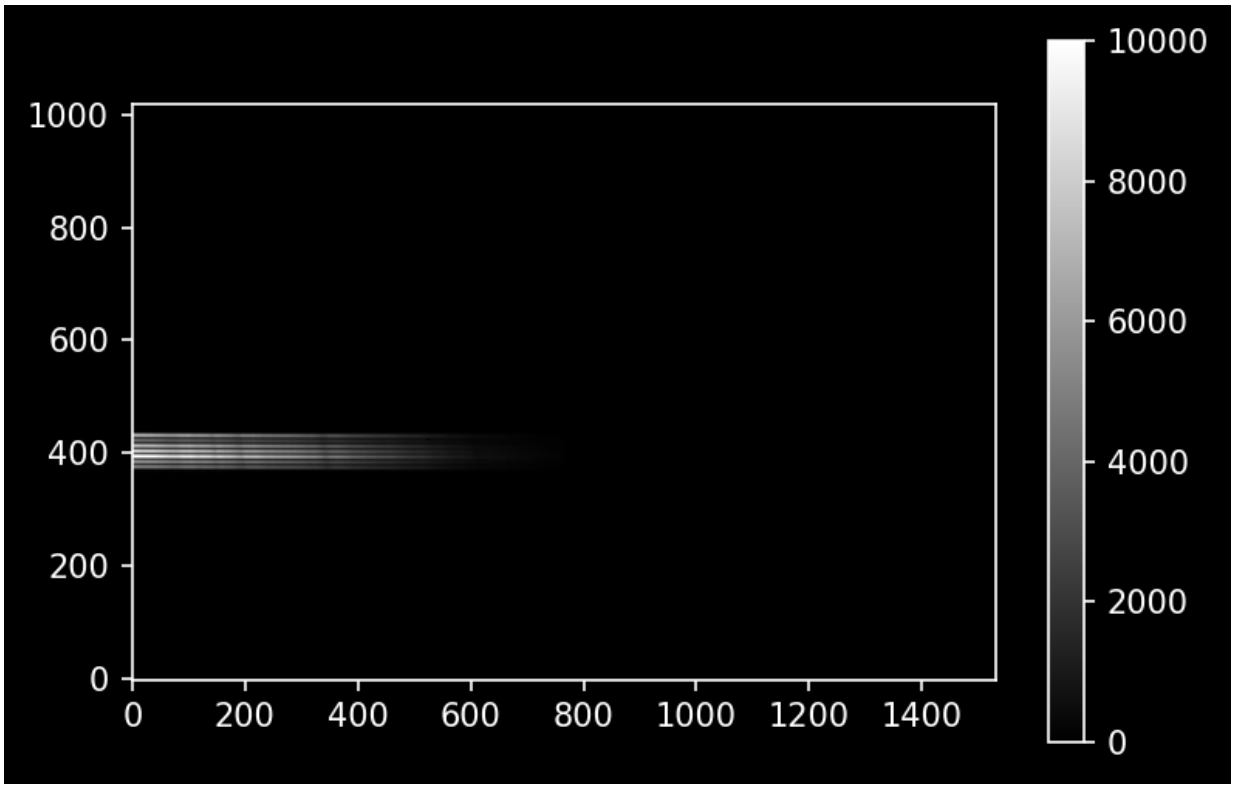
In [1]:
```
import numpy as np
import os
from astropy.io import fits
from astropy import units as u
from astropy.modeling.polynomial import Polynomial1D
from astropy.modeling.models import Gaussian1D, Linear1D
from astropy.modeling.fitting import LinearLSQFitter
from IPython.display import Image
# astroquery provides an interface to the NIST atomic line database
from astroquery.nist import Nist
from IPython.display import Image
import glob

from PIL import Image
import numpy as np
import pylab as pl
pl.style.use('dark_background')

from astropy.modeling.polynomial import Polynomial1D
from astropy.modeling.fitting import LinearLSQFitter

from astropy.modeling.models import Gaussian1D
from astropy.modeling.fitting import LevMarLSQFitter
```

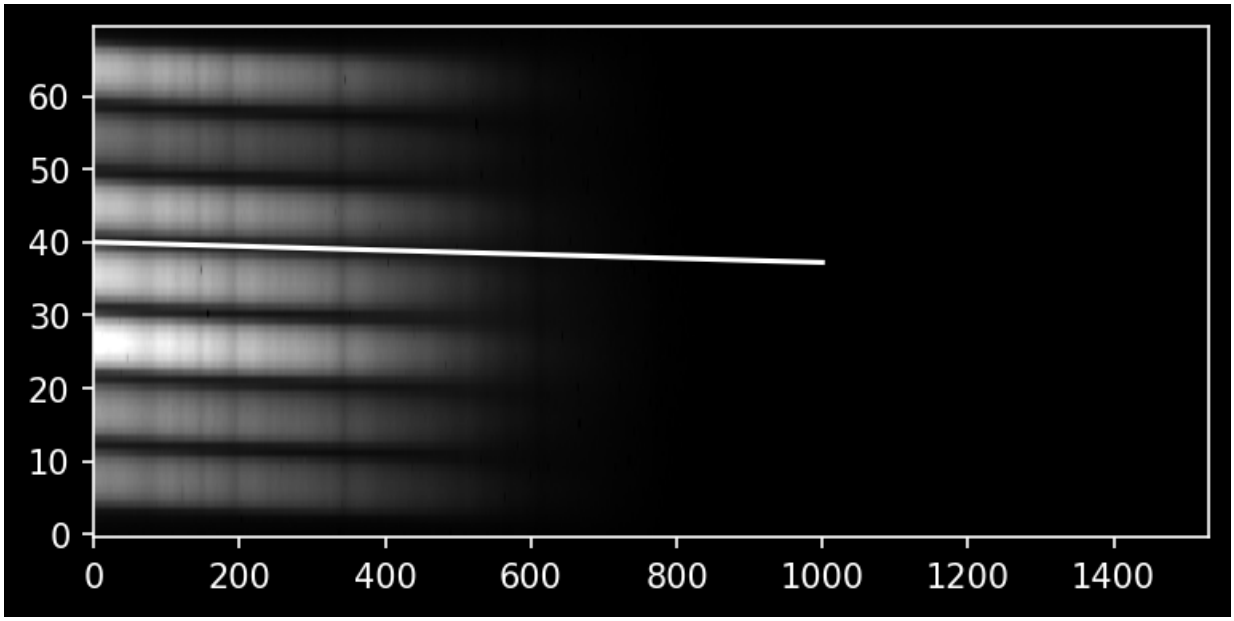
In [2]:
```
jupiter_10s_image_data =  (np.mean([fits.getdata(x) for x in glob.glob("\\Users\\
                       axis=0)
             - np.mean([fits.getdata(x)
                        for x in glob.glob("\\Users\\Sydnee O'Donnell\\OneDrive\
                       axis=0)
            )

jupiter_array = np.array(jupiter_10s_image_data)
jupiter_array = jupiter_array - np.median(jupiter_10s_image_data)
```

In [3]:
```
%matplotlib inline
import pylab as pl
pl.rcParams['image.origin'] = 'lower'
pl.rcParams['figure.dpi'] = 150
pl.matplotlib.style.use('dark_background') # Optional!
pl.imshow(jupiter_10s_image_data, cmap='gray', vmax=0, vmin=10000)
pl.colorbar()
```

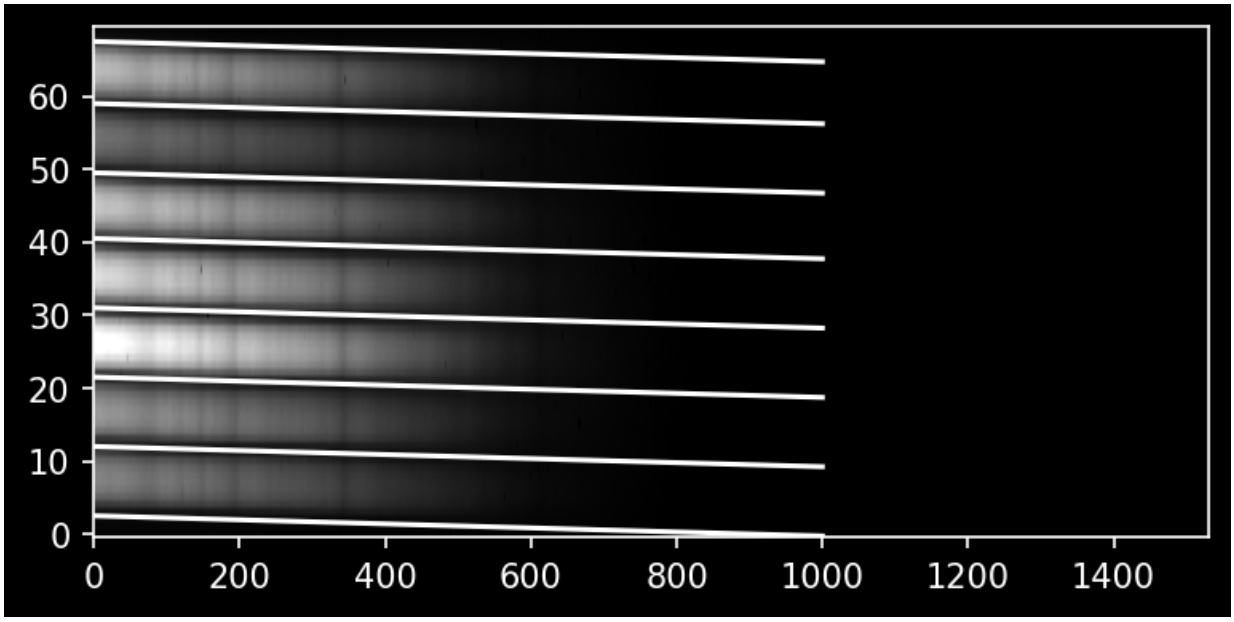
Out[3]: <matplotlib.colorbar.Colorbar at 0x22af7415070>



In [4]:
```
dy = -2.5
dx = 900
slope = dy/dx

ystart = 369
yend = 439

pl.imshow(jupiter_array[ystart:yend,:], cmap='gray', vmax=10000, vmin=0)
pl.plot([0,1000], 40 + np.array([0,1000]) * slope, color='w')
pl.gca().set_aspect(10)
```



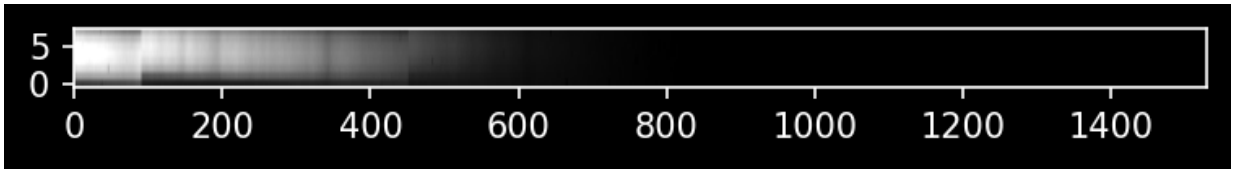
In [5]:
```
intertrace_cuts = np.array([2.5, 12, 21.5, 31, 40.5, 49.5, 59, 67.5])
pl.imshow(jupiter_array[ystart:yend,:], cmap='gray', vmax=10000, vmin=0)
pl.plot([0,1000], intertrace_cuts + np.array([0,1000])[:,None] * slope, color='w'
pl.gca().set_aspect(10)
```



