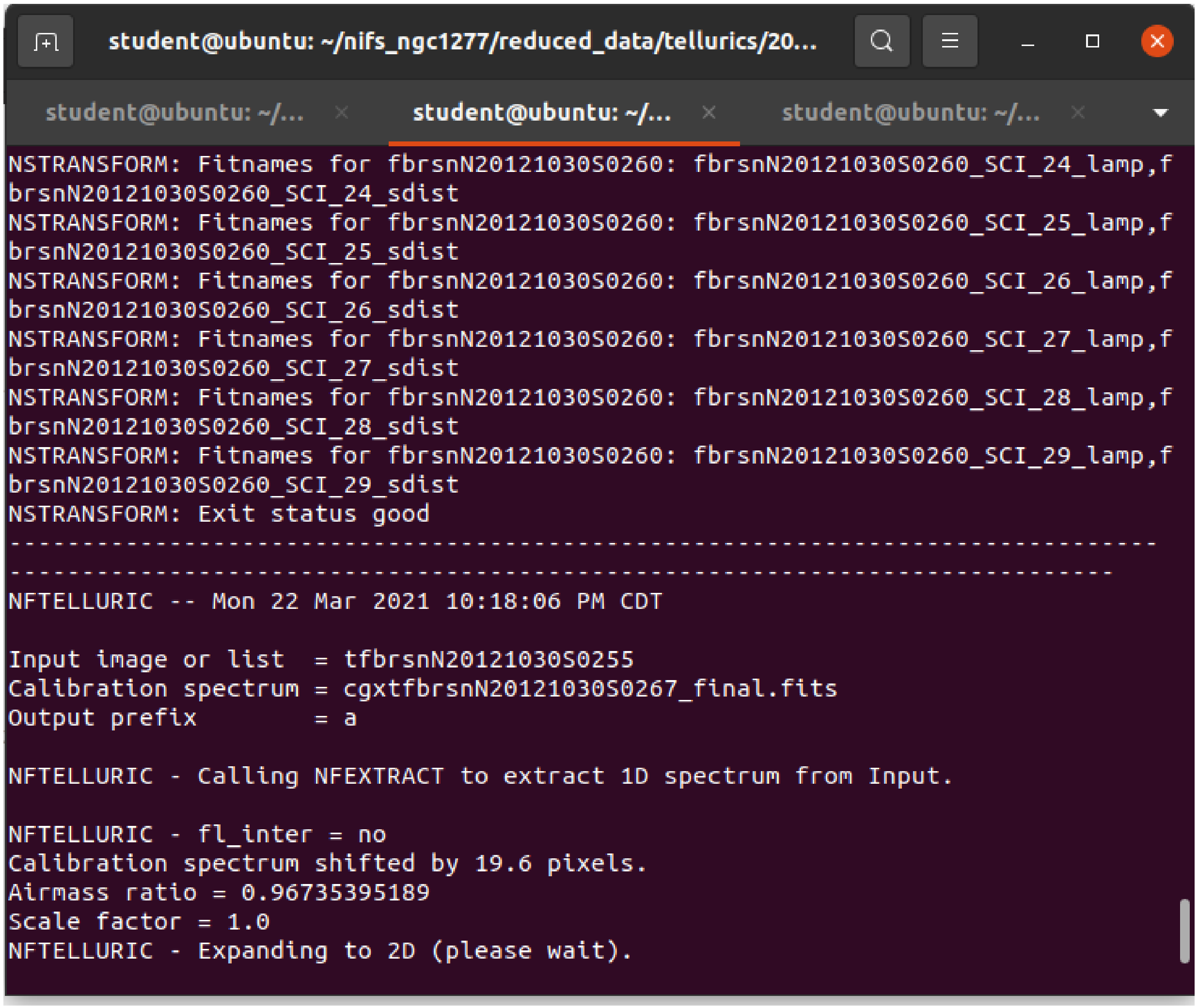

Figure 6: A screenshot of our terminal passing through the telluric correction window after picking automated scale and shift parameters.

