themis_elfin_spectra

December 3, 2024

0.1 Compare the ELFIN and THEMIS-A spectra during the 4 September 2022 substorm event.

Let's make a summary plot first.

[1]:
```
import dateutil.parser
import pathlib
from datetime import datetime
import logging

import matplotlib.pyplot as plt
import matplotlib.transforms as transforms
from mpl_toolkits.axes_grid1.axes_divider import make_axes_locatable
import matplotlib.colors
import pyspedas
import pytplot
import manylabels
import pandas as pd
import numpy as np

import pad

logger = logging.getLogger()
logger.disabled = True
```

[2]:
```
ELECTRON_CHARGE = 1.60217663E-19  # Coulombs
ELECTRON_MASS = 9.1093837E-31  # kg
PERMITTIVITY = 8.8541878188E-12        # C^2 kg^-1 m^-3 s^2
SPEED_OF_LIGHT = 3E8 # ms/s
R_E = 6378.137  # km
```

0.2 Load and analyze THEMIS probe spectra

[3]:
```
time_range = ('2022-09-04T04:14', '2022-09-04T04:23')
_time_range = [dateutil.parser.parse(t_i) for t_i in time_range]
coordinates = 'gsm'
themis_probe = 'a'
```

```python
themis_spectra_time_ranges = (
    [datetime(2022, 9, 4, 4, 14, 0), datetime(2022, 9, 4, 4, 16, 0)],
    [datetime(2022, 9, 4, 4, 17, 0), datetime(2022, 9, 4, 4, 18, 0)],
    [datetime(2022, 9, 4, 4, 18, 30), datetime(2022, 9, 4, 4, 19, 30)],
    [datetime(2022, 9, 4, 4, 20, 0), datetime(2022, 9, 4, 4, 21, 0)],
)
themis_colors = plt.cm.viridis(np.linspace(0, 1, len(themis_spectra_time_ranges)))
```

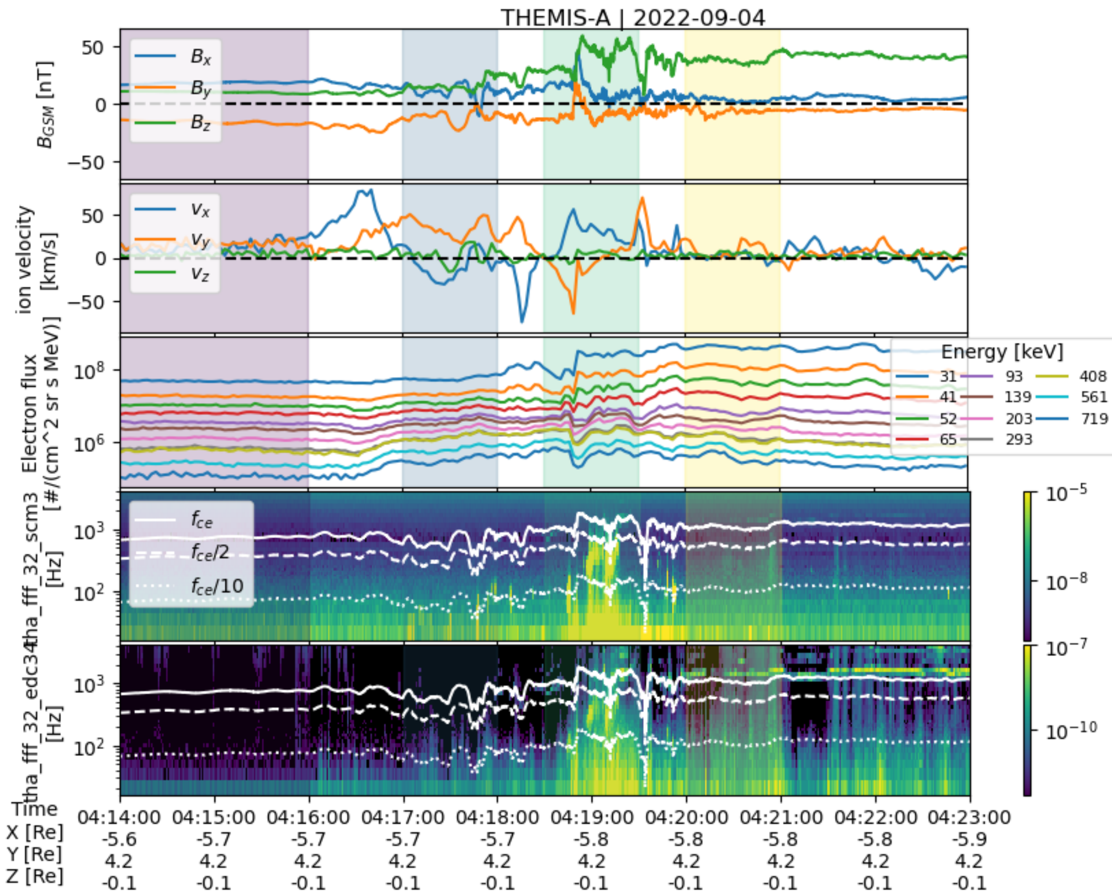
[4]:
```python
themis_probes = np.array(['a', 'd', 'e'])
themis_Ew = ('fff_32_edc34', 'fff_32_edc34', 'fff_32_edc12')[np.where(themis_probes==themis_probe)[0][0]]
themis_Bw = ('fff_32_scm3', 'fff_32_scm3', 'fff_32_scm3')[np.where(themis_probes==themis_probe)[0][0]]
```