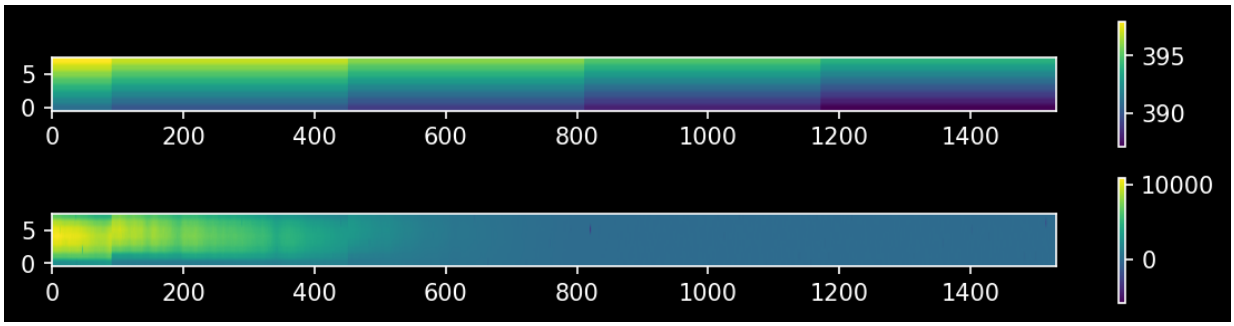
In [6]:
```
npixels_to_cut = 4 # very conservative - we'll see why below
xvals = np.arange(jupiter_array.shape[1])
trace_center = ystart+(intertrace_cuts[2] + intertrace_cuts[3])/2 + xvals * slope
cutout_trace = np.array([jupiter_array[int(yval)-npixels_to_cut:int(yval)+npixels
                         for yval, ii in zip(trace_center, xvals)]).T
cutout_trace.shape
```

Out[6]:
```
(8, 1530)
```

In [7]:
```
pl.imshow(cutout_trace, cmap='gray', vmax=10000, vmin=0)
pl.gca().set_aspect(10);
```

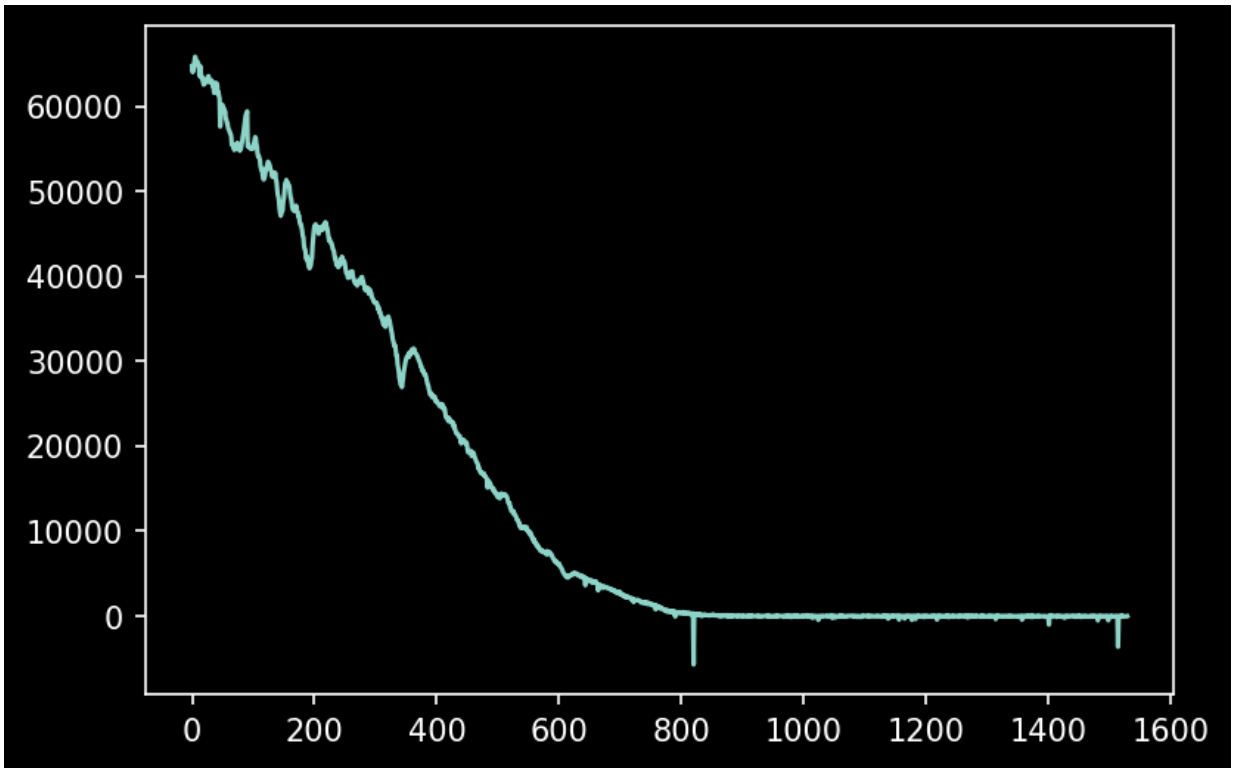


In [8]:
```
# to get the y-axis values corresponding to each part of our cutout trace, we do
yaxis_full = np.arange(jupiter_array.shape[0])
yaxis = np.array([yaxis_full[int(yval)-npixels_to_cut:int(yval)+npixels_to_cut]
                  for yval, ii in zip(trace_center, xvals)]).T

pl.figure(figsize=(8,2))
im = pl.subplot(2,1,1).imshow(yaxis)
pl.colorbar(mappable=im)
pl.gca().set_aspect(10);
im = pl.subplot(2,1,2).imshow(cutout_trace)
pl.colorbar(mappable=im)
pl.gca().set_aspect(10);
pl.tight_layout();
```

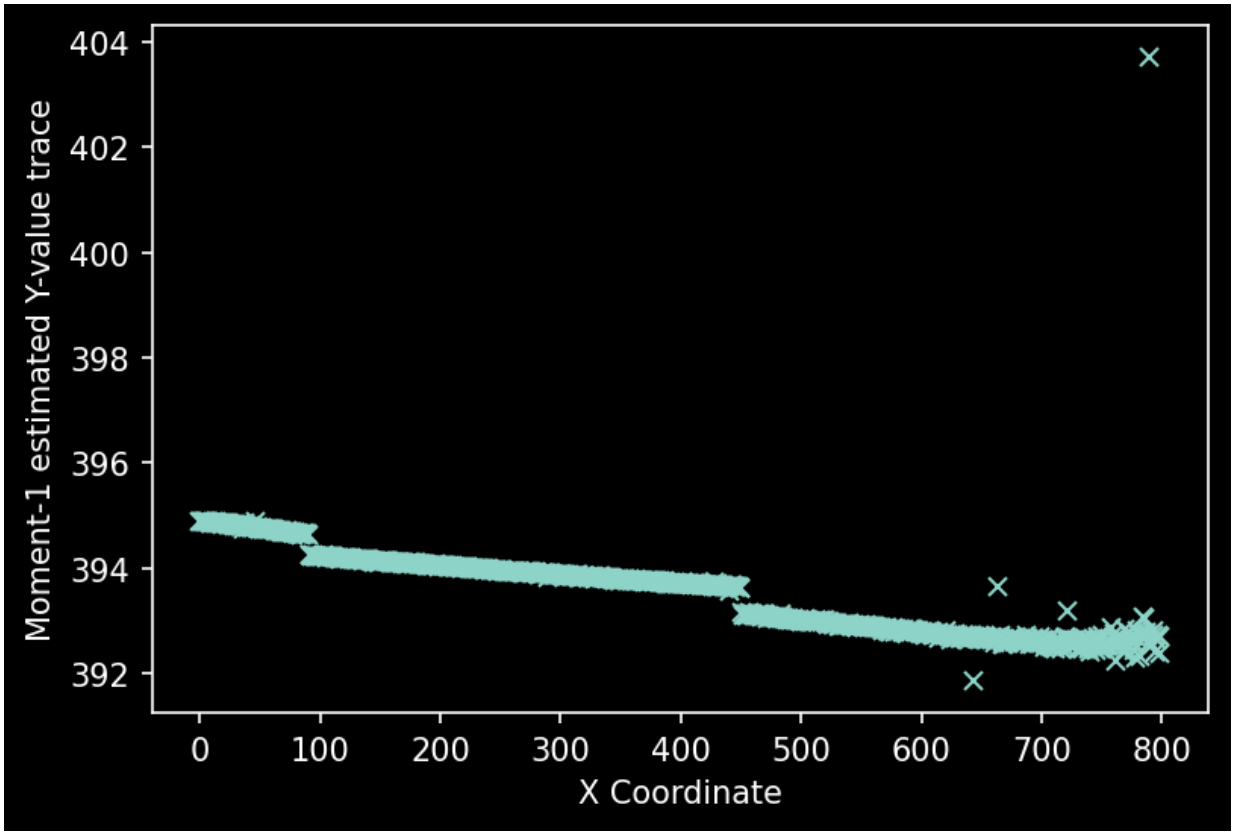


In [9]:
```
pl.plot(cutout_trace.sum(axis=0))
```

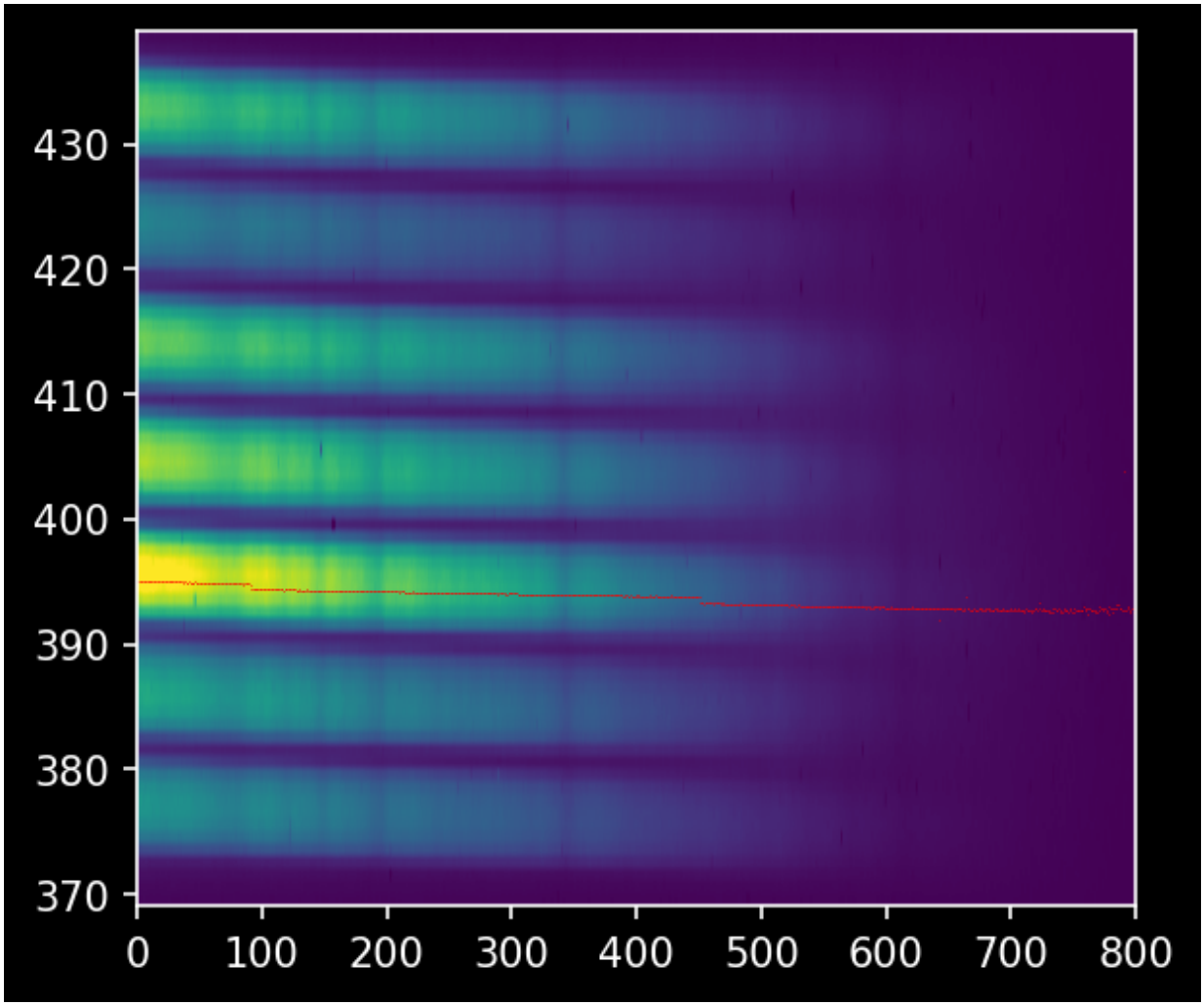
Out[9]:
```
[<matplotlib.lines.Line2D at 0x22af792daf0>]
```