2.5 Examining the Outputs of Galaxy Reduction

The main output from the previous step are the telluric corrected “almost data cubes" of the galaxy. We will be observing the file **atfbrsnN20121030S0255.fits** closer to better understand the data cube. Below is snippet of code we used to extract row 35 from extension 43 of our **atfbrsnN20121030S0255.fits** file.

```
import numpy as np
import matplotlib.pyplot as plt
import os
from astropy.io import fits

#Pulling from the correct directory
os.chdir('/home/student/nifs_ngc1277/reduced_data/ngc1277/20121030/hk_2.20')
Path = os.getcwd()

spectrum = fits.open("atfbrsnN20121030S0255.fits")[43].data[35]
header = fits.open("atfbrsnN20121030S0255.fits")[43]

#Pulling from the Header
ref = header.header['CRPIX1']
wav_ref = header.header['CRVAL1']
wav_inc = header.header['CD1_1']

#Calculating the wavelength array in units of Angstrom
wavelength = ((np.arange(len(spectrum))+1 - ref)*wav_inc)+wav_ref
```

Figure 7: A screenshot of our code used to find the spectrum of row 35 of extension 43 of our file.

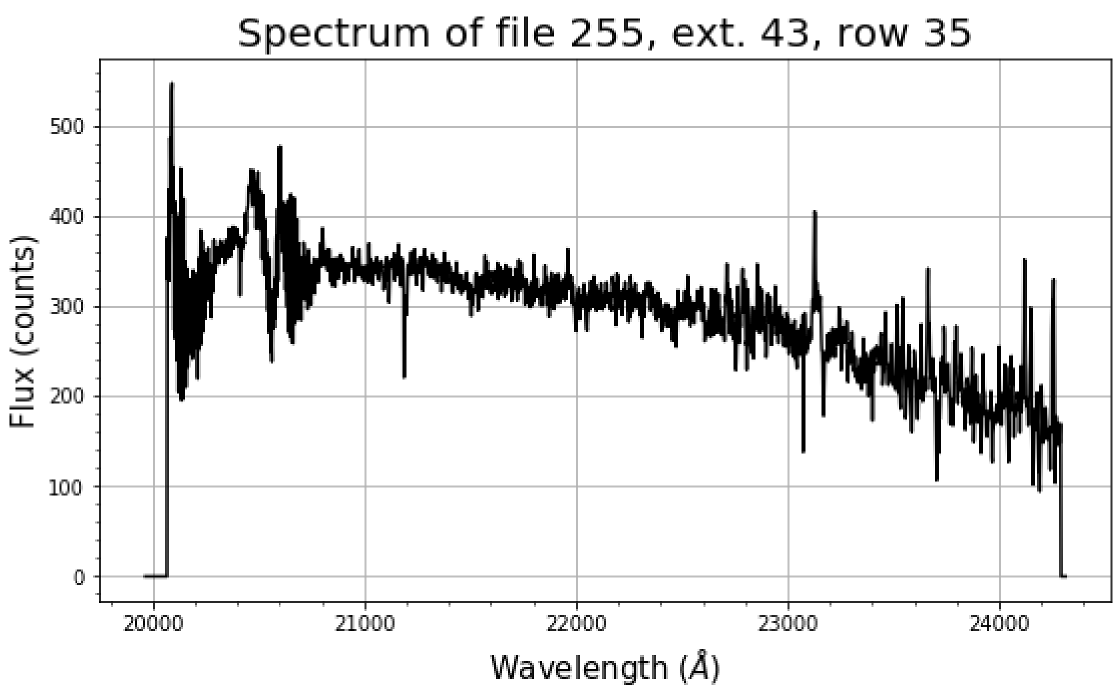

Figure 8: The output of the code above, our spectrum of row 35 of extension 43 of our file.