[5]:
```python
fgm_vars = pyspedas.themis.fgm(probe=themis_probe, trange=time_range, time_clip=True)
sst_vars = pyspedas.themis.sst(probe=themis_probe, trange=time_range, time_clip=True)
mom_vars = pyspedas.themis.mom(probe=themis_probe, trange=time_range, time_clip=True)
fft_vars = pyspedas.themis.fft(probe=themis_probe, trange=time_range, time_clip=True)
state_vars = pyspedas.themis.state(probe=themis_probe, trange=time_range, time_clip=True)

fgm_xr = pytplot.get_data(f'th{themis_probe}_fgl_{coordinates}')
vi_xr = pytplot.get_data(f'th{themis_probe}_peim_velocity_{coordinates}')
sst_xr = pytplot.get_data(f'th{themis_probe}_psef_en_eflux')
valid_sst_channels = np.where(~np.isnan(sst_xr.v[0, :]))[0]
sst_times = np.array([t_i.replace(tzinfo=None) for t_i in pyspedas.time_datetime(sst_xr.times)])
sst_spectrum = 1E6*sst_xr.y[:, valid_sst_channels]/sst_xr.v[0, valid_sst_channels]
bw_xr = pytplot.get_data(f'th{themis_probe}_{themis_Bw}')
ew_xr = pytplot.get_data(f'th{themis_probe}_{themis_Ew}')
```

[11]:
```python
fig, ax = plt.subplots(5, sharex=True, figsize=(10, 7))

_lines = ax[0].plot(pyspedas.time_datetime(fgm_xr.times), fgm_xr.y)
ax[0].legend(iter(_lines), [f'$B_{{{i}}}$' for i in ['x', 'y', 'z']], loc='upper left')
ax[0].axhline(0, c='k', ls='--')
ax[0].set(
    ylim=(-1.1*np.max(fgm_xr.y), 1.1*np.max(fgm_xr.y)),
    ylabel=f'$B_{{{coordinates.upper()}}}$ [nT]',
```

