elfin_energy_flux

April 23, 2025

1 How much did the > 50 keV electrons contribute to the atmospheric energy flux?

[1]:
```
import string

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

import elfinasi
```

```
c:\Users\shumkms1\AppData\Local\anaconda3\envs\asilib_dev_20241108\Lib\site-
packages\pandas\core\arrays\masked.py:60: UserWarning: Pandas requires version
'1.3.6' or newer of 'bottleneck' (version '1.3.5' currently installed).
  from pandas.core import (
```

[2]:
```
time_range = ('2022-09-04T04:18:00', '2022-09-04T04:23:00')
kev_erg_factor = 1.6E-9  # The conversion factor from KeV to ergs.
precipitation_solid_angle = 2*np.pi
```

1.1 Load ELFIN and ASI inversion data

[3]:
```
pad_obj_eflux = elfinasi.EPD_PAD(
    'a', time_range, start_pa=0, min_counts=None, accumulate=1,␣
 ↪spin_time_tol=(2.5, 12),
    lc_exclusion_angle=10, nflux=False
)
```

```
C:\Users\shumkms1\Documents\research\elfinasi\src\elfinasi\elfin.py:839:
UserWarning: The BLC/DLC ratios are all NaNs. This could be due to the
lc_exclusion_angle excluding all pitch angles sampled.
  warnings.warn(
```

The THEMIS ASI inversion values were derived using the Gabrielse+2021 algorithm.

[4]:
```
themis_asi_eflux = pd.read_csv(
    elfinasi.data_dir / '20220904_themis_asi_inversion.csv', index_col=0,␣
 ↪parse_dates=True, na_values=('NaN', "-1")
)
themis_asi_eflux = themis_asi_eflux.loc[themis_asi_eflux['Elevation [deg]'] >␣
 ↪10]  # Christine's suggested threshold
```

[5]:
```
themis_asi_eflux.dropna().head()
```

[5]:

date/time	PINALat	GILLlat	ClosestStation	Elevation [deg]	ELFINeflux [erg/cm^2/s]	ELFINenergy [keV]
2022-09-04 04:19:42	58.2521	58.1624	gill	11.5868	0.050685	0.823
2022-09-04 04:19:43	58.2521	58.1624	gill	11.5868	0.050685	0.823
2022-09-04 04:19:44	57.9534	58.0769	gill	11.6890	0.113653	0.857
2022-09-04 04:19:45	57.9534	58.0110	gill	12.0754	0.144092	0.857
2022-09-04 04:19:46	57.9534	57.9323	gill	12.1287	0.191217	0.930

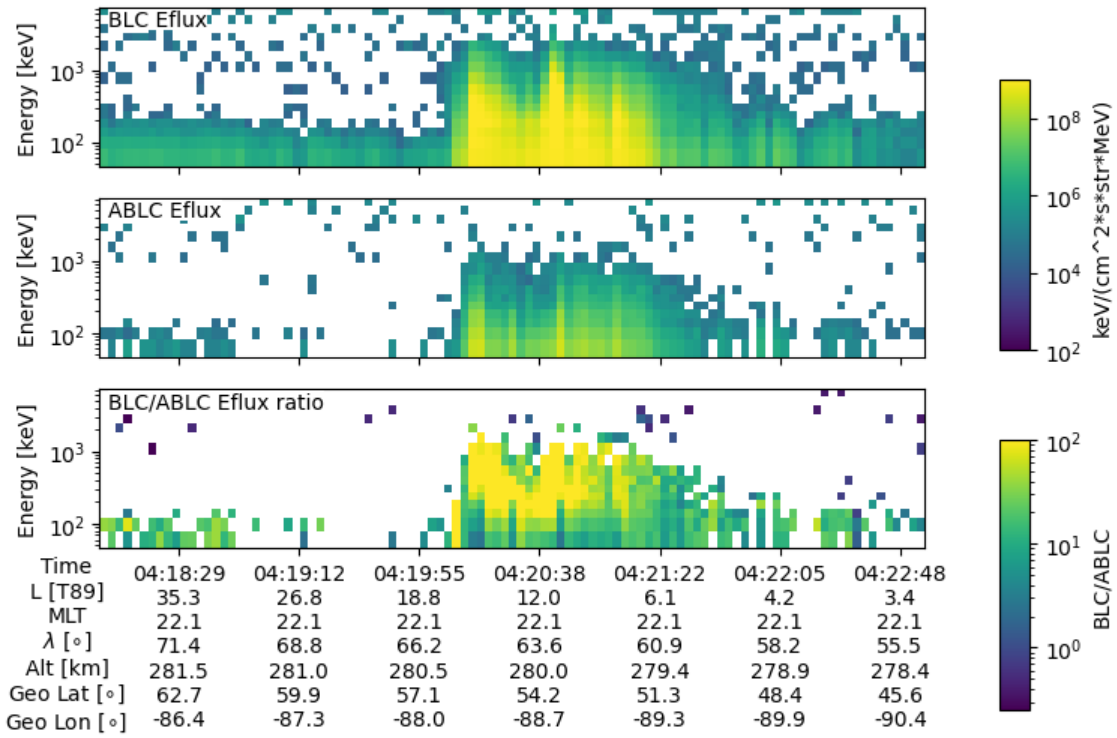
1.2 Plot the ELFIN BLC and ABLC energy fluxes

