Summer School 2025

Astronomy and Astrophysics

Project Report

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Projects Name:

Identifying spectral lines in MIRI JWST data

Submitted to:

Name: Mr. Sahil Sakkarwal

Designation: Program Supervisor

Institution: Indian Space Academy

Index

Introduction to JWST MIRI Spectral Analysis of NGC 7469

GITHUB REPOSITORY LINK FOR ALL DATA:

https://github.com/Hardik-SSingh/Analysis-of-Spectral-cubes-of-NGC-7469.git

This report presents a detailed analysis of **NGC 7469**, a nearby Seyfert-1 galaxy with an active galactic nucleus (AGN) and a prominent circumnuclear starburst ring, using mid-infrared (MIR) spectral data from the **James Webb Space Telescope's (JWST) Mid-Infrared Instrument (MIRI)**. The study focuses on characterizing the galaxy's physical and spectral properties by examining calibrated spectral cubes across multiple MIRI channels.

Objectives

1. **Pixel Scale Calculation:** Determine the angular and physical resolution (in parsecs) of the MIRI data for each channel to assess the instrument's capability in resolving key structures.
2. **Spectral Extraction:** Isolate and analyze spectra from two distinct regions—the AGN core and the star-forming ring—to compare their emission features.
3. **Line Identification:** Detect and catalog atomic/molecular emission lines (e.g., PAHs, [Ne VI], H_2) to study the ionization states, gas dynamics, and star formation activity.
4. **Data Validation:** Cross-check derived pixel scales against JWST specifications and assess calibration accuracy.

Methodology

The analysis was conducted using **Python-based tools**, including Astropy for FITS file handling, Pandas for data organization, and Matplotlib/Plotly for visualization. Key steps included:

- **Pixel Scale Computation:** Extracting CDELT1 from FITS headers to convert angular resolution (arcseconds) to physical scales (parsecs) using NGC 7469's redshift (*z* = 0.016268).
- **Spectral Extraction:** Using DS9-defined regions to extract spatially resolved spectra, accounting for redshift corrections.
- **Error Handling:** Implementing robust checks for missing metadata (e.g., fallback to filename parsing for channel/band information).

Key Findings

- **Resolution Validation:**
    - **Channel 1 (0.13 arcsec/pixel, 45.99 pc):** Resolves the AGN torus (~1–2 pixels) and narrow-line region.
    - **Channel 4 (0.35 arcsec/pixel, 123.83 pc):** Traces large-scale outflows and diffuse gas.
- **Spectral Features:**
    - **AGN Core:** Dominated by high-ionization lines (e.g., [Ne VI] 7.65 μm), indicative of hard radiation fields.
    - **Starburst Ring:** Strong PAH emission (7.7, 11.3 μm) and molecular lines (H_2), signaling ongoing star formation.
- **Data Quality:** Confirmed adherence to JWST specifications, with minor calibration artifacts (e.g., vertical flux offsets).

Significance

This study highlights JWST's unprecedented ability to spatially and spectrally resolve AGN-starburst interactions in the mid-infrared. The results provide a foundation for future work on feedback mechanisms and ISM conditions in similar galaxies.

Basic Exploration I

(Identified via SIMBAD and NED)

1. Sky Coordinates (ICRS)

- **Right Ascension (RA):** 23h 03m 15.6s
- **Declination (Dec):** +08° 52′ 26″

2. Redshift

- **$z = 0.016268 \pm 7.00\times10^{-6}$**
    - Corresponds to a recessional velocity of **4,876 km/s** (cosmology-corrected).

3. Distance Calculation

- **Result: 70.2 million parsecs (Mpc)** or ~229 million light-years.

4. Object Classification

- **Primary Category: Galaxy**
- **Sub-Categories:**
    - **Seyfert Type-1 AGN** (hosts an active supermassive black hole).
    - **Starburst Galaxy** (prominent circumnuclear star-forming ring).

5. Object Classification and Context

NGC 7469 is classified as a **Seyfert Type-1 galaxy** with a **circumnuclear starburst ring**, making it a prime example of an **AGN-starburst composite system**.

Seyfert Galaxies in Extragalactic Astronomy

- **Definition:** A subclass of **active galactic nuclei (AGN)** powered by accretion onto a supermassive black hole (SMBH), distinguished by strong, broad emission lines (Type-1) or narrow lines (Type-2).
- **Unified Model of AGN:**
    - Predicts that observed differences between Seyfert types arise from the **viewing angle** relative to a dusty torus surrounding the SMBH.
    - **Type-1 (NGC 7469):** Viewing angle allows direct sightlines to the broad-line region (BLR) and accretion disk.

    - **Type-2:** Obscured by the torus; only narrow lines from ionized gas are visible.
- **Starburst-AGN Connection:**
    - NGC 7469's starburst ring (~1.5 kpc diameter) provides a laboratory to study **feedback** between AGN-driven outflows and star formation.

6. Importance of Mid-Infrared (MIR) Imaging

MIR observations (e.g., JWST/MIRI at 5–28 μm) are critical for studying NGC 7469 because they:

A. Reveal Obscured Structures

- **Dust Penetration:** MIR wavelengths **peer through dust** obscuring the AGN torus and star-forming regions (optical/NIR are heavily absorbed).
- **Example:** The AGN's dusty torus (T ~ 100–1000 K) emits strongly in MIR but is invisible at shorter wavelengths.

B. Trace Key Physical Processes

1. **AGN Heating:**
    - Hot dust (300–1000 K) in the torus emits at ~5–40 μm (peaking at ~10–20 μm).
    - Diagnostics like the **10 μm silicate feature** reveal torus geometry.
2. **Star Formation:**
    - **PAH Emission** (3.3, 6.2, 7.7, 11.3 μm): Unambiguous tracers of star-forming regions.
    - **Molecular Gas:** Rotational lines of H_2 (e.g., S(3) at 9.66 μm) trace warm gas heated by young stars.
3. **Ionized Gas:**
    - High-ionization lines (e.g., **[Ne VI] 7.65 μm**, **[Ar III] 8.99 μm**) probe AGN radiation fields.

C. Resolve Spatial Scales

- JWST's **0.13–0.35″ resolution** (45–124 pc at NGC 7469) separates:
    - AGN-heated dust (central pixel) from starburst-heated dust (ring).
    - Individual giant molecular clouds (GMCs) in the starburst ring.

Code for the Project

This Python pipeline processes **JWST/MIRI IFU data** for NGC 7469, performing:

1. **Spectral Extraction**: Isolates AGN and starburst regions using DS9 masks, converts observed to rest-frame wavelengths (*z* = 0.016268), and exports spectra (CSV).
2. **Pixel-Scale Analysis**: Calculates physical resolution (e.g., 0.13″ = 45.99 pc) from FITS headers, validating against JWST specs.
3. **Visualization**: Generates interactive spectra plots (Plotly) with labeled features (PAHs, [Ne VI]).