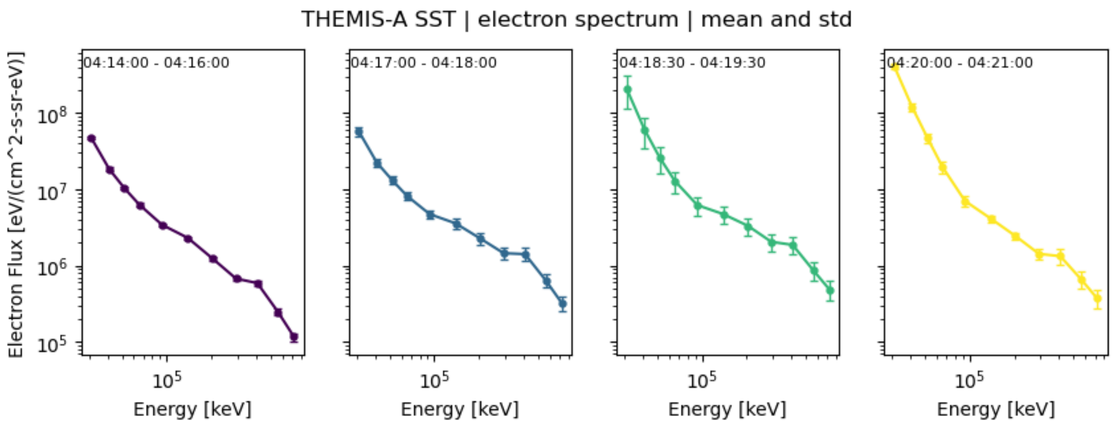
```
    xlim=_time_range
    )

_lines = ax[1].plot(pyspedas.time_datetime(vi_xr.times), vi_xr.y)
ax[1].legend(iter(_lines), [f'$v_{{{i}}}$' for i in [f'x', 'y', 'z']],␣
 ↪loc='upper left')
ax[1].axhline(0, c='k', ls='--')
ax[1].set(ylim=(-1.1*np.nanmax(vi_xr.y), 1.1*np.nanmax(vi_xr.y)), ylabel='ion␣
 ↪velocity\n[km/s]')

for valid_e_channel in valid_sst_channels:
    ax[2].plot(
        sst_times,
        sst_spectrum[:, valid_e_channel],
        label=int(sst_xr.v[0, valid_e_channel]/1000)
        )
ax[2].set(yscale='log', ylabel='Electron flux\n[#/(cm^2 sr s MeV)]')
ax[2].legend(fontsize=8, ncols=3, title='Energy [keV]', loc='upper left',␣
 ↪bbox_to_anchor=(0.9, 1.05), columnspacing=0.2)

p = ax[3].pcolormesh(
    np.array(pyspedas.time_datetime(bw_xr.times)),
    bw_xr.v,
    bw_xr.y.T,
    norm=matplotlib.colors.LogNorm(vmax=1E-5),
    shading='nearest'
    )
plt.colorbar(p, ax=ax[3])
ax[3].set(yscale='log', ylabel=f'th{themis_probe}_{themis_Bw}\n[Hz]')
f_ce = np.abs(ELECTRON_CHARGE)*1E-9*np.linalg.norm(fgm_xr.y, axis=1)/(2*np.
 ↪pi*ELECTRON_MASS)

p = ax[4].pcolormesh(
    pyspedas.time_datetime(ew_xr.times),
    ew_xr.v,
    ew_xr.y.T,
    norm=matplotlib.colors.LogNorm(vmax=1E-7)
    )
plt.colorbar(p, ax=ax[4])
ax[4].set(yscale='log', ylabel=f'th{themis_probe}_{themis_Ew}\n[Hz]')

for ax_i in ax[3:]:
    ax_i.plot(pyspedas.time_datetime(fgm_xr.times), f_ce, label=f'$f_{{ce}}$',␣
 ↪c='w', ls='-')
    ax_i.plot(pyspedas.time_datetime(fgm_xr.times), f_ce/2, label=f'$f_{{ce}}/
 ↪2$', c='w', ls='--')
```

```python
    ax_i.plot(pyspedas.time_datetime(fgm_xr.times), f_ce/10, label=f'$f_{{ce}}/
↪10$', c='w', ls=':')
    ax_i.set_facecolor('k')
ax[3].legend(loc='upper left')

plt.suptitle(f'THEMIS-{themis_probe.upper()} | {time_range[0][:10]}')

state_xr = pytplot.get_data(f'th{themis_probe}_pos_{coordinates}')
state_times = pyspedas.time_datetime(state_xr.times)
state_times = [state_time.replace(tzinfo=None) for state_time in state_times]
state_df = pd.DataFrame(
    index=state_times,
    data={f'{component.upper()} [Re]':state_xr.y[:, i]/R_E for i, component in␣
↪enumerate(['x', 'y', 'z'])}
    )
manylabels.ManyLabels(ax[-1], state_df)

for ax_i in ax[:3]:
    divider = make_axes_locatable(ax_i)
    cax = divider.append_axes("right", size="24%", pad=0.08)
    cax.remove()
plt.subplots_adjust(hspace=0.03, top=0.959)

for themis_spectra_time_range, color in zip(themis_spectra_time_ranges,␣
↪themis_colors):
    for ax_i in ax:
        ax_i.axvspan(*themis_spectra_time_range, color=color, alpha=0.2)
```