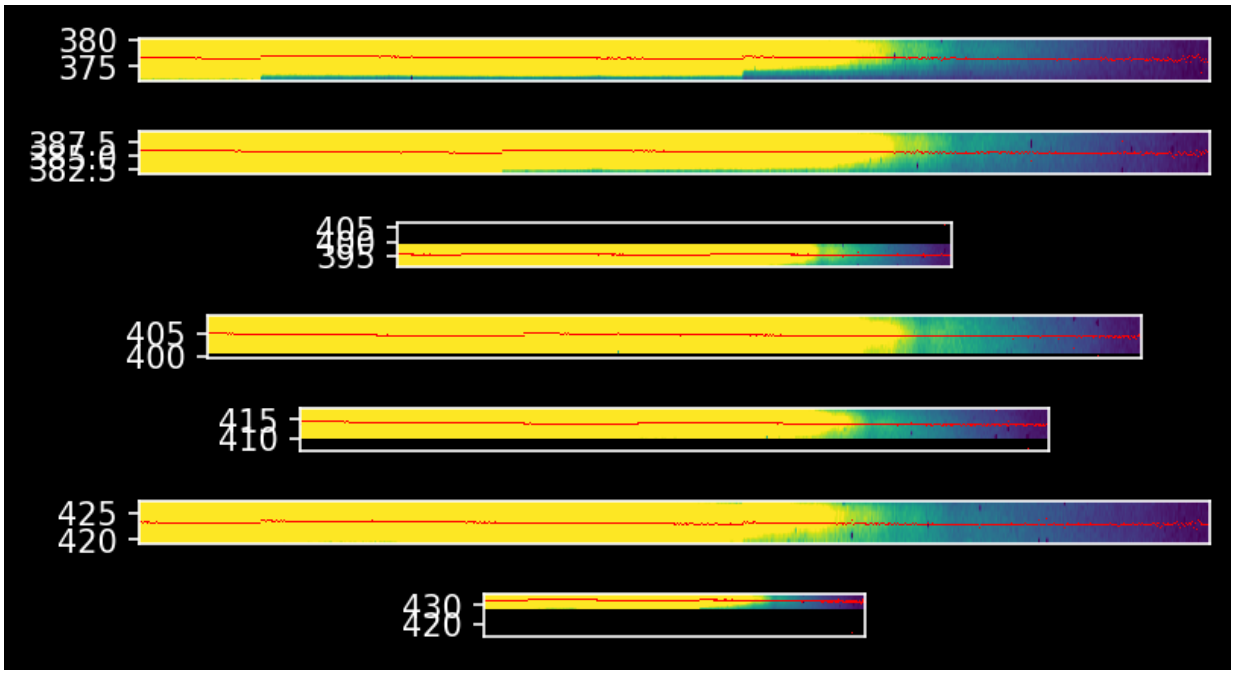
In [10]:
```
# moment 1 is the data-weighted average of the Y-axis coordinates
xend = 800
weighted_yaxis_values = np.average(yaxis[:,:xend], axis=0,
                                   weights=cutout_trace[:,:xend])
_=pl.plot(xvals[:xend], weighted_yaxis_values, 'x')
_=pl.xlabel("X Coordinate")
_=pl.ylabel("Moment-1 estimated Y-value trace")
```



In [11]:
```
# we need to use the 'extent' keyword to have the axes correctly labeled
_=pl.imshow(jupiter_array[ystart:yend, :xend],
            extent=[0,xend,ystart,yend], vmax=10000, vmin=0)
_=pl.gca().set_aspect(10) # we stretch the image out by 10x in the y-direction
_=pl.plot(xvals[:xend], weighted_yaxis_values[:xend], 'r,', alpha=0.5)
_=pl.axis((0,xend,ystart,yend))
```

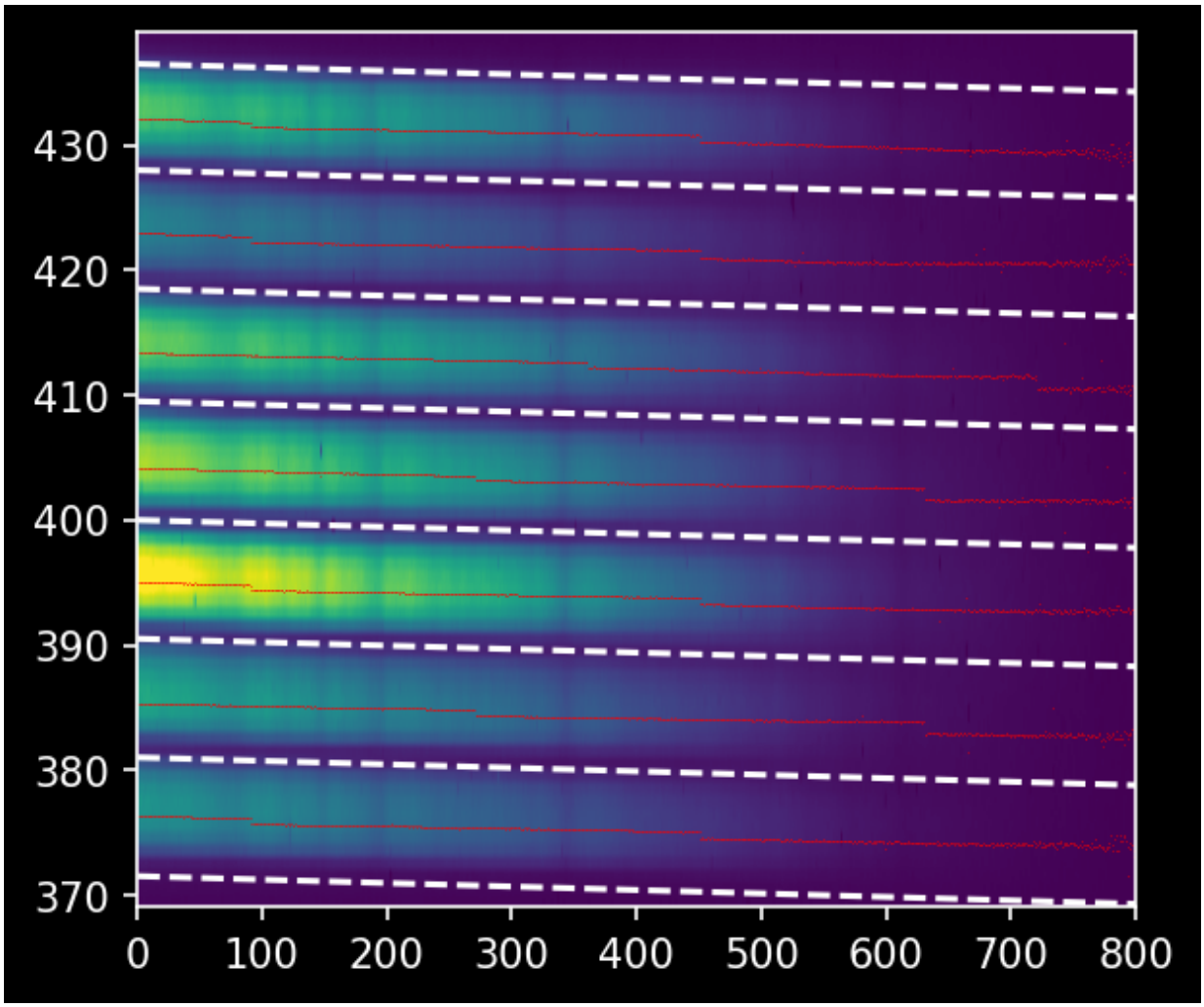


In [12]:
```
pl.figure(figsize=(8,3))
traces = {}
for trace_index in range(len(intertrace_cuts)-1):
    yoffset = ystart + (intertrace_cuts[trace_index] + intertrace_cuts[trace_inde
    trace_center = yoffset + slope * xvals

    cutout_trace = np.array([jupiter_array[int(yval)-npixels_to_cut:int(yval)+npi
                         for yval, ii in zip(trace_center, xvals)]).T
    yaxis = np.array([yaxis_full[int(yval)-npixels_to_cut:int(yval)+npixels_to_cu
                      for yval, ii in zip(trace_center, xvals)]).T
    weighted_yaxis_values = np.average(yaxis[:,:xend], axis=0,
                                       weights=cutout_trace[:,:xend])

    # it takes a little mental gymnastics to get to this, but: to show the trace
    # we need to calculate the local version
    local_weighted_yaxis_values = np.average(np.arange(npixels_to_cut*2)[:,None]
                                             axis=0, weights=cutout_trace[:,:xend

    traces[trace_index] = weighted_yaxis_values
    ax = pl.subplot(7, 1, trace_index+1)
    ax.imshow(cutout_trace[:,:xend], extent=[0, xend, yoffset-npixels_to_cut, yof
    ax.plot(xvals[:xend], yoffset - npixels_to_cut + local_weighted_yaxis_values[
    ax.set_aspect(4)
    ax.set_xticks([])
pl.tight_layout()
```



In [13]:
```
# then we can plot the "global" version here
pl.imshow(jupiter_array[ystart:yend, :xend],
          extent=[0,xend,ystart,yend], vmax=10000, vmin=0)
pl.plot([0,xend], ystart + intertrace_cuts + np.array([0,xend])[:,None] * slope,
pl.gca().set_aspect(10)
for trace in traces.values():
    pl.plot(xvals[:xend], trace[:xend], 'r,', alpha=0.5)
pl.axis((0,xend,ystart,yend))
```