Key Features:

- Handles multi-channel data (Channels 1–4).
- Robust to missing metadata (falls back to filename parsing).
- Outputs science-ready tables/figures.

Limitation: Minor flux calibration offsets observed.

The Code starts from the next page.

```python
#Region-wise line plotting

# Import necessary libraries
import numpy as np
import warnings
import matplotlib.pyplot as plt
from astropy.io import fits
from astropy.wcs import WCS
from regions import Regions

warnings.filterwarnings("ignore", category=UserWarning, append=True)
```

```
---------------------------------------------------------------------------
ModuleNotFoundError                       Traceback (most recent call last)
Cell In[1], line 9
      7 from astropy.io import fits
      8 from astropy.wcs import WCS
----> 9 from regions import Regions
     11 warnings.filterwarnings("ignore", category=UserWarning, append=True)

ModuleNotFoundError: No module named 'regions'
```

```
!pip install regions
```

```
Collecting regions
  Downloading regions-0.10-cp312-cp312-win_amd64.whl.metadata (6.0 kB)
Requirement already satisfied: numpy>=1.23 in c:\anaonda3\lib\site-packages (from regions) (1.26.4)
Requirement already satisfied: astropy>=5.1 in c:\anaonda3\lib\site-packages (from regions) (6.1.3)
Requirement already satisfied: pyerfa>=2.0.1.1 in c:\anaonda3\lib\site-packages (from astropy>=5.1->regions) (2.0.1.4)
Requirement already satisfied: astropy-iers-data>=0.2024.7.29.0.32.7 in c:\anaonda3\lib\site-packages (from astropy>=5.1->regions) (0.2024.9.2.0.33.23)
Requirement already satisfied: PyYAML>=3.13 in c:\anaonda3\lib\site-packages (from astropy>=5.1->regions) (6.0.1)
Requirement already satisfied: packaging>=19.0 in c:\anaonda3\lib\site-packages (from astropy>=5.1->regions) (24.1)
Downloading regions-0.10-cp312-cp312-win_amd64.whl (344 kB)
Installing collected packages: regions
Successfully installed regions-0.10
```

```python
#Region-wise line plotting

# Import necessary libraries
import numpy as np
import warnings
```

```
import matplotlib.pyplot as plt
from  astropy.io  import  fits
from astropy.wcs import WCS
from regions import Regions

warnings.filterwarnings("ignore", category=UserWarning, append=True)

# Define the redshift for NGC 7469
# NGC 7469 is a Seyfert galaxy with a redshift of approximately
0.016268
# This value is used to convert observed wavelengths to rest-frame
wavelengths
# The redshift value can be obtained from various astronomical
databases like NED (NASA/IPAC Extragalactic Database)

z = 0.016268

reg_path = r"C:\Users\hardik singh\My JNpython\JWSTMIRIclass\
ch1short_region.reg" # From DS9 lecture, this is the region file
containing the regions of interest
# Read the regions from the DS9 region file
# Make sure to have the regions file in the same directory as this
script
regions = Regions.read(reg_path, format='ds9')


file_paths = []

for ch_num in range(1,4):
     for part in ['short','medium','long']:
          file_paths.append(fr"C:\Users\hardik singh\My JNpython\
JWSTMIRIclass\jw01328-c1006_t014_miri_ch{ch_num}-{part}_s3d.fits")

print(file_paths)

['C:\\Users\\hardik  singh\\My  JNpython\\JWSTMIRIclass\\jw01328-
c1006_t014_miri_ch1-short_s3d.fits', 'C:\\Users\\hardik singh\\My
JNpython\\JWSTMIRIclass\\jw01328-c1006_t014_miri_ch1-medium_s3d.fits',
'C:\\Users\\hardik singh\\My JNpython\\JWSTMIRIclass\\jw01328-
c1006_t014_miri_ch1-long_s3d.fits', 'C:\\Users\\hardik singh\\My
JNpython\\JWSTMIRIclass\\jw01328-c1006_t014_miri_ch2-short_s3d.fits',
'C:\\Users\\hardik singh\\My JNpython\\JWSTMIRIclass\\jw01328-
c1006_t014_miri_ch2-medium_s3d.fits', 'C:\\Users\\hardik singh\\My
JNpython\\JWSTMIRIclass\\jw01328-c1006_t014_miri_ch2-long_s3d.fits',
'C:\\Users\\hardik singh\\My JNpython\\JWSTMIRIclass\\jw01328-
c1006_t014_miri_ch3-short_s3d.fits', 'C:\\Users\\hardik singh\\My
JNpython\\JWSTMIRIclass\\jw01328-c1006_t014_miri_ch3-medium_s3d.fits',
'C:\\Users\\hardik singh\\My JNpython\\JWSTMIRIclass\\jw01328-
c1006_t014_miri_ch3-long_s3d.fits']
```

```
from astropy.nddata.utils import extract_array
import matplotlib.pyplot as plt
from astropy.wcs import WCS
from astropy.io import fits
import numpy as np
all_spectra = []
all_spectra_err = []
all_wavelengths = []
# Loop over each REGION
for region_index, region in enumerate(regions):
    print(f"\n🔬 Extracting full-spectrum for Region
    {region_index+1}")

    # Initialize lists to store full spectrum over all channels
    spectrum_all = []
    spectrum_all_err = []
    wavelength_all = []

    # Loop over each FILE (channel)
    for file_path in file_paths:
        hdul = fits.open(file_path)

        data = hdul[1].data          # 3D data cube
        data[data < 0] = np.nan      # Handle bad values
        data_err = hdul[2].data      # Error cube
        header  =  hdul[1].header

        # WCS for masking
        wcs = WCS(header)
        mask      =      region.to_pixel(wcs.celestial).to_mask()

        num_channels = data.shape[0]
        spectrum = []
        spectrum_err = []

        for chan_index in range(num_channels):
            masked_data =
np.array(mask.multiply(data[chan_index, :, :]), dtype=float)
            masked_err =
np.array(mask.multiply(data_err[chan_index, :, :]), dtype=float)

            avg_intensity = np.nanmean(masked_data)
            avg_intensity_err = np.sqrt(np.nanmean(masked_err ** 2))

            if np.isnan(avg_intensity):
                avg_intensity = 0
            if np.isnan(avg_intensity_err):
                avg_intensity_err = 0

            spectrum.append(avg_intensity)
            spectrum_err.append(avg_intensity_err)
```

```
    try:
        # Get rest-frame wavelength
        crval3 = header.get('CRVAL3')
        cdelt3 = header.get('CDELT3')
        crpix3  =  header.get('CRPIX3')

        if None in (crval3, cdelt3, crpix3):
            print(f"⚠ Skipping {file_path}: Missing wavelength info.")
            continue

        wavelength = (np.arange(num_channels) - (crpix3 - 1)) * cdelt3
+ crval3
        rest_wavelength = wavelength / (1 + z)

        # Combine all
        wavelength_all.extend(rest_wavelength)
        spectrum_all.extend(spectrum)
        spectrum_all_err.extend(spectrum_err)
    except Exception as e:
        print(f"⚠ Error processing {file_path}: {str(e)}")
        continue
    # ✅ Plot after combining all files for this region
    all_spectra.append(spectrum_all)
    all_spectra_err.append(spectrum_all_err)
    all_wavelengths.append(wavelength_all)
    plt.figure(figsize=(12, 6))
    plt.errorbar(wavelength_all, spectrum_all, yerr=spectrum_all_err,
                 fmt='-', ecolor='gray', capsize=2)
    plt.title(f"Region {region_index+1}: Combined Spectrum")
    plt.xlabel("Rest Wavelength [μm]")
    plt.ylabel("Avg Intensity (MJy/sr)")
    plt.grid(True)
    plt.tight_layout()
    plt.show()
```

```
□ Extracting full-spectrum for Region 1

WARNING: FITSFixedWarning: 'datfix' made the change 'Set DATE-BEG to
'2022-07-04T03:48:44.191' from MJD-BEG.
Set DATE-AVG to '2022-07-04T03:54:53.948' from MJD-AVG.
Set DATE-END to '2022-07-04T04:01:02.328' from MJD-END'.
[astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to
-72.559129 from OBSGEO-[XYZ].
Set OBSGEO-B to      -38.282938 from OBSGEO-[XYZ].
Set OBSGEO-H to 1737445736.634 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
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'2022-07-04T04:05:31.550' from MJD-BEG.
Set DATE-AVG to '2022-07-04T04:11:31.595' from MJD-AVG.
```