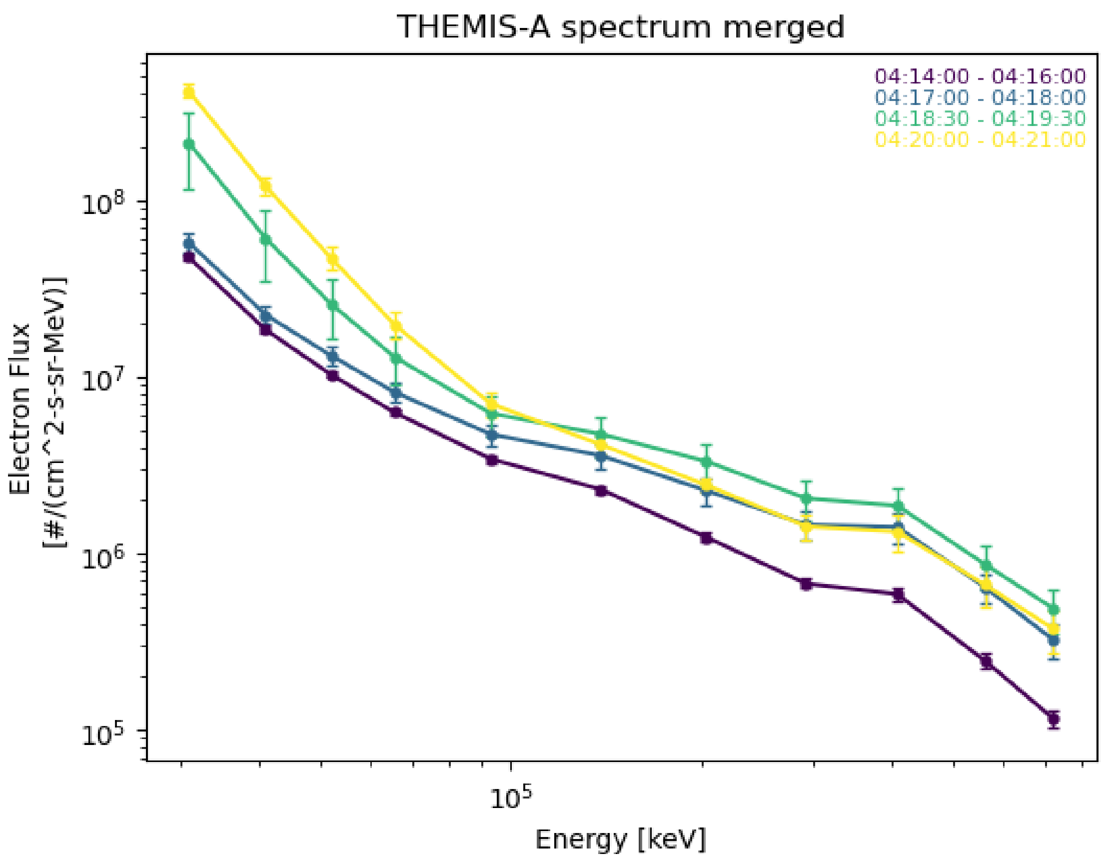


[ ]:
```
fig, bx = plt.subplots(1, len(themis_spectra_time_ranges), figsize=(10, 3),␣
↪sharey=True, sharex=True)

themis_spectra_mean = np.nan*np.zeros((len(themis_spectra_time_ranges),␣
↪valid_sst_channels.shape[0]))
themis_spectra_std = np.nan*np.zeros((len(themis_spectra_time_ranges),␣
↪valid_sst_channels.shape[0]))

for i, (themis_time_range, bx_i, color) in␣
↪enumerate(zip(themis_spectra_time_ranges, bx, themis_colors)):
    idx = np.where((sst_times>=themis_time_range[0]) &␣
↪(sst_times<=themis_time_range[1]))[0]
    themis_spectra_mean[i, :] = sst_spectrum[idx, :].mean(axis=0)
    themis_spectra_std[i, :] = sst_spectrum[idx, :].std(axis=0)
    bx_i.errorbar(sst_xr.v[0, valid_sst_channels],  themis_spectra_mean[i, :],␣
↪color=color, yerr=themis_spectra_std[i, :], capsize=2,
              markersize=7, elinewidth=1, marker='.', ls='-')
    bx_i.set(xlabel='Energy [keV]', yscale='log', xscale='log')
```

```
    bx_i.text(
        0.01, 0.98, f'{themis_time_range[0]:%H:%M:%S} - {themis_time_range[1]:
↪%H:%M:%S}',
        fontsize=8, transform=bx_i.transAxes, va='top'
        )
bx[0].set_ylabel('Electron Flux [#/(cm^2-s-sr-MeV)]')
plt.suptitle(f'THEMIS-{themis_probe.upper()} SST | electron spectrum | mean and␣
↪std');
```



[34]:
```
fig, ax = plt.subplots()
for i, (themis_time_range, color) in enumerate(zip(themis_spectra_time_ranges,␣
↪themis_colors)):
    ax.errorbar(sst_xr.v[0, valid_sst_channels],  themis_spectra_mean[i, :],␣
↪color=color, yerr=themis_spectra_std[i, :], capsize=2,
            markersize=7, elinewidth=1, marker='.', ls='-')
    ax.text(
        0.99, 0.98-0.03*i, f'{themis_time_range[0]:%H:%M:%S} -␣
↪{themis_time_range[1]:%H:%M:%S}',
        fontsize=8, transform=ax.transAxes, va='top', ha='right', color=color
        )

ax.set(xlabel='Energy [keV]', yscale='log', xscale='log', title='THEMIS-A␣
↪spectrum merged')
ax.set_ylabel(f'Electron Flux\n[#/(cm^2-s-sr-MeV)]');
```