We further wanted to find the spatial profile at 2.20 μm (22000 Å) for our **atfbrsnN20121030S0255.fits** file. We included the code we used to get this profile along with the profile itself below.

```python
dir_tools_py = '/home/student/py_scripts/'

import sys
sys.path.append(dir_tools_py)
from get_element import get_element

#Our Parameters
value = []
distance = []
lambda1 = 22000.
wave_array = np.array(wavelength)

#Finding where 2.2um is located in relation to x
index1 = get_element(wave_array,lambda1)

#Pulling from the Header to find distance
pix = header.header['CRPIX2']
pix_ref = header.header['CRVAL2']
pix_inc = header.header['CD2_2']

#Now appending the index1'th element for every row in extension 43
values = its.open("atfbrsnN20121030S0255.fits")[43].data[:,index1]

# Finding the Distance array
orig_dist = pix * pix_ref + pix_inc
for i in range(len(pix_value)):
    distance.append(orig_dist + pix_inc*i)    #In units of Arcseconds
```

Figure 9: A screenshot of our code used to find the spatial profile at 2.20 μm of our file.

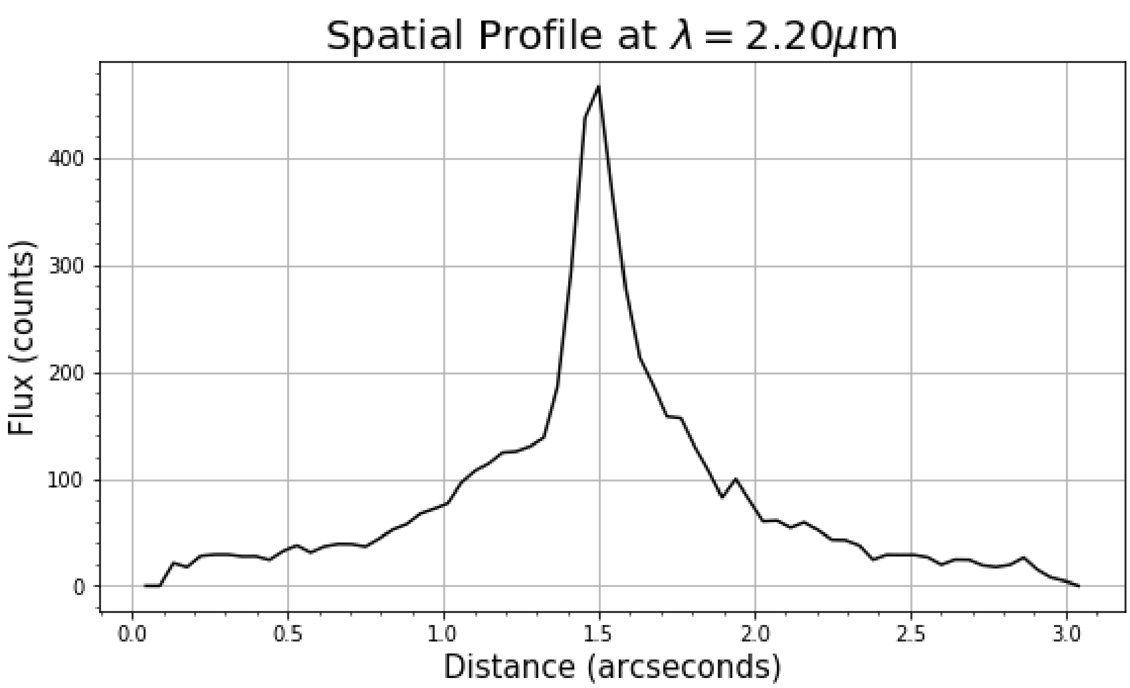

Figure 10: The spatial profile at 2.20 μm (22000 Angstrom).

When observing the header for our **atfbrsnN20121030S0255.fits** file we have noticed two different keywords: “CRVAL3" and “CD3_3". These values can help us determine the relationships between the slices for our file. “CRVAL3" provides us with the x spatial location in arcseconds of the slice we are looking at while “CD3_3" gives us the distance across the slice in arcseconds. We found these values to be: $0.103''$ for “CD3_3" and $1.545''$ for “CRVAL3" for the 43’rd extension.