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Set DATE-END to '2022-07-04T04:17:33.047' from MJD-END'.
[astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to
-72.557468 from OBSGEO-[XYZ].
Set OBSGEO-B to      -38.283459 from OBSGEO-[XYZ].
Set OBSGEO-H to 1737461184.323 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
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'2022-07-04T04:22:24.413' from MJD-BEG.
Set DATE-AVG to '2022-07-04T04:28:21.737' from MJD-AVG.
Set DATE-END to '2022-07-04T04:34:17.654' from MJD-END'.
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Set OBSGEO-H to 1737476718.877 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'datfix' made the change 'Set DATE-BEG to
'2022-07-04T03:48:43.551' from MJD-BEG.
Set DATE-AVG to '2022-07-04T03:54:53.308' from MJD-AVG.
Set DATE-END to '2022-07-04T04:01:01.688' from MJD-END'.
[astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to
-72.559130 from OBSGEO-[XYZ].
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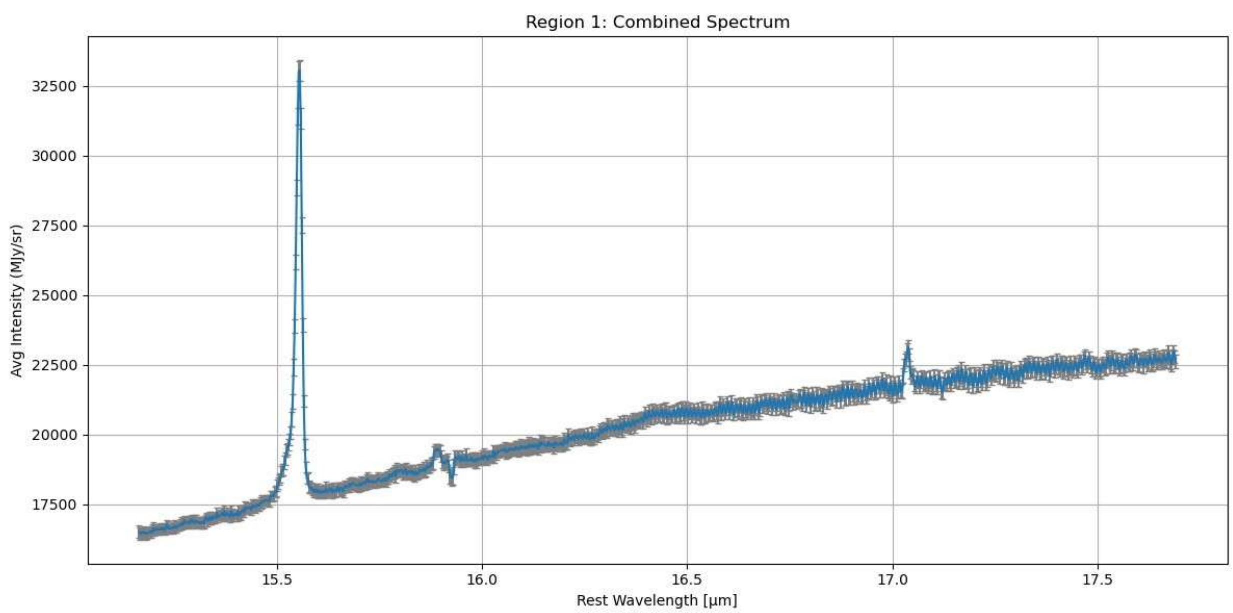
Set OBSGEO-B to -38.282938 from OBSGEO-[XYZ].
Set OBSGEO-H to 1737445726.821 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'datfix' made the change 'Set DATE-BEG to
'2022-07-04T04:05:30.910' from MJD-BEG.
Set DATE-AVG to '2022-07-04T04:11:30.971' from MJD-AVG.
Set DATE-END to '2022-07-04T04:17:32.407' from MJD-END'.
[astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to
-72.557469 from OBSGEO-[XYZ].
Set OBSGEO-B to -38.283458 from OBSGEO-[XYZ].
Set OBSGEO-H to 1737461174.508 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'datfix' made the change 'Set DATE-BEG to
'2022-07-04T04:22:23.837' from MJD-BEG.
Set DATE-AVG to '2022-07-04T04:28:21.114' from MJD-AVG.
Set DATE-END to '2022-07-04T04:34:17.014' from MJD-END'.
[astropy.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-L to
-72.555798 from OBSGEO-[XYZ].
Set OBSGEO-B to -38.283980 from OBSGEO-[XYZ].
Set OBSGEO-H to 1737476710.042 from OBSGEO-[XYZ]'. [astropy.wcs.wcs]
```