0.3 Load and analyze ELFIN spectra

[13]:
```
elfin_spectra_time_ranges = (
    [datetime(2022, 9, 4, 4, 18, 3), datetime(2022, 9, 4, 4, 20, 5)],
    [datetime(2022, 9, 4, 4, 20, 5), datetime(2022, 9, 4, 4, 20, 25)],
    [datetime(2022, 9, 4, 4, 20, 25), datetime(2022, 9, 4, 4, 21, 20)],
)
elfin_colors = plt.cm.jet(np.linspace(0, 1, len(elfin_spectra_time_ranges)))
```

[14]:
```
elfin_probe = 'a'
pad_obj = pad.EPD_PAD(
    elfin_probe, time_range, start_pa=0, min_counts=None, accumulate=1,␣
  ↪spin_time_tol=(2.5, 12),
    lc_exclusion_angle=0
)
transformed_state = pad_obj.transform_state()
```

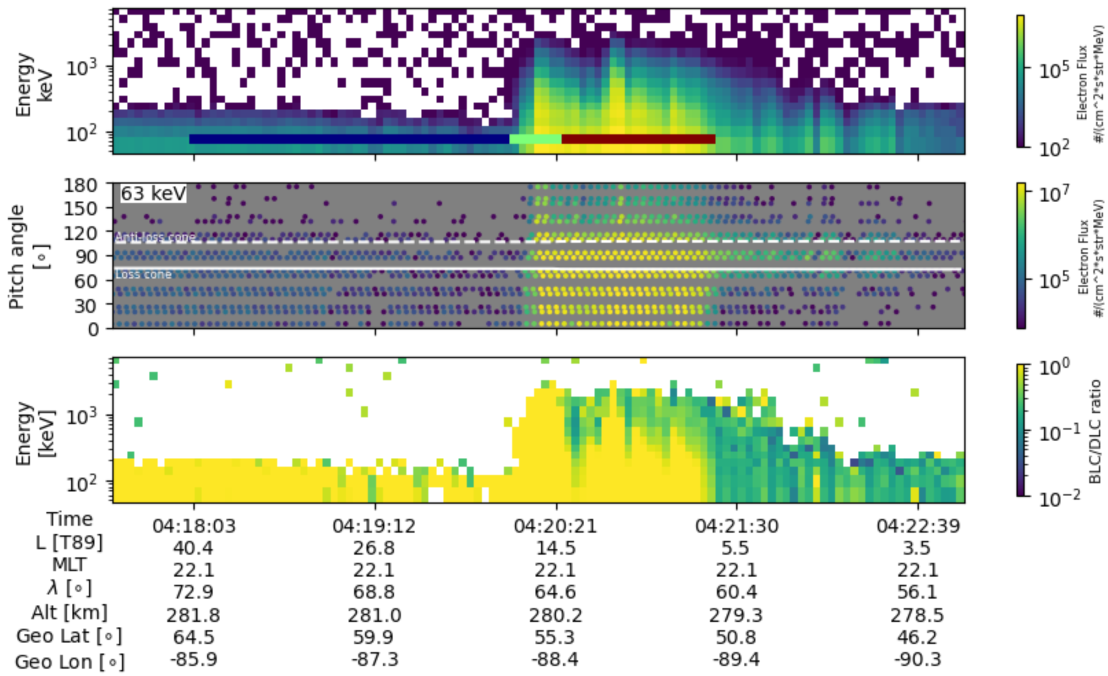
```
03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:391:
RuntimeWarning: divide by zero encountered in divide
```

```
  self.precipitation_ratio = self.blc/self.dlc

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:391:
RuntimeWarning: invalid value encountered in divide
  self.precipitation_ratio = self.blc/self.dlc

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:400:
RuntimeWarning: invalid value encountered in divide
  (self.blc_std/self.blc)**2 +

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:401:
RuntimeWarning: invalid value encountered in divide
  (self.dlc_std/self.dlc)**2

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:391:
RuntimeWarning: invalid value encountered in divide
  self.precipitation_ratio = self.blc/self.dlc

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:400:
RuntimeWarning: invalid value encountered in divide
  (self.blc_std/self.blc)**2 +

03-Dec-24 16:49:20:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:401:
RuntimeWarning: invalid value encountered in divide
  (self.dlc_std/self.dlc)**2
```

[15]:
```
fig, cx = plt.subplots(3, 1, sharex=True, figsize=(10, 6))

# transformed_state = transformed_state.loc[time_range[0]:time_range[1]]
pad_obj.plot_omni(cx[0], labels=True, colorbar=True, vmin=1E2, vmax=1E7,␣
 ↪pretty_plot=False)
pad_obj.plot_pad_scatter(cx[1])
pad_obj.plot_blc_dlc_ratio(cx[2], labels=True, colorbar=True, cmap='viridis',␣
 ↪vmin=1E-2, vmax=1)
pad_obj.plot_position(cx[2])
cx[2].xaxis.set_major_locator(plt.MaxNLocator(5))
cx[2].xaxis.set_label_coords(-0.05, -0.007*7)
cx[2].xaxis.label.set_size(10)
for elfin_spectra_time_range, color in zip(elfin_spectra_time_ranges,␣
 ↪elfin_colors):
```