Let's compare the amount of energy flux that disspiated in the atmosphere vs the amount that made it back out.

[6]:
```
fig, ax = plt.subplots(3, 1, sharex=True, figsize=(10, 6))
p = ax[0].pcolormesh(
            pad_obj_eflux.pad.time,
            pad_obj_eflux.energy,
            pad_obj_eflux.blc.T,
            shading='nearest',
            norm=matplotlib.colors.LogNorm(vmin=1E2, vmax=1E9)
            )
p2 = ax[1].pcolormesh(
            pad_obj_eflux.pad.time,
            pad_obj_eflux.energy,
            pad_obj_eflux.ablc.T,
            shading='nearest',
            norm=matplotlib.colors.LogNorm(vmin=1E2, vmax=1E9)
            )
p3 = ax[2].pcolormesh(
            pad_obj_eflux.pad.time,
            pad_obj_eflux.energy,
```

```
            pad_obj_eflux.blc.T/pad_obj_eflux.ablc.T,
            shading='nearest',
            norm=matplotlib.colors.LogNorm(vmax=10**2)
            )

pad_obj_eflux.plot_position(ax[-1])

labels = ('BLC Eflux', 'ABLC Eflux', 'BLC/ABLC Eflux ratio')
for ax_i, label in zip(ax, labels):
    ax_i.set_yscale('log')
    ax_i.set_ylabel('Energy [keV]')
    _text = ax_i.text(0.01, 0.99, label, transform=ax_i.transAxes, va='top')
    _text.set_bbox(dict(facecolor='white', linewidth=0, pad=0.1, edgecolor='k'))

fig.subplots_adjust(left=0.25, right=0.8)
cbar_ax0 = fig.add_axes([0.85, 0.5, 0.02, 0.3])
cbar_ax1 = fig.add_axes([0.85, 0.1, 0.02, 0.3])
fig.colorbar(p, cax=cbar_ax0, label=pad_obj_eflux._flux_units)
fig.colorbar(p3, cax=cbar_ax1, label='BLC/ABLC')

ax[-1].xaxis.set_major_locator(plt.MaxNLocator(7))
ax[-1].xaxis.set_label_coords(-0.04, -0.007*7)
ax[-1].xaxis.label.set_size(10)
```

```
C:\Users\shumkms1\AppData\Local\Temp\ipykernel_29040\1964764843.py:19:
RuntimeWarning: divide by zero encountered in divide
  pad_obj_eflux.blc.T/pad_obj_eflux.ablc.T,
C:\Users\shumkms1\AppData\Local\Temp\ipykernel_29040\1964764843.py:19:
RuntimeWarning: invalid value encountered in divide
  pad_obj_eflux.blc.T/pad_obj_eflux.ablc.T,
```