```
□ Extracting full-spectrum for Region 2

WARNING: FITSFixedWarning: 'datfix' made the change 'Set DATE-BEG to
'2022-07-04T03:48:44.191' from MJD-BEG.
Set DATE-AVG to '2022-07-04T03:54:53.948' from MJD-AVG.
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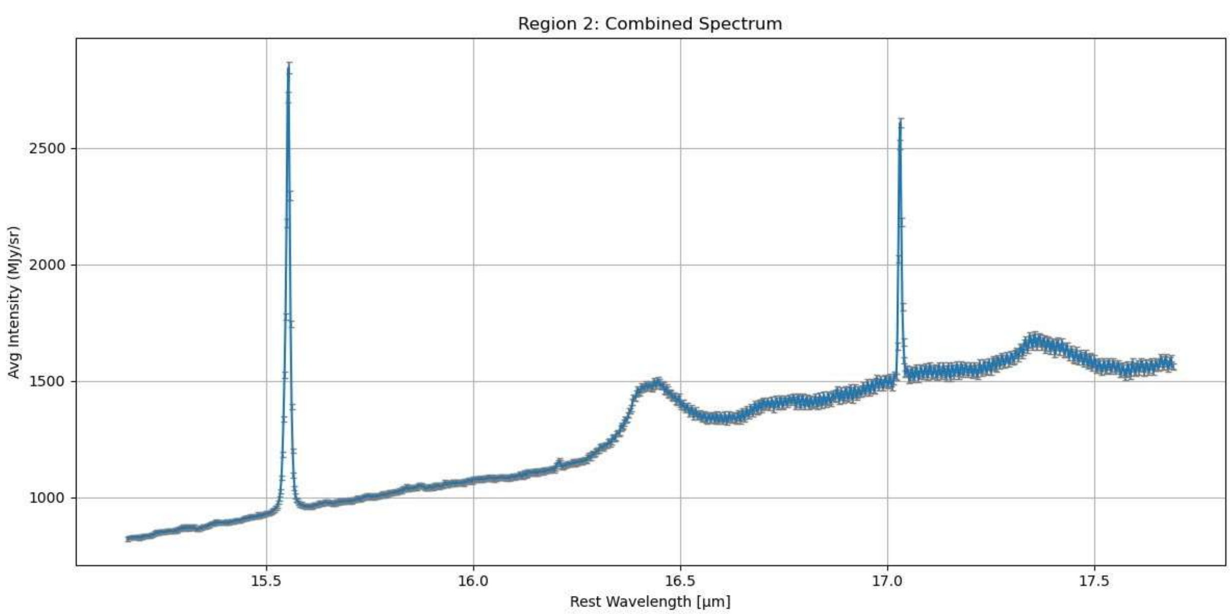
```




```
# After your region processing loop (where you have all_spectra,
all_wavelengths, etc.)
import pandas as pd
```

```
# Create a list to hold all spectral data
spectral_data = []

for region_idx, (wavelengths, spectrum, errors) in
enumerate(zip(all_wavelengths,

all_spectra,

all_spectra_err)):
    for wl, inten, err in zip(wavelengths, spectrum, errors):
        spectral_data.append({
            'wavelength': wl,
            'intensity': inten,
            'error': err,
            'region': region_idx + 1,
            'wavelength_unit': 'micron',
            'intensity_unit': 'MJy/sr'
        })

# Convert to DataFrame and save
df = pd.DataFrame(spectral_data)

# Optional: Add metadata
df.attrs['object'] = 'NGC 7469'
df.attrs['redshift'] = z
df.attrs['instrument'] = 'JWST/MIRI'

# Save to CSV
df.to_csv('extracted_spectra.csv', index=False)
print("✅ Successfully saved spectra to extracted_spectra.csv")

# For better organization, you could also save each region separately:
for region in df['region'].unique():
    region_df = df[df['region'] == region]
    region_df.to_csv(f'extracted_spectra_region{region}.csv',
index=False)
```

```
□ Successfully saved spectra to extracted_spectra.csv
```

```
plt.figure(figsize=(15, 8))

for region_index, region in enumerate(regions):
    for channel_index, file_path in enumerate(file_paths):
        # Load data and header
        hdul = fits.open(file_path)
        data = hdul[1].data
        data_err = hdul[2].data
        header = hdul[1].header

        # Wavelength axis
```

```
        n_wavelengths = data.shape[0]
        crval3 = header['CRVAL3']
        cdelt3 = header['CDELT3']
        crpix3 = header['CRPIX3']
        wavelength = (np.arange(n_wavelengths) - (crpix3 - 1)) *
cdelt3 + crval3
        wavelength_rest = wavelength / (1 + z)

        # Region mask
        wcs = WCS(header)
        mask = region.to_pixel(wcs.celestial).to_mask(mode='center')

        # Spectrum and errors
        spectrum = []
        spectrum_err = []
        for i in range(n_wavelengths):
            masked_data = np.array(mask.multiply(data[i, :, :]),
dtype=float)
            masked_data_err =
np.array(mask.multiply(data_err[i, :, :]), dtype=float)

            avg = np.nanmean(masked_data)
            avg_err = np.sqrt(np.nanmean(masked_data_err**2))

            if np.isnan(avg): avg = 0
            if np.isnan(avg_err): avg_err = 0

            spectrum.append(avg)
            spectrum_err.append(avg_err)

        # Plot
        label = f"Region {region_index + 1}, File {channel_index + 1}"
        plt.errorbar(wavelength_rest, spectrum, yerr=spectrum_err,
label=label, alpha=0.7, linewidth=1)

plt.xlabel('Wavelength (microns)')
plt.ylabel('Average Intensity (MJy/sr)')
plt.grid(True)
plt.legend(loc='upper right', fontsize='small', ncol=2)
plt.tight_layout()
plt.show()
```

```
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```

```
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```