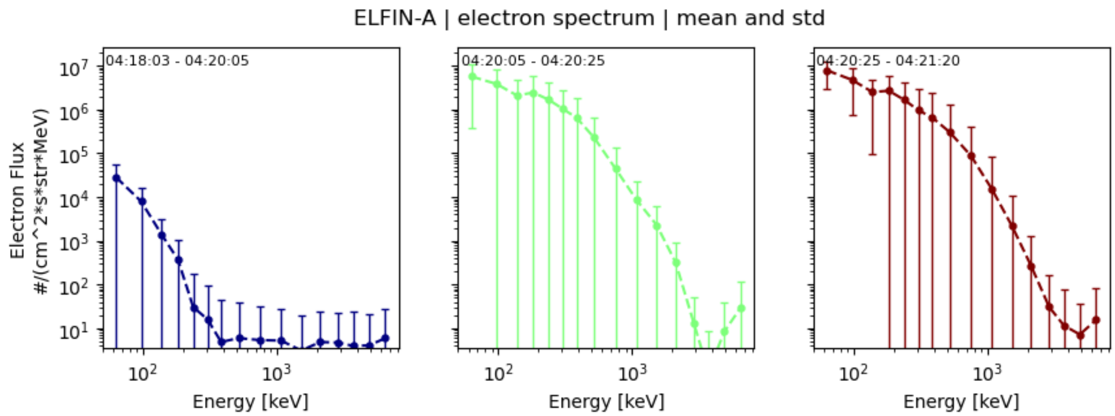
```python
    mixed_transform = transforms.blended_transform_factory(cx[0].transData,␣
↪cx[0].transAxes)
    cx[0].plot(
        [elfin_spectra_time_range[0], elfin_spectra_time_range[1]], [0.1,0.1],␣
↪color=color, alpha=1, transform=mixed_transform, linewidth=5
        )
```

```
03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:677:
RuntimeWarning: divide by zero encountered in divide
  if np.prod((self.blc/self.dlc).shape) != 0:

03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:677:
RuntimeWarning: invalid value encountered in divide
  if np.prod((self.blc/self.dlc).shape) != 0:

03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:681:
RuntimeWarning: divide by zero encountered in divide
  (self.blc/self.dlc).T,

03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:681:
RuntimeWarning: invalid value encountered in divide
  (self.blc/self.dlc).T,

03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:689:
RuntimeWarning: divide by zero encountered in divide
  if colorbar and np.prod((self.blc/self.dlc).shape) != 0:

03-Dec-24 16:49:21:
C:\Users\shumkms1\Documents\research\pad\src\pad\analysis\_pad.py:689:
RuntimeWarning: invalid value encountered in divide
  if colorbar and np.prod((self.blc/self.dlc).shape) != 0:
```