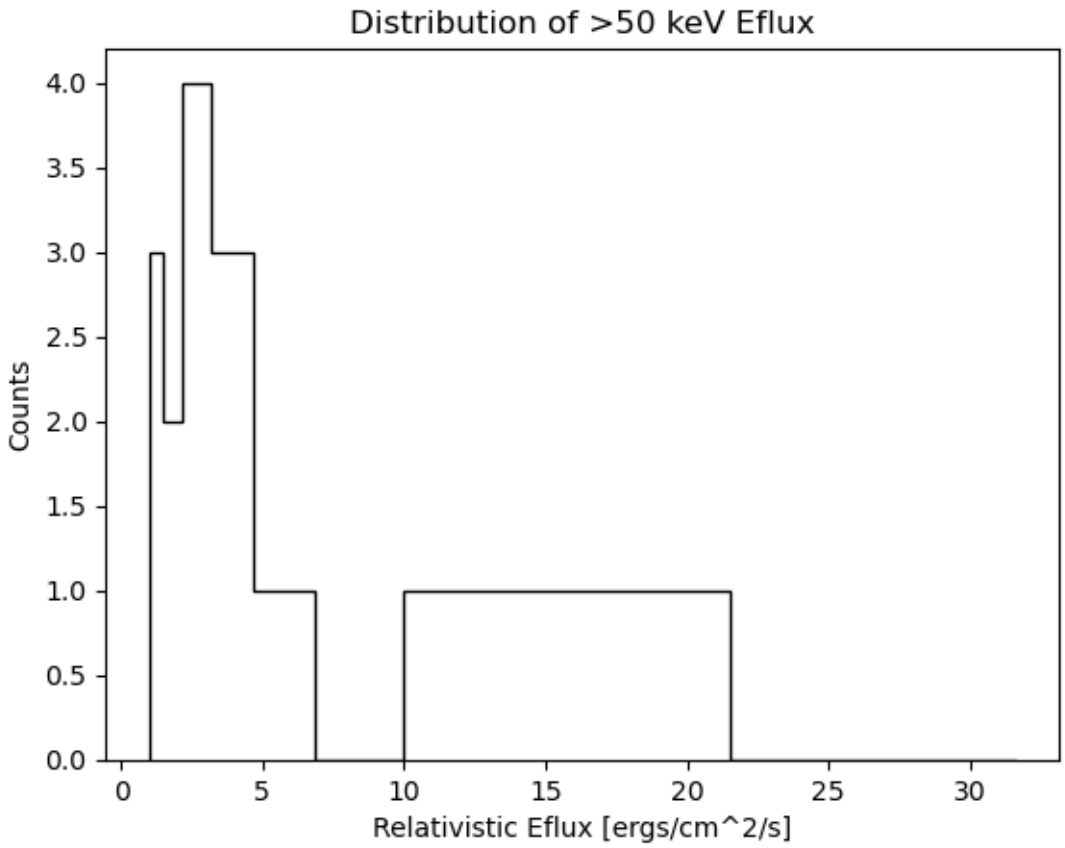


The bottom panel shows us that typically the precipitating energy flux was 10x-100x of the energy flux going back up. In other words, the $>$ 50 keV energy flux was mostly deposited into the atmosphere.

1.3 What was the integrated $>$ 50 keV energy flux that ELFIN observed?

[7]:
```
energy_widths_mev = (pad_obj_eflux.energy_widths[:, 1]-pad_obj_eflux.
↪energy_widths[:, 0])/1E3
eflux_ergs = kev_erg_factor*precipitation_solid_angle*(pad_obj_eflux.blc -␣
↪pad_obj_eflux.ablc)*energy_widths_mev
relativistic_eflux = np.nansum(eflux_ergs, axis=1)
```

[8]:
```
plt.hist(relativistic_eflux, bins=np.logspace(0, 1.5, 10), histtype='step',␣
↪color='k')
plt.title('Distribution of >50 keV Eflux')
plt.xlabel('Relativistic Eflux [ergs/cm^2/s]')
plt.ylabel('Counts');
```