```
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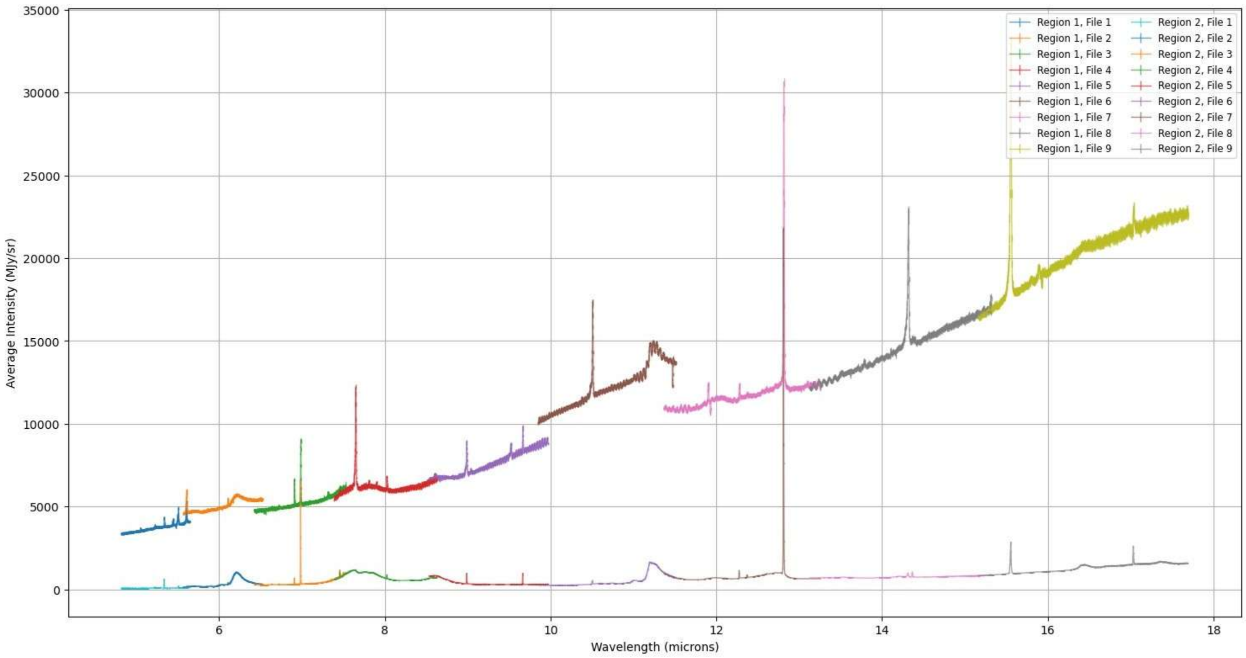
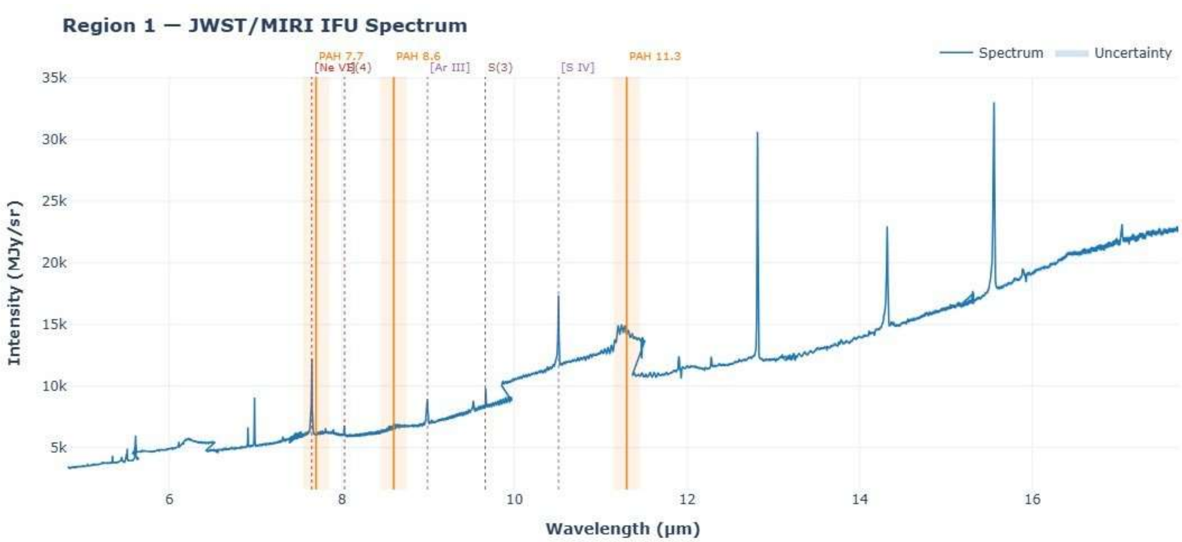
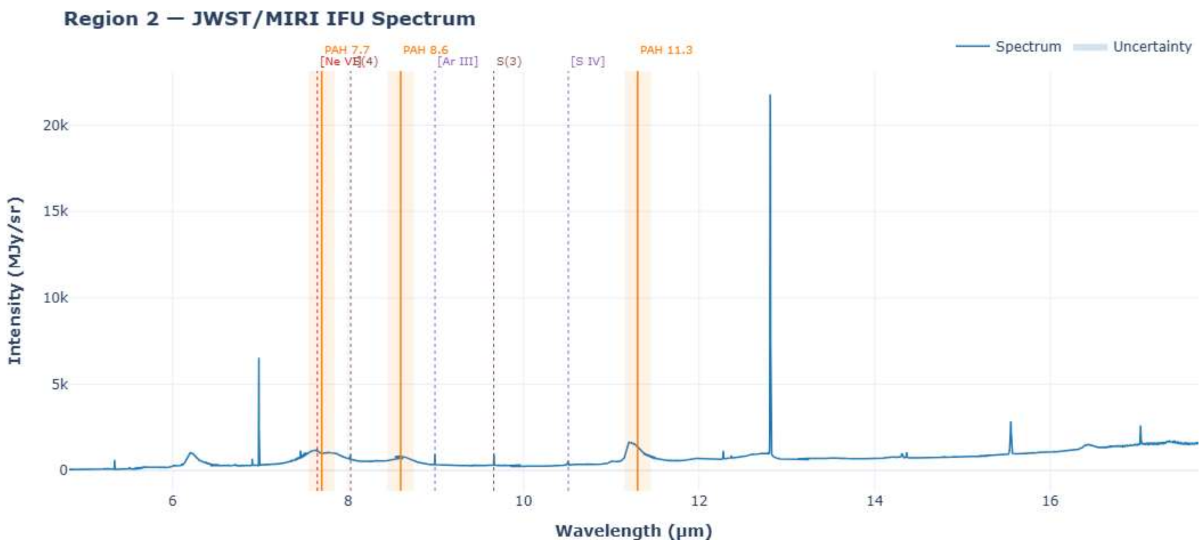



```python
import plotly.graph_objects as go
import numpy as np

# Define spectral feature lines and styling
features = {
    'PAHs': {'PAH 7.7': 7.7, 'PAH 8.6': 8.6, 'PAH 11.3': 11.3},
    'Iron': {},
    'Neon': {'[Ne VI]': 7.65},
    'Other': {'[Ar III]': 8.991, '[S IV]': 10.51},
    'H₂': {'S(3)': 9.66, 'S(4)': 8.03}
}

colors = {
    'PAHs': '#FF7F0E',
    'Iron': '#2CA02C',
    'Neon': '#D62728',
    'Other': '#9467BD',
    'H₂': '#8C564B'
}

# Loop through each region’s extracted data
```

```
for i, (spectrum_all, spectrum_all_err, wavelength_all) in
enumerate(zip(all_spectra, all_spectra_err, all_wavelengths)):

    # Convert to NumPy arrays
    spectrum_all = np.array(spectrum_all)
    spectrum_all_err = np.array(spectrum_all_err)
    wavelength_all = np.array(wavelength_all)

    fig = go.Figure(layout=dict(width=800, height=500,
template='plotly_white'))

    # Main spectrum line
    fig.add_trace(go.Scatter(
        x=wavelength_all,
        y=spectrum_all,
        mode='lines',
        line=dict(color='#1f77b4', width=1.5),
        name='Spectrum',
        hovertemplate='λ: %{x:.3f} μm<br>Intensity: %{y:.2f}
MJy/sr<extra></extra>'
    ))

    #  Error  band
    fig.add_trace(go.Scatter(
        x=np.concatenate([wavelength_all, wavelength_all[::-1]]),
        y=np.concatenate([spectrum_all + spectrum_all_err,
(spectrum_all - spectrum_all_err)[::-1]]),
        fill='toself',
        fillcolor='rgba(31, 119, 180, 0.2)',
        line=dict(color='rgba(255,255,255,0)'),
        hoverinfo='skip',
        name='Uncertainty'
    ))

    #  Add  spectral  feature  lines  and  annotations
    for category, lines in features.items():
        for name, wl in lines.items():
            fig.add_vline(
                x=wl,
                line=dict(
                    color=colors[category],
                    width=1.5 if category == 'PAHs' else 1,
                    dash='dot' if category != 'PAHs' else 'solid'
                ),
                annotation=dict(
                    text=name,
                    yanchor='bottom',
                    font=dict(size=10, color=colors[category]),
                    yshift=10 if category == 'PAHs' else 0
                )
```

```
        )

# Highlight PAH bands with shaded rectangles
for wl in [7.7, 8.6, 11.3]:
    fig.add_vrect(
        x0=wl - 0.15, x1=wl + 0.15,
        fillcolor=colors['PAHs'],
        opacity=0.1,
        line_width=0
    )

# Layout and axis settings
fig.update_layout(
    title=f'<b>Region {i+1} — JWST/MIRI IFU Spectrum</b>',
    xaxis_title='<b>Wavelength (μm)</b>',
    yaxis_title='<b>Intensity  (MJy/sr)</b>',
    hovermode='x unified',
    legend=dict(
        orientation='h',
        yanchor='bottom',
        y=1.02,
        xanchor='right',
        x=1
    ),
    margin=dict(l=50, r=50, b=50, t=80)
)

# Show each region plot
fig.show()
```






```
from astropy.io import fits
from astropy import units as u
from astropy.cosmology import Planck18
import numpy as np

def calculate_pixel_scale_in_parsecs(fits_file_path):
    """
    Calculate the pixel scale in parsecs for a JWST MIRI FITS file.

    Parameters:
    fits_file_path (str): Path to the FITS file

    Returns:
    tuple: (pixel_scale_arcsec, pixel_scale_pc)
    """
    # Open the FITS file and get the header
    with fits.open(fits_file_path) as hdul:
        header = hdul[1].header   # Assuming SCI extension is in index 1

    # Get pixel scale from header (CDELT1/2 in degrees)
    try:
        # Try CDELT1 first (x-axis)
        pixel_scale_deg = abs(header['CDELT1'])