Finding similar values of $0.103''$ for “CD3_3" and $1.648''$ for “CRVAL3" for extension 40 and $0.103''$ for “CD3_3" and $1.751''$ for “CRVAL3" for extension 37. Using these values, we are able to determine at what extension we are able to find a “CRVAL3" value of $0.206''$ to be extension 82.

2.6 Constructing a Merged Galaxy Cube and Applying a Flux Calibration

Now we have fully reduced “almost data cubes" for four of NGC 1277 exposures. We can use other, previously reduced “almost data cubes" for the next step, constructing a merged galaxy cube. We can do this by once again editing **nifs_main_Lp.py** to set the parameter “reduce_combined_gal" to ‘yes’, and all other pipeline steps to ‘no’. This will create a wavelength axis for the final merged cube, using the starting and ending wavelength to set boundaries, and the change in wavelength per pixel to create the differences.

After dividing by the exposure time to get counts s^{-1}, the pipeline then uses all of the modified galaxy “almost data cubes" to produce a single cube with science, variance, and data quality extensions and with the wavelength axis. The main output from the pipeline is the merged data cube for NGC 1277 called **ncg1277_combined.fits**.

To apply the flux calibration we must first create a directory following the chain:
∼**nifs_ngc1277/reduced_data/tellurics/20121031/hip20063/**. Then we must copy **N20121031S0242.fits** and **catfbrsnN20121031S0242.fits** into this new directory. We must also edit **nifs_main_Lp.py** by setting the parameter “reduce_fluxcal" to ‘yes’, and all other pipeline steps to ‘no’.

This step allows the pipeline to take a data cube previously constructed for one of the telluric star observation, and applies a telluric correction, leaving just the spectra of the A0 V star. The pipeline then extracts a 1D spectrum from the A0 V star data cube using a circular aperture centered on the location of the star. Then it queries a database to get the flux density of the A0 V star (in units of ergs s^{-1} cm^{-1} $\mathring{A}^{-1}$) at a characteristic wavelength of the 2MASS *K*-band filter. The main output of the pipeline is a flux-calibrated NGC 1277 merged data cube called **ngc1277_combined_flux.fits**.

2.7 Examining the Outputs in the NGC 1277 Merged Directory

When we set ‘’reduce_galaxies" to ‘yes’ in and ran the pipeline, we constructed a temporary data cube from each galaxy “almost data cube" and summing along the wavelength axis to get an image of the galaxy. Specifically, we used the files **image_catfbrsnN20121031S0232.fits**, as well as **image_catfbrsnN20121125S0056.fits** and **image_catfbrsnN20121227S0119.fits**. After further observing these fits files in DS9, we were able to record the x and y location of the galaxy center (defined as the brightest pixel) from each of these images. Our findings are found in the table on the next page.

Table 1. Galaxy Center of our “almost data cubes"

file name	x (pixel)	RA	y (pixel)	DEC
image_catfbrsnN20121031S0232.fits	30	3:19:51.59	30	41:34: 24.062
image_catfbrsnN20121125S0056.fits	30	3:19:51.686	32	41:34: 23.155
image_catfbrsnN20121227S0119.fits	28	3:19:51.58	32	41:34: 23.725

We then decided to further examine the combined flux data cube (**ngc1277_combined_flux.fits**) in DS9. Below are some screen shots of the galaxy image at different wavelength slices.