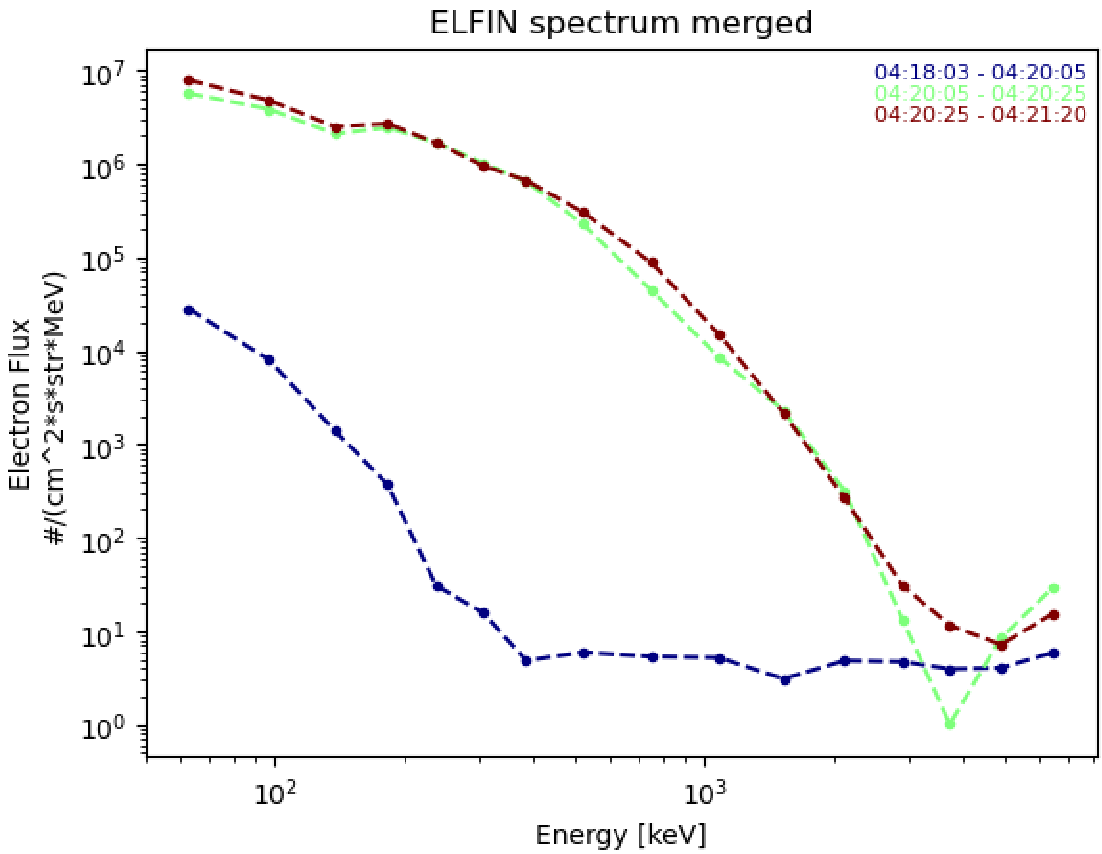


[27]:
```python
fig, dx = plt.subplots(1, len(elfin_spectra_time_ranges), figsize=(10, 3), sharey=True, sharex=True)

elfin_spectra_mean = np.nan*np.zeros((len(elfin_spectra_time_ranges), pad_obj.energy.shape[0]))
elfin_spectra_std = np.nan*np.zeros((len(elfin_spectra_time_ranges), pad_obj.energy.shape[0]))

for i, (elfin_spectra_time_range, dx_i, color) in enumerate(zip(elfin_spectra_time_ranges, dx, elfin_colors)):
    pad_flt = pad_obj.pad.sel(time=slice(elfin_spectra_time_range[0], elfin_spectra_time_range[1]))
    elfin_spectra_mean[i, :] = pad_flt.mean(dim=('time', 'pa'), skipna=True).sel(energy=pad_obj._flux_keys)
    elfin_spectra_std[i, :] = pad_flt.std(dim=('time', 'pa'), skipna=True).sel(energy=pad_obj._flux_keys)
    dx_i.errorbar(pad_obj.energy, elfin_spectra_mean[i, :], color=color, yerr=elfin_spectra_std[i, :], capsize=2,
            markersize=7, elinewidth=1, marker='.', ls='--')
    dx_i.set(xlabel='Energy [keV]', yscale='log', xscale='log')
    dx_i.text(
        0.01, 0.98, f'{elfin_spectra_time_range[0]:%H:%M:%S} - {elfin_spectra_time_range[1]:%H:%M:%S}',
        fontsize=8, transform=dx_i.transAxes, va='top'
```

```
        )
dx[0].set_ylabel(f'Electron Flux\n{pad_obj._flux_units}')
plt.suptitle(f'ELFIN-{themis_probe.upper()} | electron spectrum | mean and␣
↪std');
```



[32]:
```
fig, ax = plt.subplots()
for i, (elfin_spectra_time_range, color) in␣
↪enumerate(zip(elfin_spectra_time_ranges, elfin_colors)):
    ax.plot(pad_obj.energy, elfin_spectra_mean[i, :], color=color, marker='.',␣
↪ls='--')
    ax.text(
        0.99, 0.98-0.03*i, f'{elfin_spectra_time_range[0]:%H:%M:%S} -␣
↪{elfin_spectra_time_range[1]:%H:%M:%S}',
        fontsize=8, transform=ax.transAxes, va='top', ha='right', color=color
        )

ax.set(xlabel='Energy [keV]', yscale='log', xscale='log', title='ELFIN spectrum␣
↪merged')
ax.set_ylabel(f'Electron Flux\n{pad_obj._flux_units}');
```