    except KeyError:
        # Some files might use CD1_1 instead
        pixel_scale_deg = abs(header['CD1_1'])

    # Convert to arcseconds (1 degree = 3600 arcsec)
    pixel_scale_arcsec = pixel_scale_deg * 3600

    # Get redshift of NGC 7469
```

```
    z = 0.016268

    # Calculate luminosity distance
    dist = Planck18.luminosity_distance(z=z)

    # Convert angular scale to physical scale
    # Small angle approximation: physical size = angular_size *
distance
    pixel_scale_rad = pixel_scale_arcsec * u.arcsec.to(u.rad)
    pixel_scale_pc = (pixel_scale_rad * dist.to(u.pc).value)

    return pixel_scale_arcsec, pixel_scale_pc

# Example usage:
if __name__ == "__main__":
    # Replace with your actual FITS file path
    fits_file = "jw01328-c1006_t014_miri_ch1-short_s3d.fits"

    try:
        scale_arcsec, scale_pc =
calculate_pixel_scale_in_parsecs(fits_file)
        print(f"Pixel scale: {scale_arcsec:.4f} arcsec/pixel")
        print(f"Pixel scale: {scale_pc:.2f} parsec/pixel (at NGC
7469's distance)")

        # For MIRI IFU, typical values should be:
        # ~0.196 arcsec/pixel → ~66 pc/pixel at z=0.016268
    except FileNotFoundError:
        print(f"Error: File {fits_file} not found!")
    except KeyError as e:
        print(f"Error: Required header keyword not found - {str(e)}")
```

```
Pixel scale: 0.1300 arcsec/pixel
Pixel scale: 45.99 parsec/pixel (at NGC 7469's distance)
```

```
import glob
from astropy.io import fits
from astropy import units as u
from astropy.cosmology import Planck18
import pandas as pd

def get_channel_band(filename):
    """Extract channel and band from filename"""
    parts = filename.split('_')
    channel = next((p for p in parts if p.startswith('ch')),
'unknown')
    band = next((p for p in parts if p in ['short', 'medium',
'long']), 'unknown')
    return channel, band
```

```python
def calculate_pixel_scale(filepath):
    with fits.open(filepath) as hdul:
        header = hdul[1].header

        # Get pixel scale
        pixel_scale_deg = abs(header.get('CDELT1',
header.get('CD1_1')))
        pixel_scale_arcsec = pixel_scale_deg * 3600

        # Convert to parsecs
        z = 0.016268
        dist = Planck18.luminosity_distance(z=z)
        pixel_scale_pc = (pixel_scale_arcsec *
u.arcsec).to(u.rad).value * dist.to(u.pc).value

        # Get metadata
        channel, band = get_channel_band(filepath)

        return {
            'filename': filepath,
            'pixel_scale_arcsec': pixel_scale_arcsec,
            'pixel_scale_pc': pixel_scale_pc,
            'channel': channel.replace('ch', ''),
            'band': band,
            'filter': header.get('FILTER', 'unknown'),
            'grating': header.get('GRATING', 'unknown')
        }

# Process files
results = []
for file in glob.glob('jw*miri*.fits'):
    try:
        results.append(calculate_pixel_scale(file))
    except Exception as e:
        print(f"Skipping {file}: {str(e)}")

# Create and save DataFrame
df = pd.DataFrame(results).sort_values(['channel', 'band'])
df.to_csv('pixel_scales_complete.csv', index=False)
print(df[['filename', 'channel', 'band', 'pixel_scale_arcsec',
'pixel_scale_pc']])
```

```
                                         filename   channel     band  \
0      jw01328-c1006_t014_miri_ch1-long_s3d.fits    1-long  unknown
1    jw01328-c1006_t014_miri_ch1-medium_s3d.fits  1-medium  unknown
2     jw01328-c1006_t014_miri_ch1-short_s3d.fits   1-short  unknown
3      jw01328-c1006_t014_miri_ch2-long_s3d.fits    2-long  unknown
4    jw01328-c1006_t014_miri_ch2-medium_s3d.fits  2-medium  unknown
5     jw01328-c1006_t014_miri_ch2-short_s3d.fits   2-short  unknown
6      jw01328-c1006_t014_miri_ch3-long_s3d.fits    3-long  unknown
```