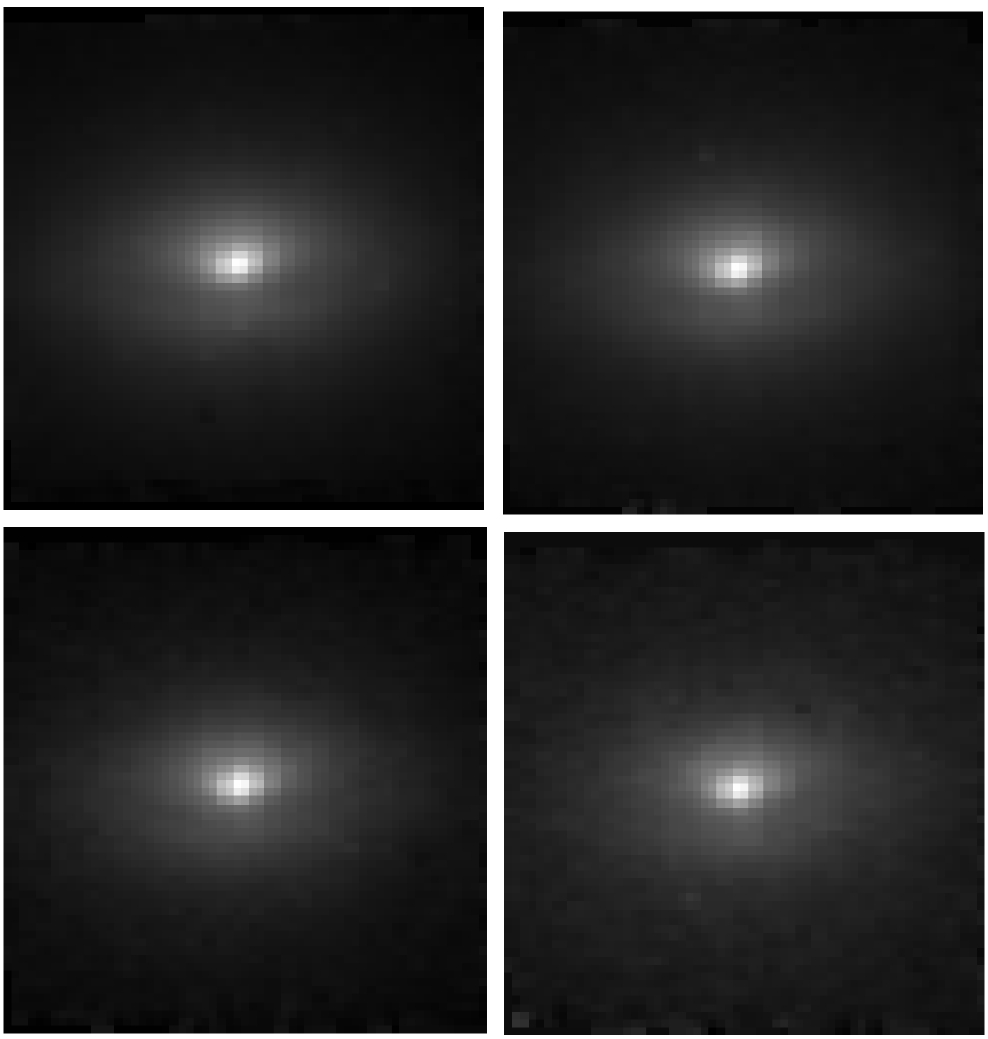

Figure 11: The upper left image is held at frame 226, which coincides with a wavelength of 20450.4Å. The upper right image is held at frame 985, which coincides with a wavelength of 22068.6 Å. The lower left image is held at frame 1622 which coincides with a wavelength of 23426.7Å. The lower right image is held at frame 1881, which coincides with a wavelength of 23978.9Å.