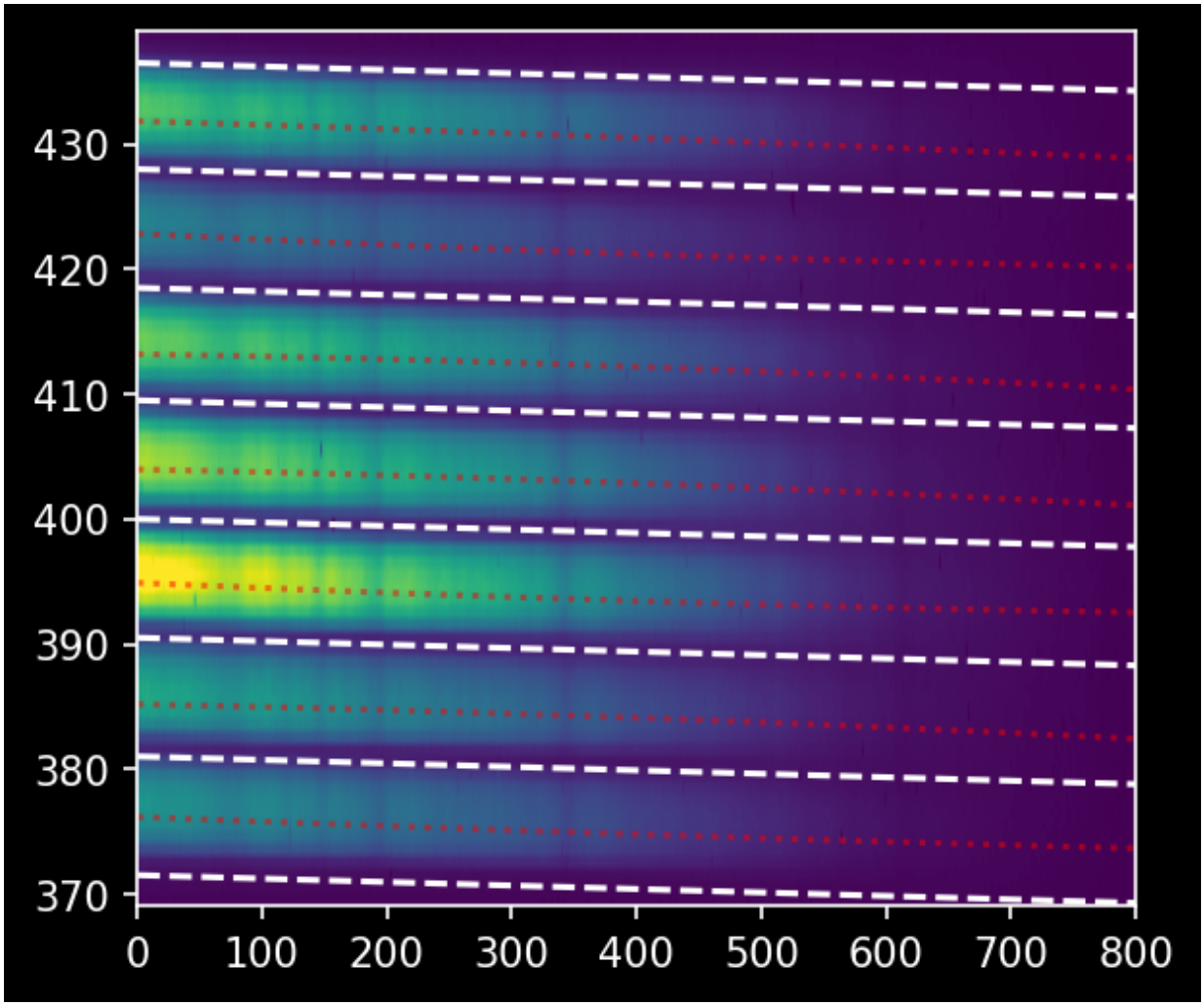
Out[13]: (0.0, 800.0, 369.0, 439.0)



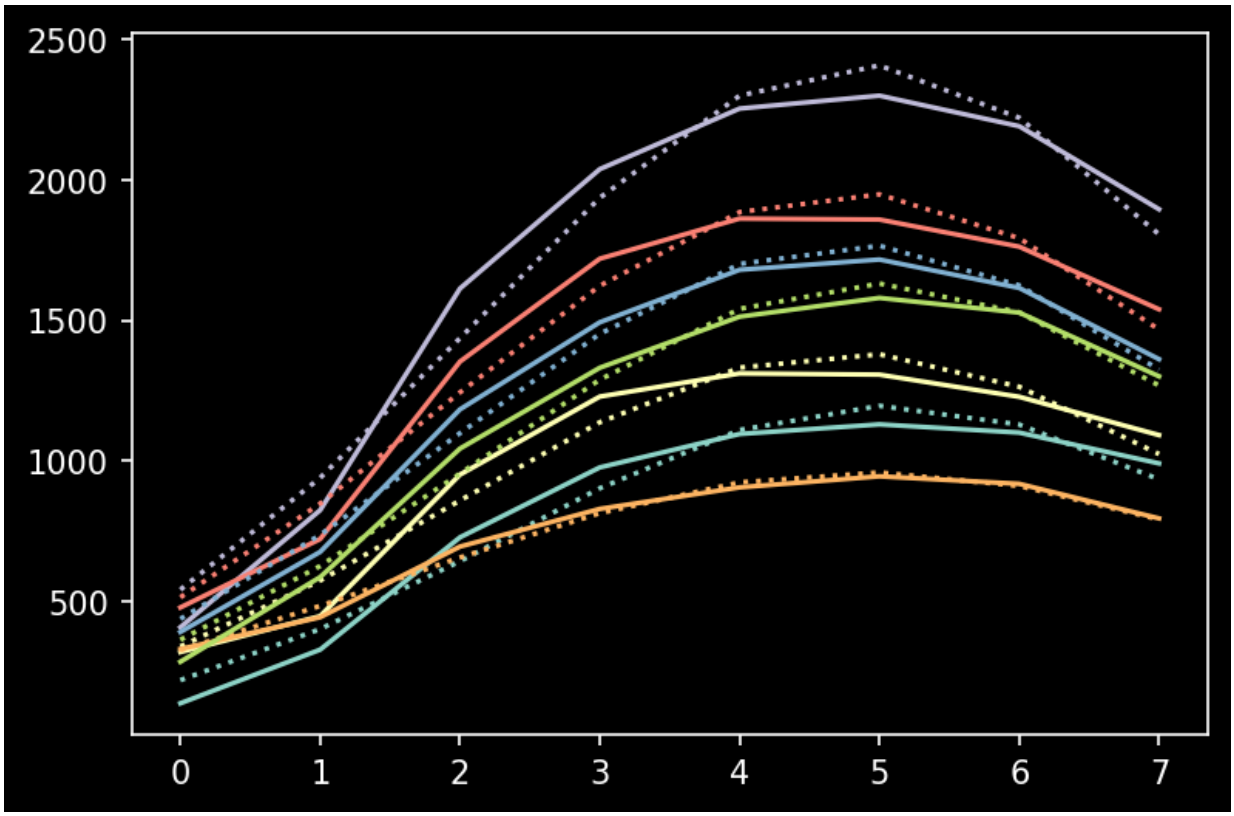
In [14]:
```
# We fit a 2rd-order polynomial
polymodel = Polynomial1D(degree=2)
linfitter = LinearLSQFitter()
fitted_polymodels = {index: linfitter(polymodel, xvals[:xend], weighted_yaxis_val
                     for index, weighted_yaxis_values in traces.items()}
```

In [15]:
```
pl.imshow(jupiter_array[ystart:yend, :xend],
          extent=[0,xend,ystart,yend],
          vmin=0, vmax=10000,
         )
pl.plot([0,xend], ystart + intertrace_cuts + np.array([0,xend])[:,None] * slope,
pl.gca().set_aspect(10)
for tracefit in fitted_polymodels.values():
    pl.plot(xvals[:xend], tracefit(xvals[:xend]), 'r:', alpha=0.5)
pl.axis((0,xend,ystart,yend))
```

Out[15]: (0.0, 800.0, 369.0, 439.0)



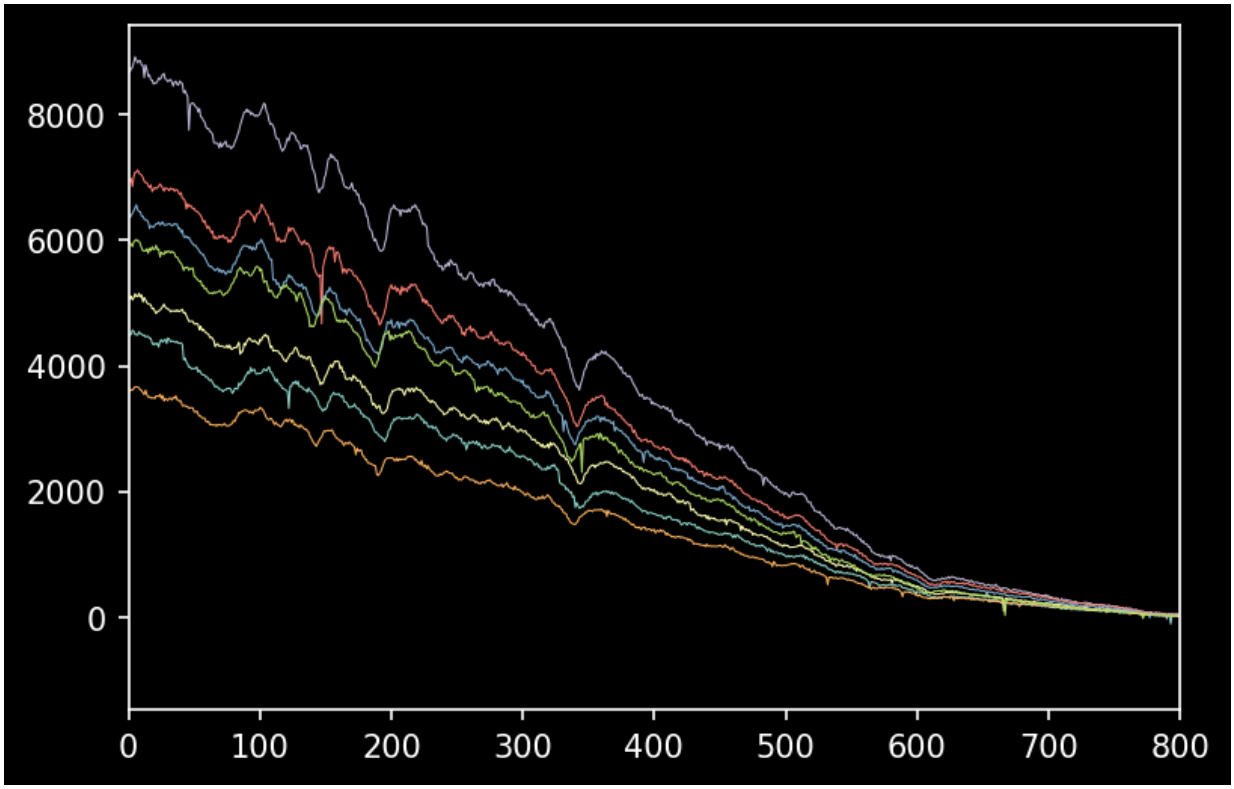
In [16]:
```
lmfitter = LevMarLSQFitter()
guess = Gaussian1D(amplitude=160, mean=0, stddev=5)
npixels_to_cut_trace = 4

for trace_index, polymodel_trace in fitted_polymodels.items():
    trace_center = polymodel_trace(xvals)

    cutout_trace = np.array([jupiter_array[int(yval)-npixels_to_cut_trace:int(yva
                        for yval, ii in zip(trace_center, xvals)]).T

    trace_profile = cutout_trace.mean(axis=1)
    trace_profile_xaxis = np.arange(len(trace_profile))
    fitted_trace_profile = lmfitter(model=guess, x=trace_profile_xaxis, y=trace_p
    model_trace_profile = fitted_trace_profile(trace_profile_xaxis)

    line, = pl.plot(trace_profile, label=trace_index)
    pl.plot(trace_profile_xaxis, model_trace_profile, color=line.get_color(), lin
```



In [17]:
```
spectra = {}
for trace_index, polymodel_trace in fitted_polymodels.items():
    trace_center = polymodel_trace(xvals)

    cutout_trace = np.array([jupiter_array[int(yval)-npixels_to_cut_trace:int(yva
                        for yval, ii in zip(trace_center, xvals)]).T

    trace_profile = cutout_trace.mean(axis=1)
    trace_profile_xaxis = np.arange(len(trace_profile))
    fitted_trace_profile = lmfitter(model=guess, x=trace_profile_xaxis, y=trace_p
    model_trace_profile = fitted_trace_profile(trace_profile_xaxis)

    trace_avg_spectrum = np.array([np.average(
            jupiter_array[int(yval)-npixels_to_cut:int(yval)+npixels_to_cut, ii],
            weights=trace_profile)
                                for yval, ii in zip(trace_center, xvals)])
    spectra[trace_index] = trace_avg_spectrum
```