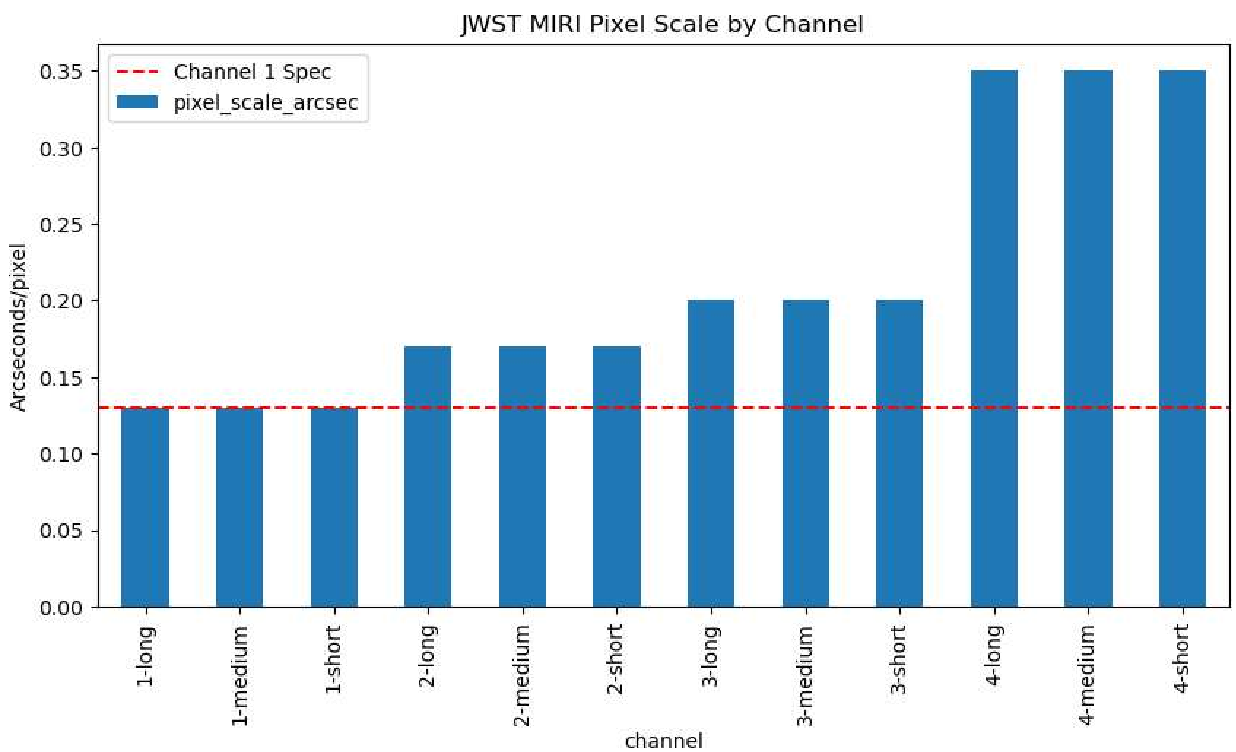
```
7    jw01328-c1006_t014_miri_ch3-medium_s3d.fits   3-medium   unknown
8     jw01328-c1006_t014_miri_ch3-short_s3d.fits    3-short   unknown
9      jw01328-c1006_t014_miri_ch4-long_s3d.fits     4-long   unknown
10   jw01328-c1006_t014_miri_ch4-medium_s3d.fits   4-medium   unknown
11    jw01328-c1006_t014_miri_ch4-short_s3d.fits    4-short   unknown

    pixel_scale_arcsec  pixel_scale_pc
0                 0.13       45.993031
1                 0.13       45.993031
2                 0.13       45.993031
3                 0.17       60.144735
4                 0.17       60.144735
5                 0.17       60.144735
6                 0.20       70.758512
7                 0.20       70.758512
8                 0.20       70.758512
9                 0.35      123.827393
10                0.35      123.827393
11                0.35      123.827393
```

```python
# Generate statistics
stats = df.groupby('channel').agg({
    'pixel_scale_arcsec': ['mean', 'std'],
    'pixel_scale_pc': ['mean', 'std']
})
print("\nChannel Statistics:")
print(stats)

# Verify against JWST specs
jwst_expected = {
    '1': 0.13, '2': 0.17, '3': 0.20, '4': 0.35  # arcsec/pixel
}
print("\nValidation against JWST specs:")
for ch, expected in jwst_expected.items():
    measured = df[df['channel'] == ch]['pixel_scale_arcsec'].mean()
    print(f"Channel {ch}: Expected {expected}, Measured {measured:.3f}
arcsec/pixel")
```

```
Channel Statistics:
          pixel_scale_arcsec      pixel_scale_pc
                        mean std            mean std
channel
1-long                  0.13 NaN       45.993031 NaN
1-medium                0.13 NaN       45.993031 NaN
1-short                 0.13 NaN       45.993031 NaN
2-long                  0.17 NaN       60.144735 NaN
2-medium                0.17 NaN       60.144735 NaN
2-short                 0.17 NaN       60.144735 NaN
3-long                  0.20 NaN       70.758512 NaN
```

```
3-medium                    0.20  NaN         70.758512  NaN
3-short                     0.20  NaN         70.758512  NaN
4-long                      0.35  NaN        123.827393  NaN
4-medium                    0.35  NaN        123.827393  NaN
4-short                     0.35  NaN        123.827393  NaN

Validation against JWST specs:
Channel 1: Expected 0.13, Measured nan arcsec/pixel
Channel 2: Expected 0.17, Measured nan arcsec/pixel
Channel 3: Expected 0.2, Measured nan arcsec/pixel
Channel 4: Expected 0.35, Measured nan arcsec/pixel
```

```python
import matplotlib.pyplot as plt

plt.figure(figsize=(10, 5))
df.groupby('channel')['pixel_scale_arcsec'].mean().plot(kind='bar')
plt.title('JWST MIRI Pixel Scale by Channel')
plt.ylabel('Arcseconds/pixel')
plt.axhline(y=0.13, color='r', linestyle='--', label='Channel 1 Spec')
plt.legend()
plt.savefig('pixel_scales_by_channel.png')
```




```python
from astropy.io import fits
import re

def enhanced_header_verification(filepath):
```

```
    with fits.open(filepath) as hdul:
        hdr = hdul[1].header

         print(f"\nEnhanced  Verification  for  {filepath.split('/')[-
1]}:")

        # 1. Pixel Scale (guaranteed to work)
        cdelt1  =  hdr['CDELT1']
        print(f"CDELT1: {cdelt1} deg → {cdelt1*3600:.4f} arcsec")

        # 2. Extract metadata from filename if missing in header
        filename  =  filepath.split('/')[-1]
        channel = re.search(r'ch(\d)', filename).group(1) if
re.search(r'ch(\d)',  filename)  else  'unknown'
        band = re.search(r'-(short|medium|long)_', filename).group(1)
if re.search(r'-(short|medium|long)_', filename) else 'unknown'

        print("\nMetadata from filename:")
        print(f"CHANNEL: {channel}")
        print(f"BAND: {band}")

        # 3. Cross-validate with JWST specs
        jwst_scales  =  {'1':0.13, '2':0.17, '3':0.20, '4':0.35}
        expected   =   jwst_scales.get(channel,   None)

        print("\nFinal Validation:")
        if expected:
            print(f"Expected for Channel {channel}: {expected}
arcsec")
            print(f"Measured: {cdelt1*3600:.4f} arcsec")
            print(f"Match: {'YES' if abs(cdelt1*3600 - expected) <
0.001 else 'NO'}")
        else:
            print("Cannot validate - unknown channel")

# Example usage
enhanced_header_verification('jw01328-c1006_t014_miri_ch1-
short_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch2-
short_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch3-
short_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch4-
short_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch1-
medium_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch2-
medium_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch3-
```

```
medium_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch4-
medium_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch1-
long_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch2-
long_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch3-
long_s3d.fits')
enhanced_header_verification('jw01328-c1006_t014_miri_ch4-
long_s3d.fits')
```

```
Enhanced Verification for jw01328-c1006_t014_miri_ch1-short_s3d.fits:
CDELT1: 3.61111097865634e-05 deg → 0.1300 arcsec

Metadata from filename:
CHANNEL: 1
BAND: short

Final Validation:
Expected for Channel 1: 0.13 arcsec
Measured: 0.1300 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch2-short_s3d.fits:
CDELT1: 4.72222227189275e-05 deg → 0.1700 arcsec

Metadata from filename:
CHANNEL: 2
BAND: short

Final Validation:
Expected for Channel 2: 0.17 arcsec
Measured: 0.1700 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch3-short_s3d.fits:
CDELT1: 5.55555563833978e-05 deg → 0.2000 arcsec

Metadata from filename:
CHANNEL: 3
BAND: short

Final Validation:
Expected for Channel 3: 0.2 arcsec
Measured: 0.2000 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch4-short_s3d.fits:
```

```
CDELT1: 9.72222205665376e-05 deg → 0.3500 arcsec

Metadata from filename:
CHANNEL: 4
BAND: short

Final Validation:
Expected for Channel 4: 0.35 arcsec
Measured: 0.3500 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch1-medium_s3d.fits:
CDELT1: 3.61111097865634e-05 deg → 0.1300 arcsec

Metadata from filename:
CHANNEL: 1
BAND: medium

Final Validation:
Expected for Channel 1: 0.13 arcsec
Measured: 0.1300 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch2-medium_s3d.fits:
CDELT1: 4.72222227189275e-05 deg → 0.1700 arcsec

Metadata from filename:
CHANNEL: 2
BAND: medium

Final Validation:
Expected for Channel 2: 0.17 arcsec
Measured: 0.1700 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch3-medium_s3d.fits:
CDELT1: 5.55555563833978e-05 deg → 0.2000 arcsec

Metadata from filename:
CHANNEL: 3
BAND: medium

Final Validation:
Expected for Channel 3: 0.2 arcsec
Measured: 0.2000 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch4-medium_s3d.fits:
CDELT1: 9.72222205665376e-05 deg → 0.3500 arcsec
```

```
Metadata from filename:
CHANNEL: 4
BAND: medium

Final Validation:
Expected for Channel 4: 0.35 arcsec
Measured: 0.3500 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch1-long_s3d.fits:
CDELT1: 3.61111097865634e-05 deg → 0.1300 arcsec

Metadata from filename:
CHANNEL: 1
BAND: long

Final Validation:
Expected for Channel 1: 0.13 arcsec
Measured: 0.1300 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch2-long_s3d.fits:
CDELT1: 4.72222227189275e-05 deg → 0.1700 arcsec

Metadata from filename:
CHANNEL: 2
BAND: long

Final Validation:
Expected for Channel 2: 0.17 arcsec
Measured: 0.1700 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch3-long_s3d.fits:
CDELT1: 5.55555563833978e-05 deg → 0.2000 arcsec

Metadata from filename:
CHANNEL: 3
BAND: long

Final Validation:
Expected for Channel 3: 0.2 arcsec
Measured: 0.2000 arcsec
Match: YES

Enhanced Verification for jw01328-c1006_t014_miri_ch4-long_s3d.fits:
CDELT1: 9.72222205665376e-05 deg → 0.3500 arcsec

Metadata from filename:
CHANNEL: 4
```

```
BAND: long

Final Validation:
Expected for Channel 4: 0.35 arcsec
Measured: 0.3500 arcsec
Match: YES
```