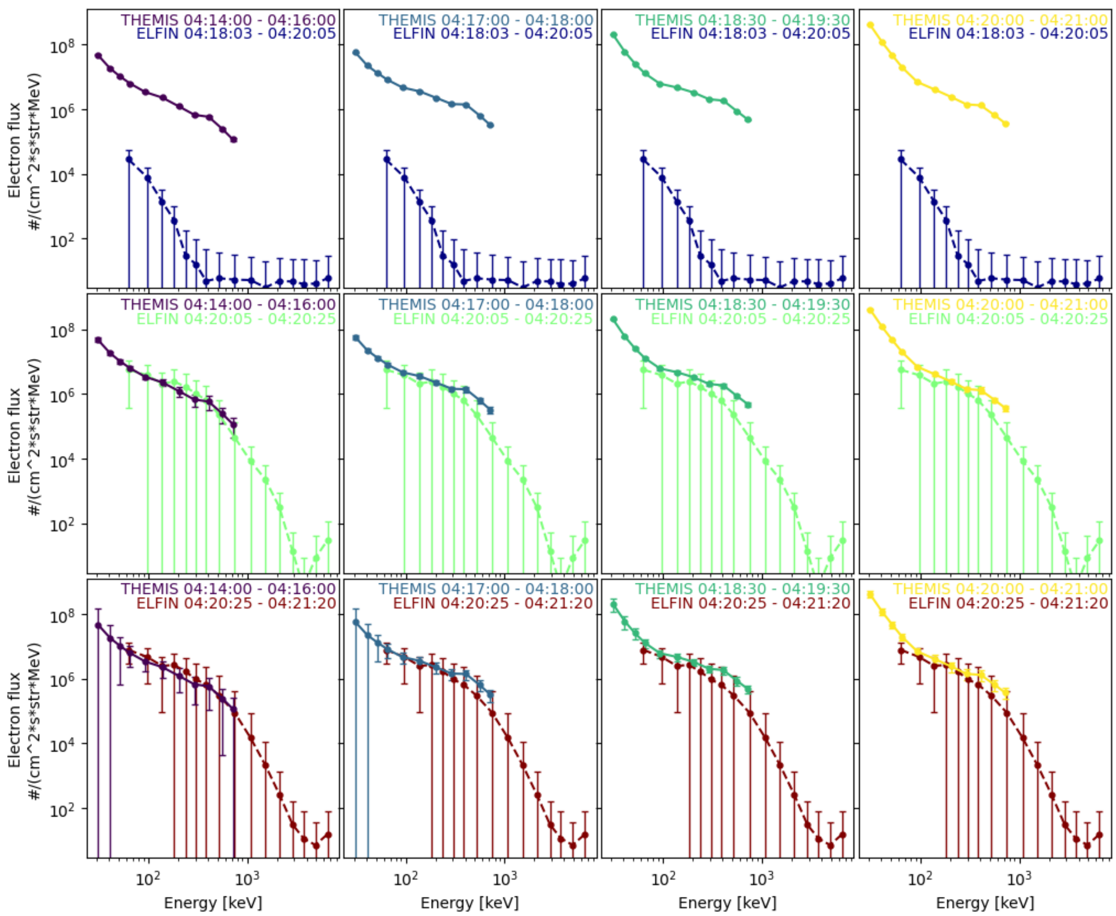


Both the IB and chorus-driven spectrum are essentially the same.

0.4 Compare the ELFIN and THEMIS spectra in a grid-form

[19]:
```
fig, ex = plt.subplots(len(elfin_spectra_time_ranges),␣
↪len(themis_spectra_time_ranges), sharex=True, sharey=True, figsize=(12, 10))

for i, (ex_row, elfin_color) in enumerate(zip(ex, elfin_colors)):
    for j, (ex_col, themis_color) in enumerate(zip(ex_row, themis_colors)):
        ex_col.errorbar(pad_obj.energy, elfin_spectra_mean[i, :],␣
↪color=elfin_color, yerr=elfin_spectra_std[i, :], capsize=2,
            markersize=7, elinewidth=1, marker='.', ls='--')
        ex_col.errorbar(sst_xr.v[0, valid_sst_channels]/1E3, ␣
↪themis_spectra_mean[j, :], color=themis_color, yerr=themis_spectra_std[i, :
↪], capsize=2,
            markersize=7, elinewidth=1, marker='.', ls='-')
        ex_col.set(yscale='log', xscale='log')
        ex_col.text(
            0.99, 0.99,
```

```
            f'THEMIS {themis_spectra_time_ranges[j][0]:%H:%M:%S} - {themis_spectra_time_ranges[j][1]:%H:%M:%S}',
            va='top', ha='right', transform=ex_col.transAxes, color=themis_color)
        ex_col.text(
            0.99, 0.94,
            f'ELFIN {elfin_spectra_time_ranges[i][0]:%H:%M:%S} - {elfin_spectra_time_ranges[i][1]:%H:%M:%S}',
            va='top', ha='right', transform=ex_col.transAxes, color=elfin_color)
for ex_i in ex[-1, :]:
    ex_i.set_xlabel('Energy [keV]')
for ex_i in ex[:, 0]:
    ex_i.set_ylabel(f'Electron flux\n{pad_obj._flux_units}')
plt.subplots_adjust(wspace=0.02, hspace=0.02)
```



Takeaways: 1. THEMIS-A did not map to the plasma sheet since the ELFIN spectrum is so different. 2. The ELFIN spectra in the IB and rad belts agree very well with all THEMIS spectra