In [18]:
```
for index in spectra:
    pl.plot(spectra[index], linewidth=0.5)
pl.xlim(0,800)
```

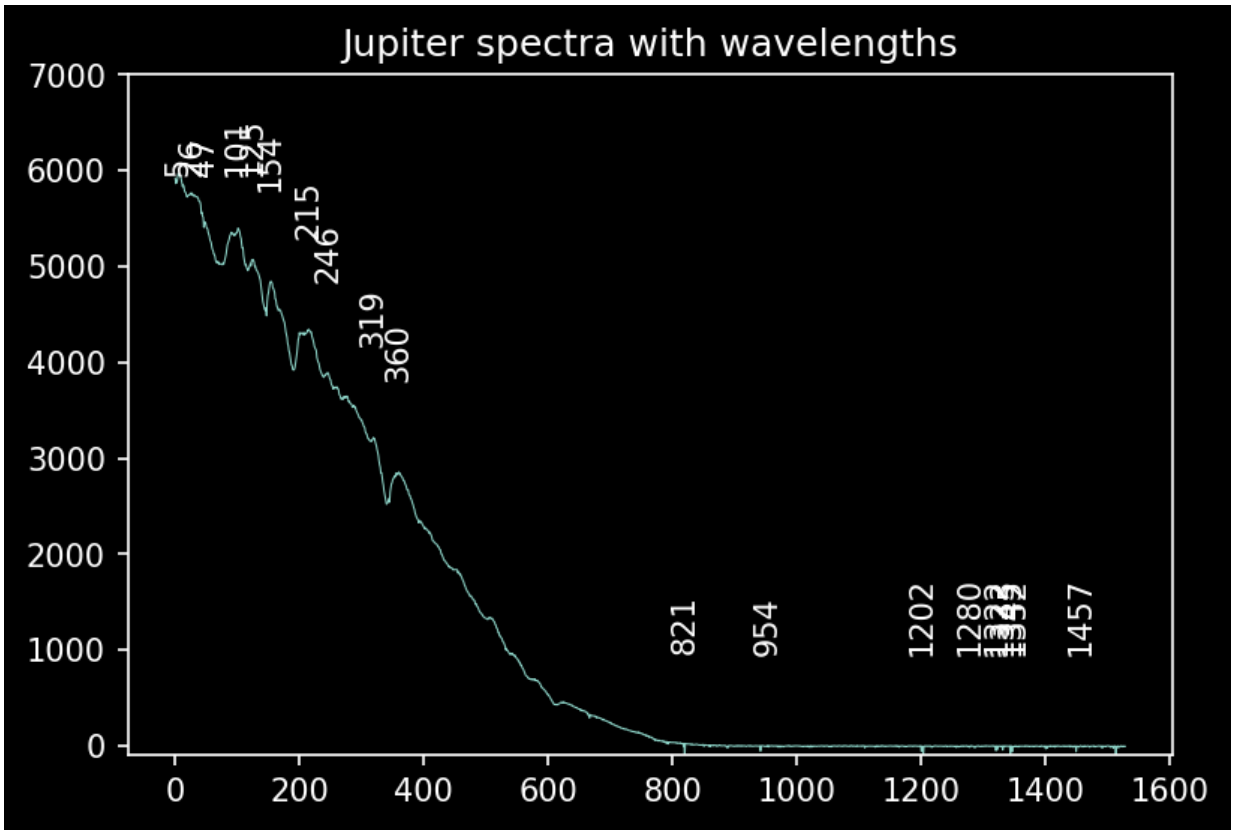
Out[18]: (0.0, 800.0)



In [19]:
```
fitted_polymodels
```

Out[19]:
```
{0: <Polynomial1D(2, c0=376.15424871, c1=-0.00379299, c2=0.00000082)>,
 1: <Polynomial1D(2, c0=385.17841428, c1=-0.00194809, c2=-0.00000189)>,
 2: <Polynomial1D(2, c0=394.89094474, c1=-0.00428583, c2=0.00000166)>,
 3: <Polynomial1D(2, c0=403.96841129, c1=-0.00191925, c2=-0.00000208)>,
 4: <Polynomial1D(2, c0=413.19331433, c1=-0.0014969, c2=-0.00000251)>,
 5: <Polynomial1D(2, c0=422.83141761, c1=-0.00475088, c2=0.00000182)>,
 6: <Polynomial1D(2, c0=431.84757099, c1=-0.00298514, c2=-0.0000009)>}
```

In [39]:
```
import scipy.signal

mean_jup = np.nanmean([spectra[ind] for ind in spectra], axis = 0)
pl.plot(mean_jup, linewidth = 0.5)
pl.title("Jupiter spectra with wavelengths")
pl.ylim(-100,7000)

peaks,_ = scipy.signal.find_peaks(mean_jup, prominence = 40)

for peak in peaks:
    pl.text(peak,
            min([mean_jup[peak] + 1000, 6000]), peak,
            rotation = 90, horizontalalignment = 'center',)
```



In [40]:
```
peaks
```

Out[40]:
```
array([   5,   26,   47,  101,  125,  154,  215,  246,  319,  360,  821,
        954, 1202, 1280, 1322, 1333, 1345, 1352, 1457], dtype=int64)
```

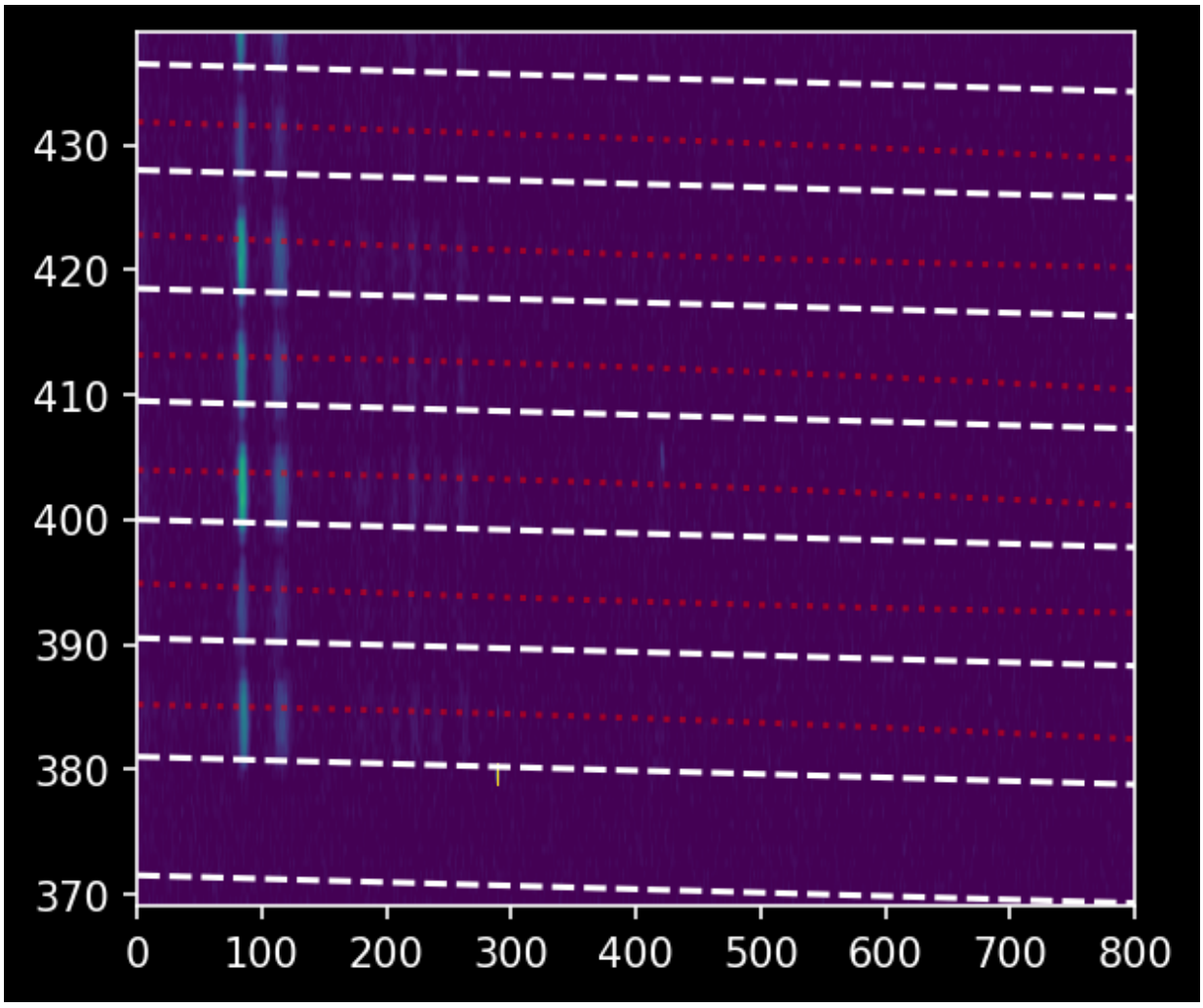
Neon

In [41]:
```
ne_30s_image_data =  (np.mean([fits.getdata(x) for x in glob.glob("\\Users\\Sydne
                       axis=0)
               - np.mean([fits.getdata(x)
                          for x in glob.glob("\\Users\\Sydnee O'Donnell\\OneDrive\
                         axis=0)
             )

ne_array = np.array(ne_30s_image_data)
ne_array = ne_array - np.median(ne_30s_image_data)
```

In [42]:
```
traces = {key: traces[key] for key in [1,2,3,4,5,6]}
```

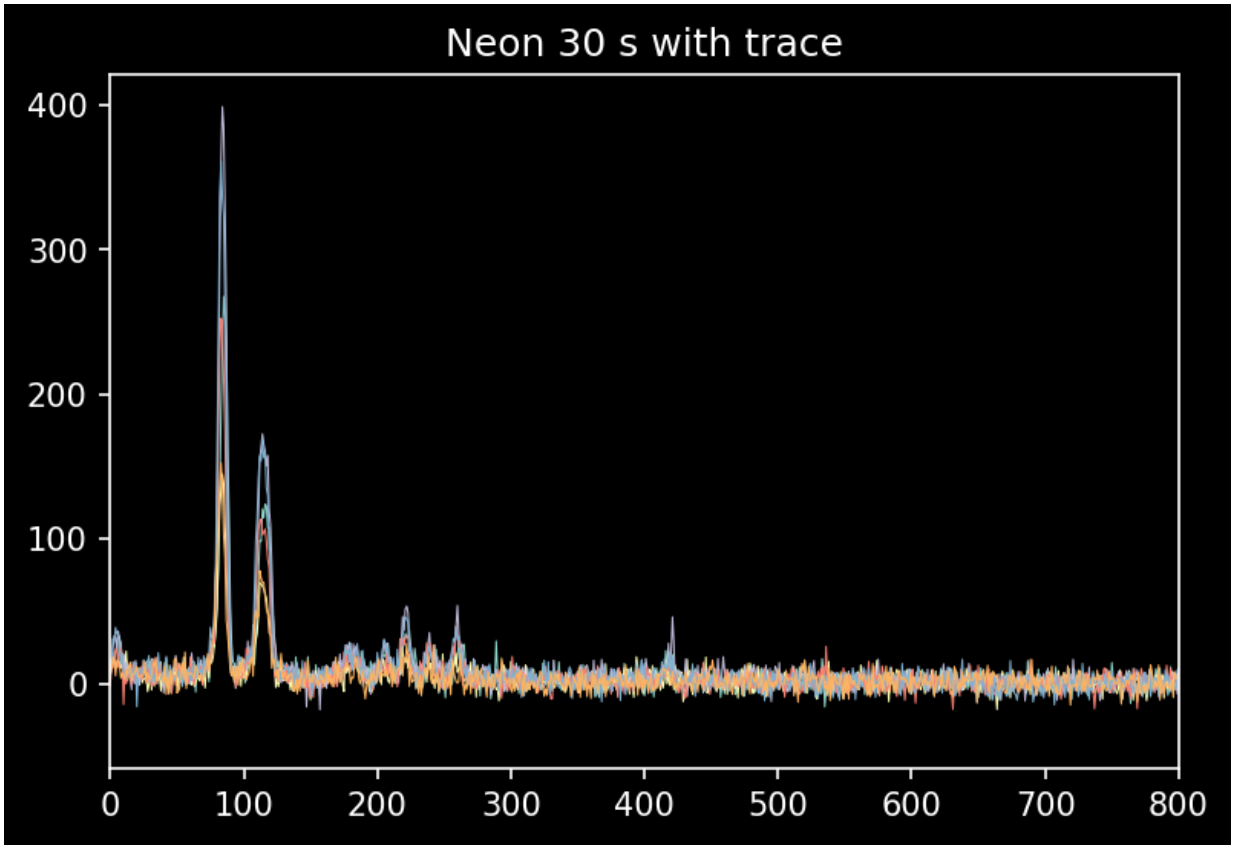
In [43]:
```
# We fit a 2rd-order polynomial
polymodel = Polynomial1D(degree=2)
linfitter = LinearLSQFitter()
fitted_polymodels = {index: linfitter(polymodel, xvals[:xend], weighted_yaxis_val
                     for index, weighted_yaxis_values in traces.items()}

pl.imshow(ne_array[ystart:yend, :xend],
          extent=[0,xend,ystart,yend],
          vmin=0, vmax=700,
         )
pl.plot([0,xend], ystart + intertrace_cuts + np.array([0,xend])[:,None] * slope,
pl.gca().set_aspect(10)
for tracefit in fitted_polymodels.values():
    pl.plot(xvals[:xend], tracefit(xvals[:xend]), 'r:', alpha=0.5)
pl.axis((0,xend,ystart,yend))
```