Next we wanted to find and plot the galaxy spectrum of our data cube at 3 different positions: a) x = -0.7″, y = 0.1″, b) x = 0.07″, y = –0.01″, and c) x= 0.0″, y = –0.3″, where our origin (x = 0.0//, y = 0.0″) is located at the pixel x = 29, y = 31. Below is a snippet of code on how we found the spectrum followed by the spectrum of the three positions plotted as a function of wavelength.

```python
import os
import numpy as np
import matplotlib.pyplot as plt
from astropy.io import fits

#Pulling from the correct directory
os.chdir('/home/student/nifs_ngc1277/reduced_data/ngc1277/merged/hk_2.20')
Path = os.getcwd()

combined_flux = fits.open("ngc1277_combined_flux.fits")[1].data
header = fits.open("ngc1277_combined_flux.fits")[1]

#Defining our [0,0] point along with finding the pixscale
pix_scale=header.header['PIXSCALE']
center_pix = [29,31]

#Offset for each of our points in arcseconds
ax,ay = -0.7,0.1
bx,by = 0.7,-0.1
cx,cy = 0.0,-0.7

#converting the offset to pixels
ax_dist = ax/pix_scale
ay_dist = ay/pix_scale

bx_dist = bx/pix_scale
by_dist = by/pix_scale

cx_dist = cx/pix_scale
cy_dist = cy/pix_scale

#finding the pixel location of our observation points
a_position = [round(center_pix[0] + ax_dist), round(center_pix[1] + ay_dist)]
b_position = [round(center_pix[0] + bx_dist), round(center_pix[1] + by_dist)]
c_position = [round(center_pix[0] + cx_dist), round(center_pix[1] + cy_dist)]

#appending the spectrums for each position
a_spectrum, b_spectrum, c_spectrum = [], [], []

for i in range(len(combined_flux)):
    a_spectrum.append(combined_flux[i][a_position[0],a_position[1]])
    b_spectrum.append(combined_flux[i][b_position[0],b_position[1]])
    c_spectrum.append(combined_flux[i][c_position[0],c_position[1]])
```

Figure 12: A screenshot of our code used to find the spectrum of our 3 different positions.

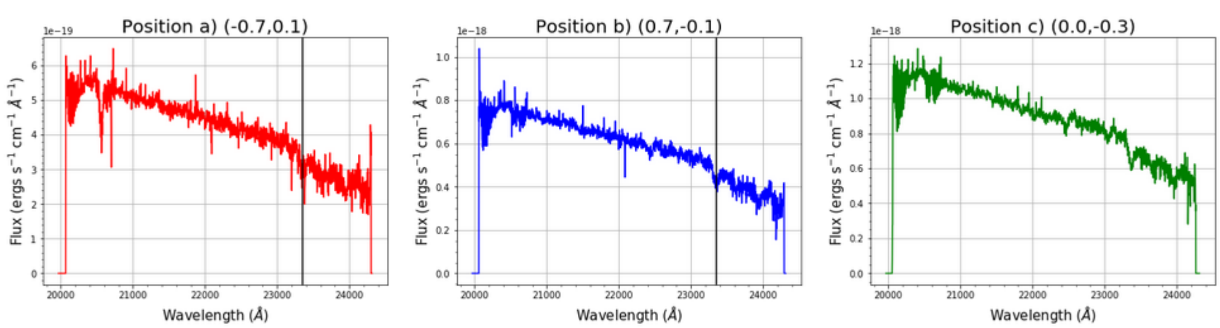

Figure 13: The spectrum of our code found at the 3 different positions. The grey vertical is where we believe the (2-0)[12] C0 absorption line occurs. This line is positioned on the first plot (position a) at λ_a = 23355 Å, and on the second plot (position b) at λ_b = 23350 Å.

As described in Figure 13, we also estimated the wavelength at which (2-0)^{12} C0 absorption occurs for position a) and position b). We know that (2-0)^{12} C0 absorption occurs at a rest frame of 2.2935 microns (22935 Å). So when taking in account redshift moving this value to a longer wavelength, believe that the CO (2-0) absorption line occurs at λ_a = 23355 Åfor position a), and at λ_b = 23350 Åfor position b). While these approximations are made by eye, we do believe there is a slight offset for a redder wavelength for position a) rather than position b).

Using these wavelength estimates, we believe we can calculate the difference in the line-of-site velocity of spectrum b relative to spectrum a using this equation:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v_r}{c} \tag{1}$$

Where $\Delta\lambda$ is our wavelength offset $(\lambda_b - \lambda_a)$, λ_0 is the rest frame wavelength for C0 (2-0), and c is the speed of light in m/s. After plugging in our values to this equation, we estimate that the line-of-site velocity for NGC 1277 using positions a) and b) is -65402.22 m/s.

2.8 Additional Questions

When taking measurements, we normally do not take long exposure dark frames as the purpose of these frames is to finding and removing unwanted noise, mainly to remove “hot or cold" pixels. The only situation in which we believe we would want a dark exposure to have the same exposure time as our galaxy exposures is to remove thermal noise from the ground, caused by the machinery in the telescope or just the earths surface itself.