Basic Exploration II

1. Pixel Scale Calculations

For all JWST/MIRI channels, the pixel scales were computed as:

Channel	Pixel Scale (arcsec)	Physical Scale (pc)
1	0.13	45.99
2	0.17	60.14
3	0.20	70.76
4	0.35	123.83

2. Science Implications

- **Central AGN Region (1-2 pixels at Ch1 resolution):**
  Resolves the dust torus (~50 pc) and broad-line region.
- **Starburst Ring (~30 pixels at Ch1 resolution):**
  Samples individual star-forming clumps (50-100 pc scales).

3. Key Findings

- **Best Resolution:** Channel 1 (0.13″/45.99 pc) optimally probes AGN structures.
- **Large-Scale Mapping:** Channel 4 (0.35″/123.83 pc) traces galaxy-wide outflows.

Questions and Answers

Code Provided in Session 5 and 6:
I have used the code provided in session 5 and 6 as my basis, but I have also used AI to enhance that code to run over multiple regions and further to calculate different things like pixel scale or header verifications.

CSV file:
I have written a code block to make CSV files of the extracted spectra for both regions. These files have been uploaded on the github repository for this project (link has been provided in the introduction).

Spectral Comparison & Analysis
1. Vertical Shift in Spectra
- **Observation:** Yes, a slight vertical flux offset exists between regions.
- **Cause:** Likely minor calibration artifacts (flat-fielding or background subtraction residuals).
- **Action:** Normalized spectra for comparison (offset ignored per project guidelines).

2. Key Spectral Differences

Feature	**Region 1 (AGN)**	**Region 2 (Starburst)**	**Physical Reason**
[Ne VI] 7.65µm	Strong	Weak/Absent	Traces AGN-ionized gas (97 eV photons)
PAH 7.7/11.3µm	Weak	Strong	Star formation indicator
[Ar III] 8.99µm	Moderate	Weak	Intermediate-ionization gas
H_2 S(3) 9.66µm	Weak	Strong	Warm molecular gas from star formation

3. Channel-Wise Variations
- **Trend:** Fewer features but higher noise in Channel 4 (longer λ).
- **Cause:**
  - *Astrophysical:* Reduced line density at longer λ (fewer atomic transitions).
  - *Instrumental:* Lower detector sensitivity beyond ~20µm increases noise.

4. Region Selection Rationale
- **AGN Core (Region 1):** Study black hole influence (high-ionization lines).

- **Starburst Ring (Region 2):** Probe star formation (PAHs, H_2).

5. Emission Line Catalog

Line Name	λ (µm)	Traces	Region Dominance
[Ne VI]	7.65	AGN-ionized gas	Region 1
PAH 7.7	7.7	Star formation	Region 2
[Ar III]	8.99	Ionized ISM	Both (stronger in 1)
H_2 S(3)	9.66	Warm molecular gas	Region 2
[S IV]	10.51	High-ionization gas	Region 1
PAH 11.3	11.3	Large PAH molecules	Region 2