Out[43]: (0.0, 800.0, 369.0, 439.0)



In [44]:
```
lmfitter = LevMarLSQFitter()
guess = Gaussian1D(amplitude=160, mean=0, stddev=5)

npixels_to_cut_trace = 4
spectra = {}
for trace_index, polymodel_trace in fitted_polymodels.items():
    trace_center = polymodel_trace(xvals)

    cutout_trace = np.array([ne_array[int(yval)-npixels_to_cut_trace:int(yval)+np
                        for yval, ii in zip(trace_center, xvals)]).T

    trace_profile = cutout_trace.mean(axis=1)
    trace_profile_xaxis = np.arange(len(trace_profile))
    fitted_trace_profile = lmfitter(model=guess, x=trace_profile_xaxis, y=trace_p
    model_trace_profile = fitted_trace_profile(trace_profile_xaxis)

    trace_avg_spectrum = np.array([np.average(
            ne_array[int(yval)-npixels_to_cut:int(yval)+npixels_to_cut, ii],
            weights=trace_profile)
                                for yval, ii in zip(trace_center, xvals)])
    spectra[trace_index] = trace_avg_spectrum

for index in spectra:
    pl.plot(spectra[index], linewidth=0.5)
    pl.title("Neon 30 s with trace")
pl.xlim(0,800)
```

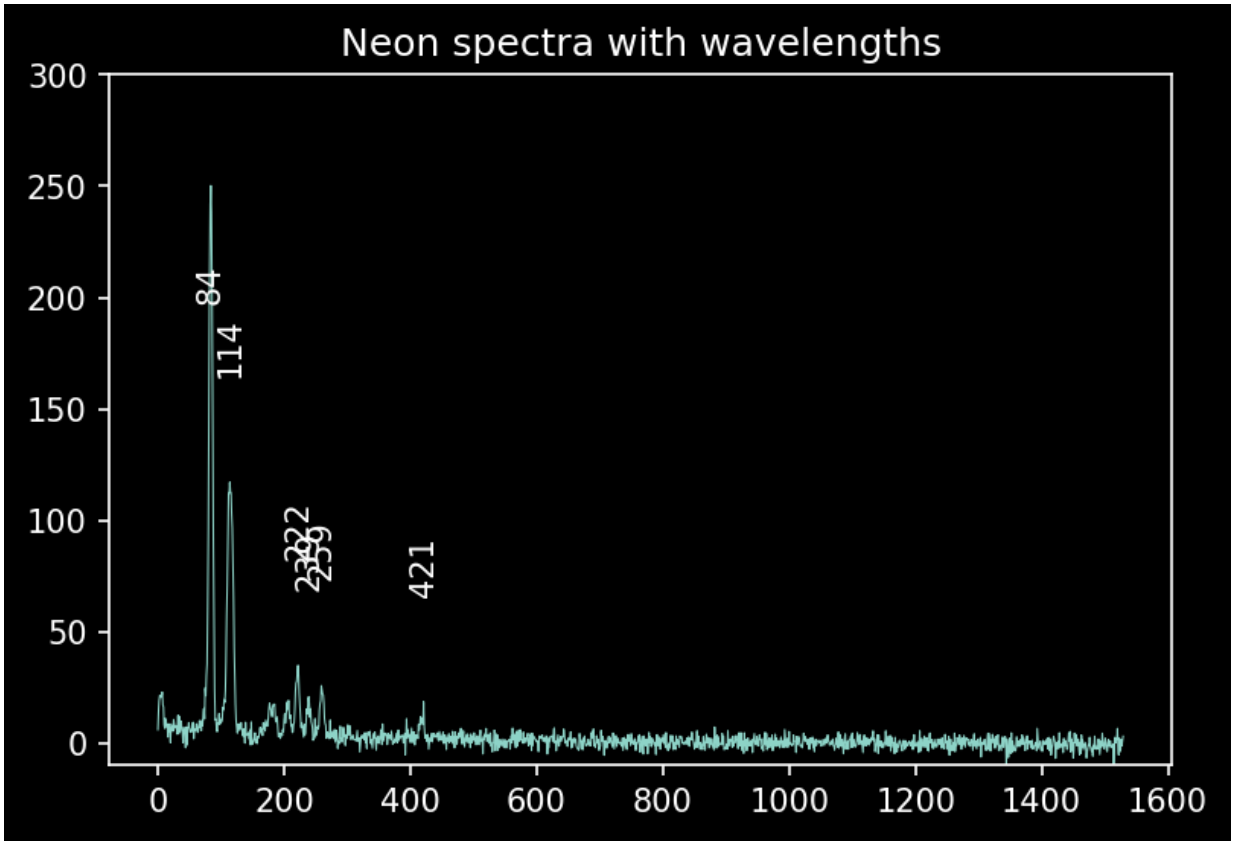
Out[44]: (0.0, 800.0)



In [45]:
```
fitted_polymodels
```

Out[45]:
```
{1: <Polynomial1D(2, c0=385.17841428, c1=-0.00194809, c2=-0.00000189)>,
 2: <Polynomial1D(2, c0=394.89094474, c1=-0.00428583, c2=0.00000166)>,
 3: <Polynomial1D(2, c0=403.96841129, c1=-0.00191925, c2=-0.00000208)>,
 4: <Polynomial1D(2, c0=413.19331433, c1=-0.0014969, c2=-0.00000251)>,
 5: <Polynomial1D(2, c0=422.83141761, c1=-0.00475088, c2=0.00000182)>,
 6: <Polynomial1D(2, c0=431.84757099, c1=-0.00298514, c2=-0.0000009)>}
```

In [55]:
```
import scipy.signal

mean_ne = np.nanmean([spectra[ind] for ind in spectra], axis = 0)
pl.plot(mean_ne, linewidth = 0.5)
pl.title("Neon spectra with wavelengths")
pl.ylim(-10,300)

peaks,_ = scipy.signal.find_peaks(mean_ne, prominence = 17)

for peak in peaks:
    pl.text(peak,
            min([mean_ne[peak] + 50, 200]), peak,
            rotation = 90, horizontalalignment = 'center',)
```



In [56]:
```
peaks
```

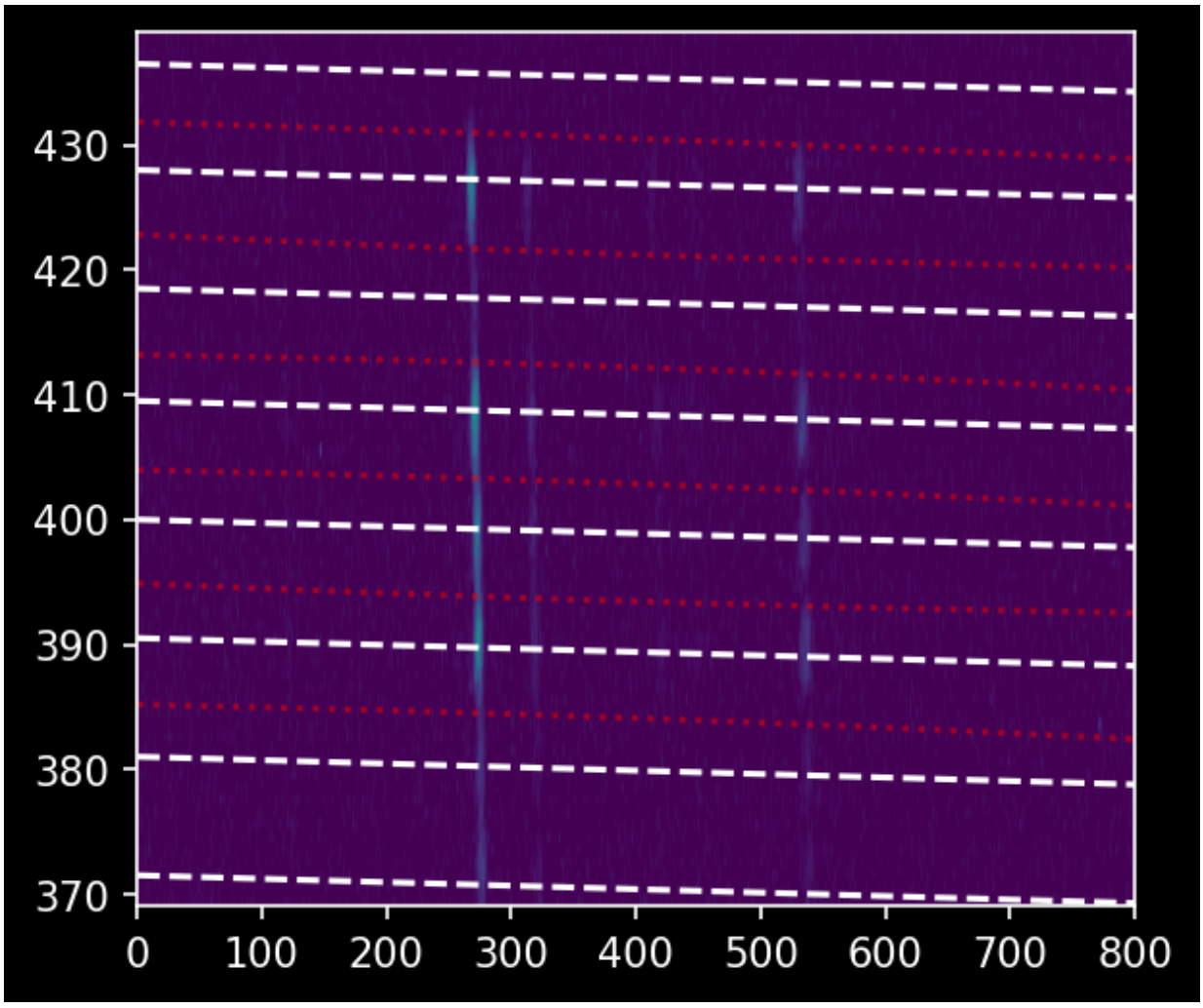
Out[56]:
```
array([ 84, 114, 222, 239, 259, 421], dtype=int64)
```