When using the NIFS integration time calculator (ITC), we found that the total time we need to request for an object with a central surface brightness of K = 13.3 mag arcsec^{-2} to get a S/N =40 for 600s exposures at 2.25 μm to be 7 hours 53 mins and 5 seconds. Below are screen shots of our completed ITC form and the output plot showing the S/N per spectral pixel versus wavelength.

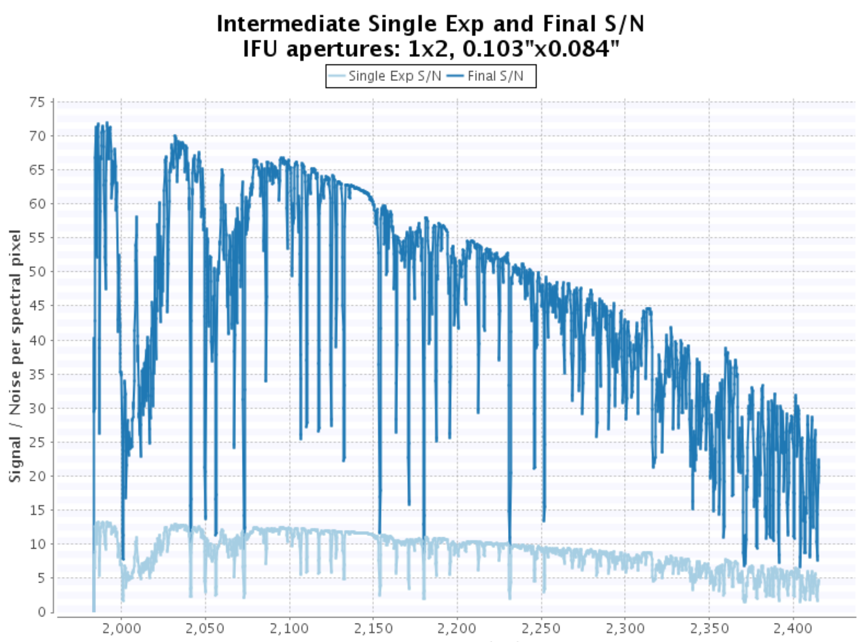

Figure 14: A screenshot of our output plot showing S/N per spectral pixel vs. wavelength.

Input Parameters:
Instrument: NIFS

Source spatial profile, brightness, and spectral distribution:
The z = 0.00000 uniform surface brightness source is a 13.3 Vega mag/arcsec^2 A0V star in the K band.

Instrument configuration:
Optical Components:
- Filter: HK_FILTER
- Fixed Optics
- IFU Transmission
- Grating Optics: K
- Detector - 2K x 2K HgCdTe HAWAII-2 CCD
- Focal Plane Mask: ifu
- Read Noise: 8.1
- Well Depth: 90000.0

Central Wavelength: 2200.0 nm
Pixel Size in Spatial Direction: 0.0658 arcsec
Pixel Size in Spectral Direction: 0.212 nm
IFU is selected,with multiple summed IFU elements arranged in a 1x2 (0.103"x0.084") grid.

Altair Guide Star properties:
- Natural Guide Star Mode selected
- Guide Star Seperation 15.0
- Guide Star Magnitude 14.1
- Altair Field Lens position: OUT

Telescope configuration:
- silver mirror coating.
- up looking port.
- wavefront sensor: aowfs

Observing Conditions:
- Image Quality: 70.00%
- Sky Transparency (cloud cover): 50.00%
- Sky transparency (water vapour): 100.00%
- Sky background: 100.00%
- Airmass: 1.50

Likelihood of execution: 35.00%

Calculation and analysis methods:
- Mode: spectroscopy
- Calculation of S/N ratio with 40 exposures of 600.00 secs, and 100.00% of them on source.
- Analysis performed for aperture that gives 'optimum' S/N and 1 fibres on sky.

Output:
- Spectra autoscaled.

Figure 15: A screenshot of input parameters for our ITC form.