Looks good! Now let's merge the ELFIN and THEMIS-ASI Eflux values on the same time stamps and calculate the percentage contribution of the >50 keV electrons to the total energy flux

[9]:
```
elfin_eflux = pd.DataFrame(relativistic_eflux, index=pad_obj_eflux.pad.time,␣
 ↪columns=['energetic'])
auroral_eflux = pd.DataFrame(themis_asi_eflux['ELFINeflux [erg/cm^2/s]']).
 ↪rename(columns={'ELFINeflux [erg/cm^2/s]':'auroral'})

merged_eflux = pd.merge_asof(
    elfin_eflux,
    auroral_eflux,
    left_index=True,
    right_index=True,
    direction='nearest',
    tolerance=pd.Timedelta('1s')
    )
merged_eflux['energetic_contribution'] = 100*merged_eflux['energetic']/
 ↪(merged_eflux['auroral'] + merged_eflux['energetic'])
```

[10]:
```
merged_eflux
```

[10]:
```
                            energetic  auroral  energetic_contribution
2022-09-04 04:18:01.896945   0.006678      NaN                     NaN
2022-09-04 04:18:04.762952   0.001689      NaN                     NaN
2022-09-04 04:18:07.659442   0.001947      NaN                     NaN
2022-09-04 04:18:10.525450   0.002996      NaN                     NaN
2022-09-04 04:18:13.421940   0.004960      NaN                     NaN
…                                 …      …                       …
2022-09-04 04:22:44.012952  -0.003151      NaN                     NaN
2022-09-04 04:22:46.887953   0.002618      NaN                     NaN
2022-09-04 04:22:49.784443   0.001415      NaN                     NaN
2022-09-04 04:22:52.650450  -0.002075      NaN                     NaN
2022-09-04 04:22:55.525450  -0.000581      NaN                     NaN

[103 rows x 3 columns]
```

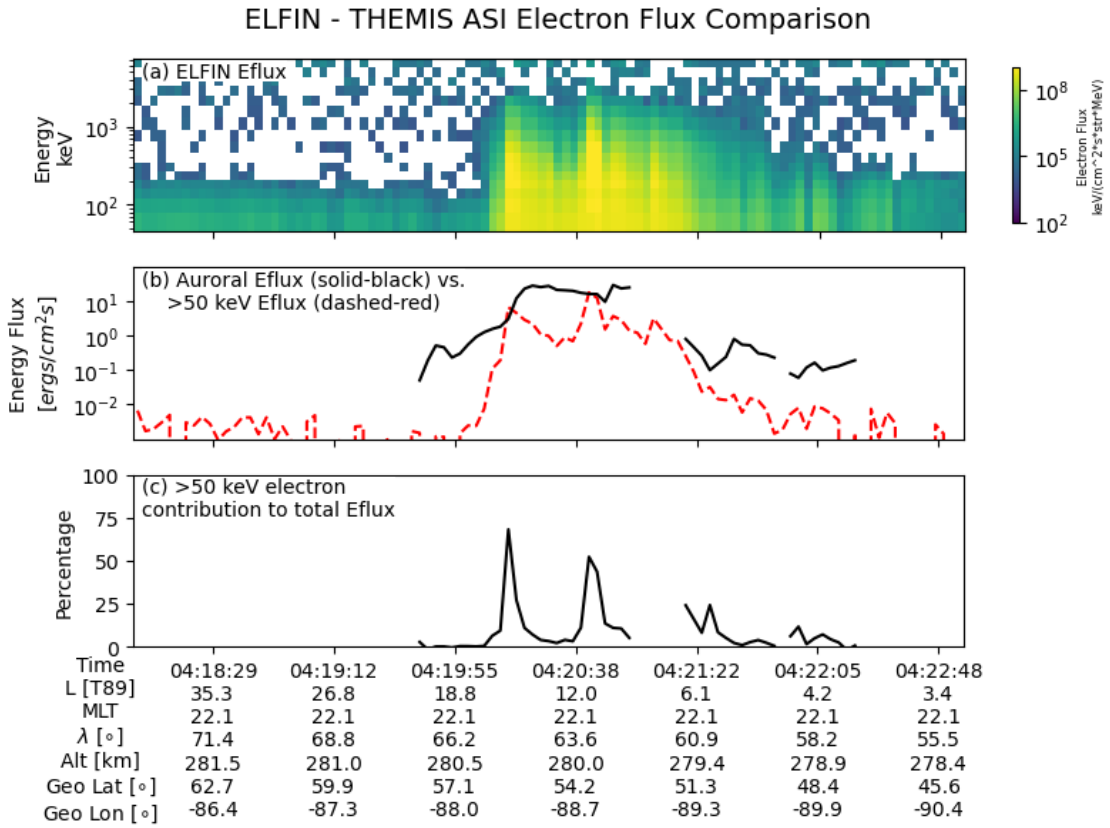
[11]:
```
merged_eflux.dropna().describe().round(3)
```