Helium

In [57]:
```
## don't have darks for these so using 30 s - if hot pixles are sensitive then th
he_20s_image_data =  (np.mean([fits.getdata(x) for x in glob.glob("\\Users\\Sydne
                      axis=0)
              - np.mean([fits.getdata(x)
                         for x in glob.glob("\\Users\\Sydnee O'Donnell\\OneDrive\
                        axis=0)
             )

he_array = np.array(he_20s_image_data)
he_array = he_array - np.median(he_20s_image_data)
```

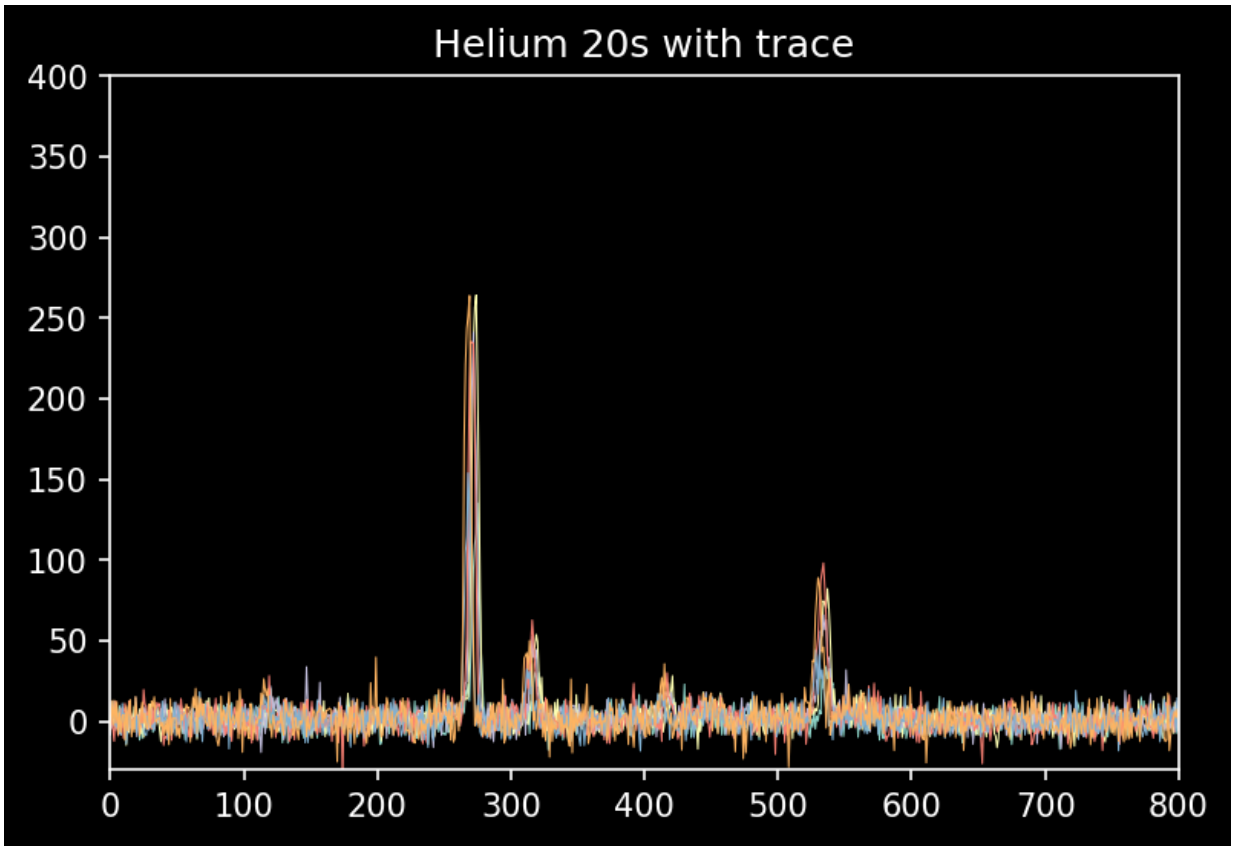
In [58]:
```
# We fit a 2rd-order polynomial
polymodel = Polynomial1D(degree=2)
linfitter = LinearLSQFitter()
fitted_polymodels = {index: linfitter(polymodel, xvals[:xend], weighted_yaxis_val
                     for index, weighted_yaxis_values in traces.items()}

pl.imshow(he_array[ystart:yend, :xend],
          extent=[0,xend,ystart,yend],
          vmin=0, vmax=700,
         )
pl.plot([0,xend], ystart + intertrace_cuts + np.array([0,xend])[:,None] * slope,
pl.gca().set_aspect(10)
for tracefit in fitted_polymodels.values():
    pl.plot(xvals[:xend], tracefit(xvals[:xend]), 'r:', alpha=0.5)
pl.axis((0,xend,ystart,yend))
```

Out[58]: (0.0, 800.0, 369.0, 439.0)



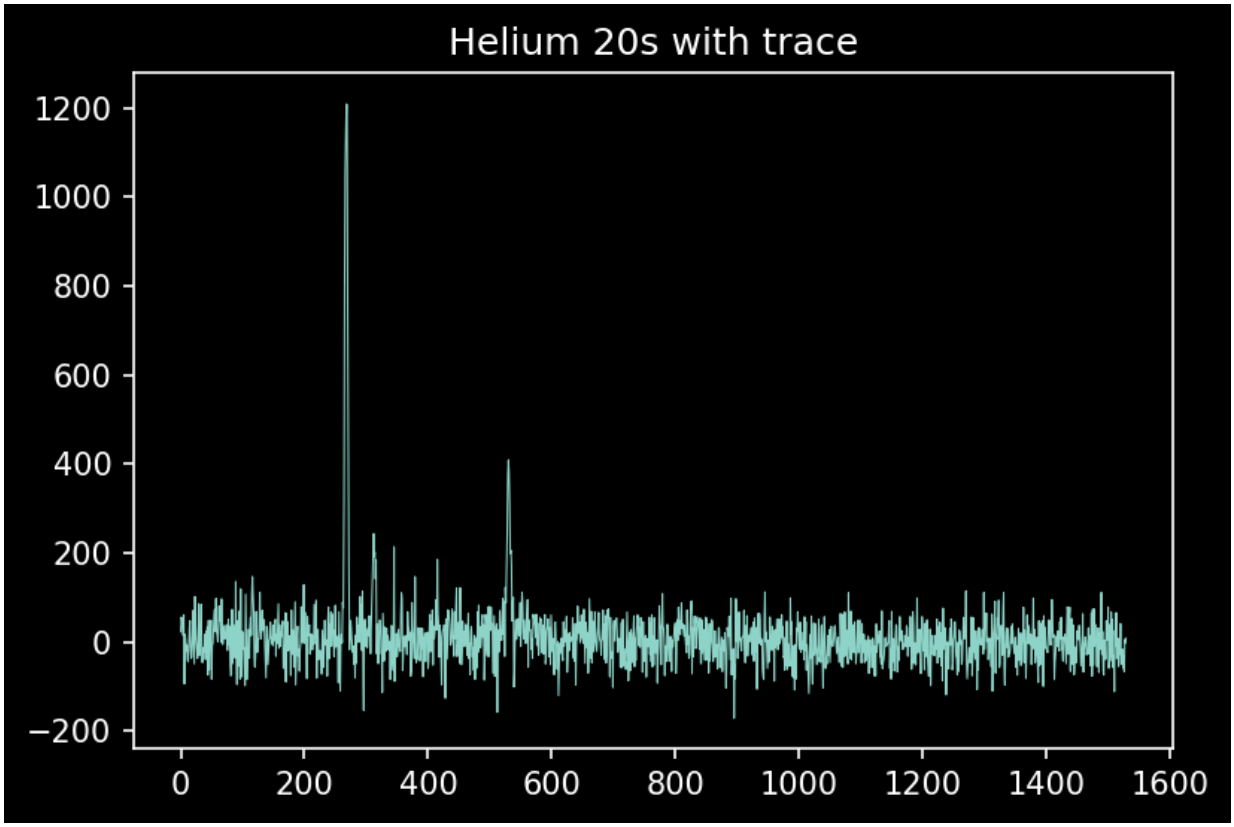
In [59]:
```
lmfitter = LevMarLSQFitter()
guess = Gaussian1D(amplitude=160, mean=0, stddev=5)

npixels_to_cut_trace = 4
spectra = {}
for trace_index, polymodel_trace in fitted_polymodels.items():
    trace_center = polymodel_trace(xvals)

    cutout_trace = np.array([he_array[int(yval)-npixels_to_cut_trace:int(yval)+np
                        for yval, ii in zip(trace_center, xvals)]).T

    trace_profile = cutout_trace.mean(axis=1)
    trace_profile_xaxis = np.arange(len(trace_profile))
    fitted_trace_profile = lmfitter(model=guess, x=trace_profile_xaxis, y=trace_p
    model_trace_profile = fitted_trace_profile(trace_profile_xaxis)

    trace_avg_spectrum = np.array([np.average(
            he_array[int(yval)-npixels_to_cut:int(yval)+npixels_to_cut, ii],
            weights=trace_profile)
                                for yval, ii in zip(trace_center, xvals)])
    spectra[trace_index] = trace_avg_spectrum

for index in spectra:
    pl.plot(spectra[index], linewidth=0.5)
    pl.title("Helium 20s with trace")
    pl.xlim(0,800)
    pl.ylim(-30,400)
```

```
WARNING: The fit may be unsuccessful; check fit_info['message'] for more inform
ation. [astropy.modeling.fitting]
```



In [60]:
```
pl.plot(cutout_trace.sum(axis=0), linewidth=0.5)
pl.title("Helium 20s with trace")
```

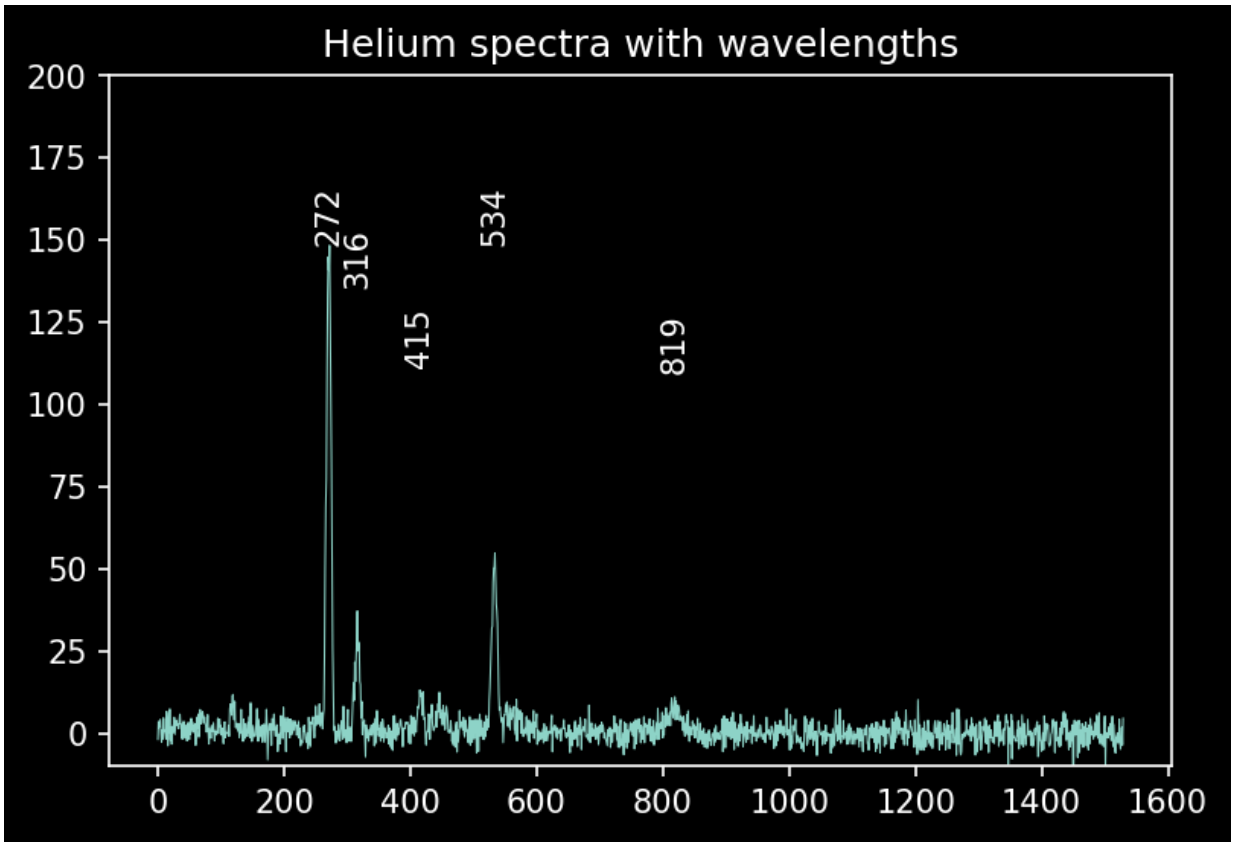
Out[60]:
```
Text(0.5, 1.0, 'Helium 20s with trace')
```