[11]:
```
       energetic  auroral  energetic_contribution
count     48.000   48.000                  48.000
mean       1.340    7.054                   9.090
std        3.338   10.350                  13.850
min       -0.003    0.051                  -1.869
25%        0.003    0.193                   1.484
50%        0.015    0.539                   4.266
75%        1.019   16.367                  10.810
max       18.236   30.025                  68.381
```

Note: the negative min energetic EFlux is a result of the space-time aliasing, with higher fluxes in the ABLC than the BLC during the ELFIN half-spin period

[12]:
```
fig, bx = plt.subplots(3, 1, sharex=True, figsize=(8, 6))
pad_obj_eflux.plot_omni(bx[0], labels=True, colorbar=True, vmin=1E2, vmax=1E9,␣
 ↪pretty_plot=False, fraction=0.05)
bx[1].plot(
    merged_eflux.index,
    merged_eflux['energetic'],
    label='>50 keV Eflux (BLC-ABLC)',
    color='r',
    linestyle='--'
    )
bx[1].plot(
    merged_eflux.index,
    merged_eflux['auroral'],
    label='THEMIS ASI Eflux', color='k'
    )

bx[2].plot(merged_eflux.index, merged_eflux['energetic_contribution'],␣
 ↪color='k')
```

```
pad_obj_eflux.plot_position(bx[-1])
bx[-1].xaxis.set_major_locator(plt.MaxNLocator(7))
bx[-1].xaxis.set_label_coords(-0.04, -0.007*7)
bx[-1].xaxis.label.set_size(10)

for bx_i in bx[[1, 2]]:
    divider = make_axes_locatable(bx_i)
    cax = divider.append_axes("right", size="10%", pad=0.08)
    cax.remove()

bx[1].set_yscale('log')
bx[1].set_ylabel(f'Energy Flux\n$[ergs/cm^{{2}}s]$')
bx[1].set_yticks([1E-2, 1E-1, 1E0, 1E1])
bx[1].set_ylim(1E-3, 1E2)

bx[2].set_ylabel(f'Percentage')
bx[2].set_ylim(0, 1E2)

labels = (
    'ELFIN Eflux',
    'Auroral Eflux (solid-black) vs.\n    >50 keV Eflux (dashed-red)',
    '>50 keV electron\ncontribution to total Eflux'
    )
for ax_i, label, letter in zip(bx, labels, string.ascii_lowercase):
    _text = ax_i.text(0.01, 0.99, f'({letter}) {label}', transform=ax_i.
 ↪transAxes, va='top')
    _text.set_bbox(dict(facecolor='white', linewidth=0, pad=0.1, edgecolor='k'))
plt.suptitle('ELFIN - THEMIS ASI Electron Flux Comparison', fontsize=14)
plt.tight_layout()
```



Not a bad comparison considering that the Gabrielse+2021 inversion for this event did not include the MSP data (those instruments stopped operating then). We should compare this with Calgary's inversion.

Two lessons learned from this first comparison: 1. Typically the energetic energy fluxes make up a small portion (4% median and 8% percent mean), and 2. Occasionally the energetic energy fluxes can make up as much as 68% of the energetic+auroral energy flux.