In [61]:
```
fitted_polymodels
```

Out[61]:
```
{1: <Polynomial1D(2, c0=385.17841428, c1=-0.00194809, c2=-0.00000189)>,
 2: <Polynomial1D(2, c0=394.89094474, c1=-0.00428583, c2=0.00000166)>,
 3: <Polynomial1D(2, c0=403.96841129, c1=-0.00191925, c2=-0.00000208)>,
 4: <Polynomial1D(2, c0=413.19331433, c1=-0.0014969, c2=-0.00000251)>,
 5: <Polynomial1D(2, c0=422.83141761, c1=-0.00475088, c2=0.00000182)>,
 6: <Polynomial1D(2, c0=431.84757099, c1=-0.00298514, c2=-0.0000009)>}
```

In [62]:
```
import scipy.signal

mean_he = np.nanmean([spectra[ind] for ind in spectra], axis = 0)
pl.plot(mean_he, linewidth = 0.5)
pl.title("Helium spectra with wavelengths")
pl.ylim(-10,200)

peaks,_ = scipy.signal.find_peaks(mean_he, prominence = 17)

for peak in peaks:
    pl.text(peak,
            min([mean_he[peak] + 100, 150]), peak,
            rotation = 90, horizontalalignment = 'center',)
```



In [63]:
```
peaks
```

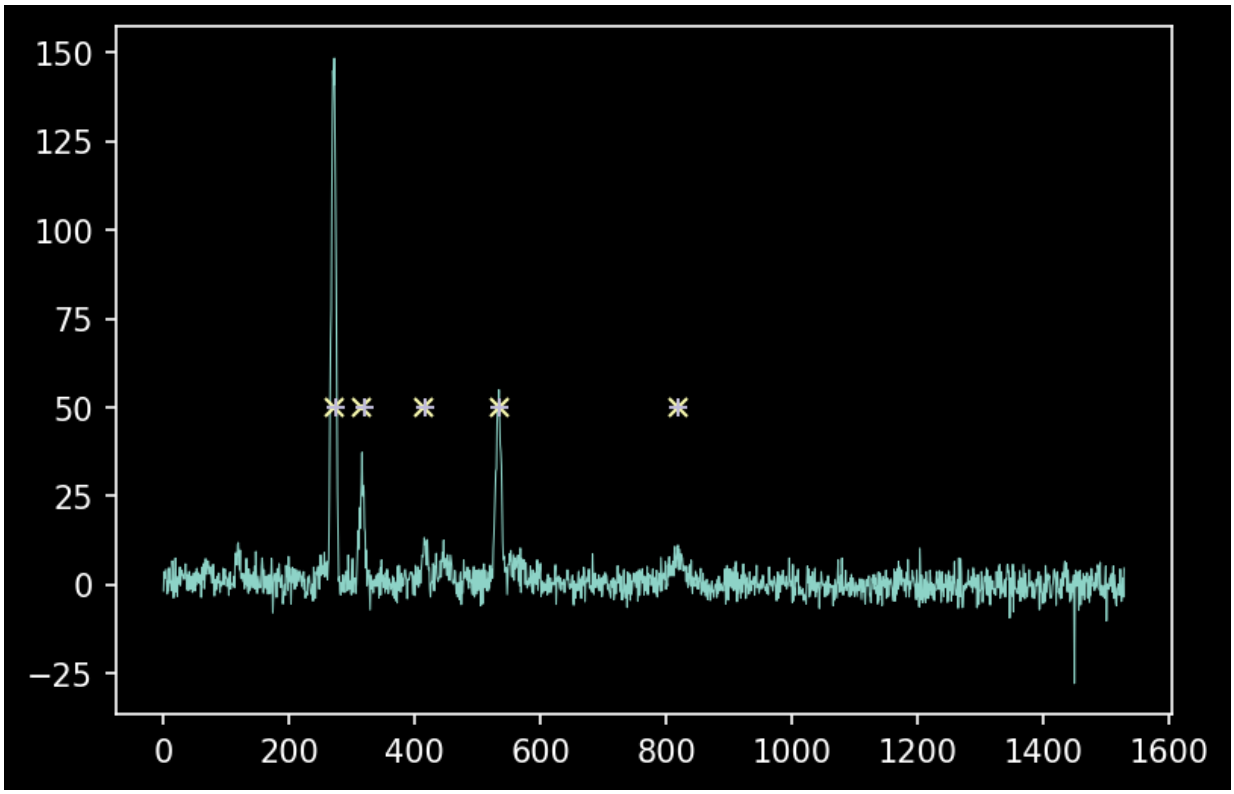
Out[63]:
```
array([272, 316, 415, 534, 819], dtype=int64)
```

In [65]:
```
xaxis = np.arange(he_20s_image_data.shape[1])
```

In [82]:
```
guessed_xvals = peaks
guessed_wavelengths = peaks#[303.78,320.30,505.5,522.21,584.22]
# https://physics.nist.gov/PhysRefData/Handbook/Tables/heliumtable2_a.htm
npixels = 15
improved_xval_guesses = [np.average(xaxis[g-npixels:g+npixels],
                                    weights=spectra[2][g-npixels:g+npixels] - np.
                         for g in guessed_xvals]
improved_xval_guesses
```

Out[82]:
```
[273.0266247785954,
 319.8742839925894,
 416.58896591491316,
 535.386496252356,
 819.9953733054045]
```

In [83]:
```
pl.plot(mean_he, linewidth = 0.5)
pl.plot(guessed_xvals, [50]*5, 'x')
pl.plot(improved_xval_guesses, [50]*5, '+');
```

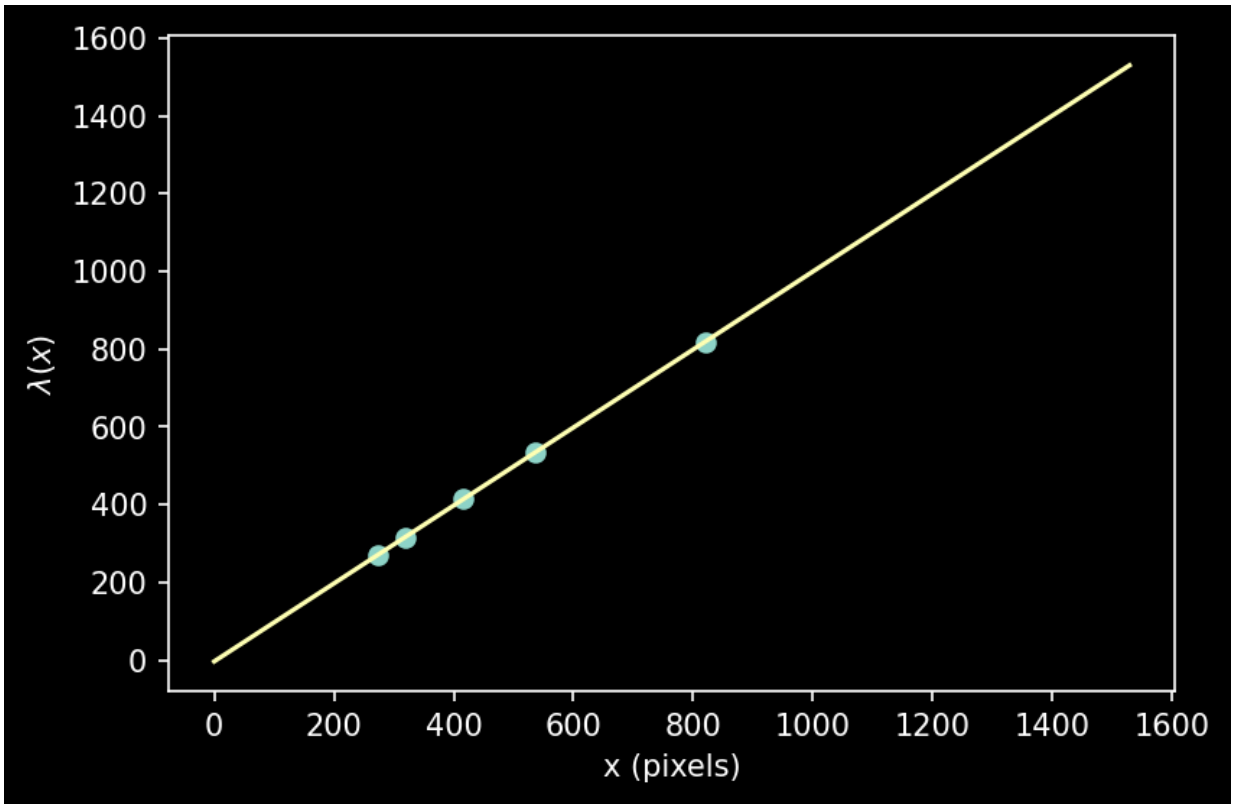


In [84]:
```
wlmodel = Linear1D()
linfit_wlmodel = linfitter(model=wlmodel, x=improved_xval_guesses, y=guessed_wave
wavelengths = linfit_wlmodel(xaxis) * u.nm
linfit_wlmodel
```

Out[84]:
```
<Linear1D(slope=1.00238884, intercept=-2.90420708)>
```

In [86]:
```
pl.plot(improved_xval_guesses, guessed_wavelengths, 'o')
pl.plot(xaxis, wavelengths, '-')
pl.ylabel("$\lambda(x)$")
pl.xlabel("x (pixels)")
```

Out[86]: Text(0.5, 0, 'x (pixels)')



In [89]:
```
# we adopt the minimum/maximum wavelength from our linear fit
minwave = wavelengths.min()
maxwave = wavelengths.max()
# then we search for atomic lines
# We are only interested in neutral lines, assuming the lamps are not hot enough
helium_lines = Nist.query(minwav=minwave,
                          maxwav=maxwave,
                          linename='He I')
```

In [100]:
```
pl.plot(wavelengths, mean_he, linewidth = 0.5)
pl.ylim(-10,100)
pl.title("helium with wavelength soln")
pl.vlines(helium_lines['Observed'], 0, 250, 'w', alpha=0.25, linewidth = 0.5);
```