Photometry - Calculating Zero Points

Once you've measured how much light you received from a star, the next step is to figure out what that means in calibrated units - i.e., what you would have observed if there were no inefficiencies caused by the instrument or atmosphere.

This calibration process is critical for comparing observations!

For more details, have a look at [Stuart Littlefair's detailed description (http://slittlefair.staff.shef.ac.uk/teaching/phy217/lectures/principles/L04/index.html#stacks_out_1244](http://slittlefair.staff.shef.ac.uk/teaching/phy217/lectures/principles/L04/index.html#stacks_out_1244)

Learning goals are:

- Practice looking up stars
- Practice photometry measurement
- Learn to use magnitude measurements to determine the magnitude zero-point for an observation

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In [60]:
```
%matplotlib inline
```

In [61]:
```
import numpy as np
import pylab as pl
pl.rcParams['image.origin'] = 'lower' # make images display right-side-up
pl.style.use('dark_background')
```

Step 1: Repeat all operations from "Basic Photometry" exercise

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If you saved your dark- and sky-subtracted, flat-fielded image, you could just load that up here instead.

In [62]:
```
from astropy.io import fits
import os
```

In [63]:
```
# on my computer, the data are in a subdirectory called 'data/', so I chdir there
os.chdir("C:\\Users\\Sydnee O'Donnell\\OneDrive\\UF\\Obs Tech 1\\In CLass\\data_m
```

In [64]:
```
pleiades_clear_darksub_flattened = fits.getdata('pleiades_30s_C_other_001_darksub
pleiades_clear_darksub_flattened_uncertainty = fits.getdata('pleiades_30s_C_other
```

In [65]:
```
sky_mean = pleiades_clear_darksub_flattened.mean()
sky_median = np.median(pleiades_clear_darksub_flattened)
print(sky_mean, sky_median)
```

```
1035.2701922573067 1034.4351460591993
```

In [66]:
```
sky_stddev = pleiades_clear_darksub_flattened.std() # estimate of the per-pixel e
print(f"Standard deviation of the data: {sky_stddev:0.1f}")
print(f"Average of the per-pixel uncertainty from error propagation: {pleiades_cl
```

```
Standard deviation of the data: 53.1
Average of the per-pixel uncertainty from error propagation: 41.3
```

In [67]:
```
sky_subtracted_pleiades_clear = pleiades_clear_darksub_flattened - sky_mean
```

Find all stars we want to measure

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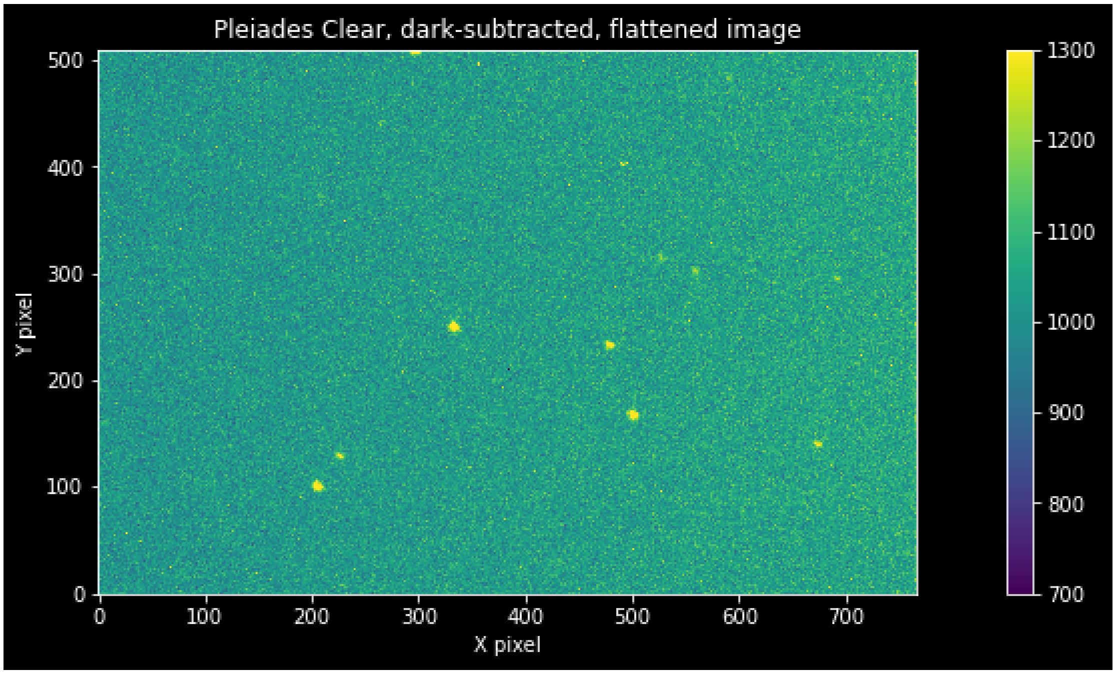
The process is:

- Show an image
- Look at the image and identify some stars
- Record the X,Y coordinates of the stars

This is probably easiest to do if you load up the image in ds9.

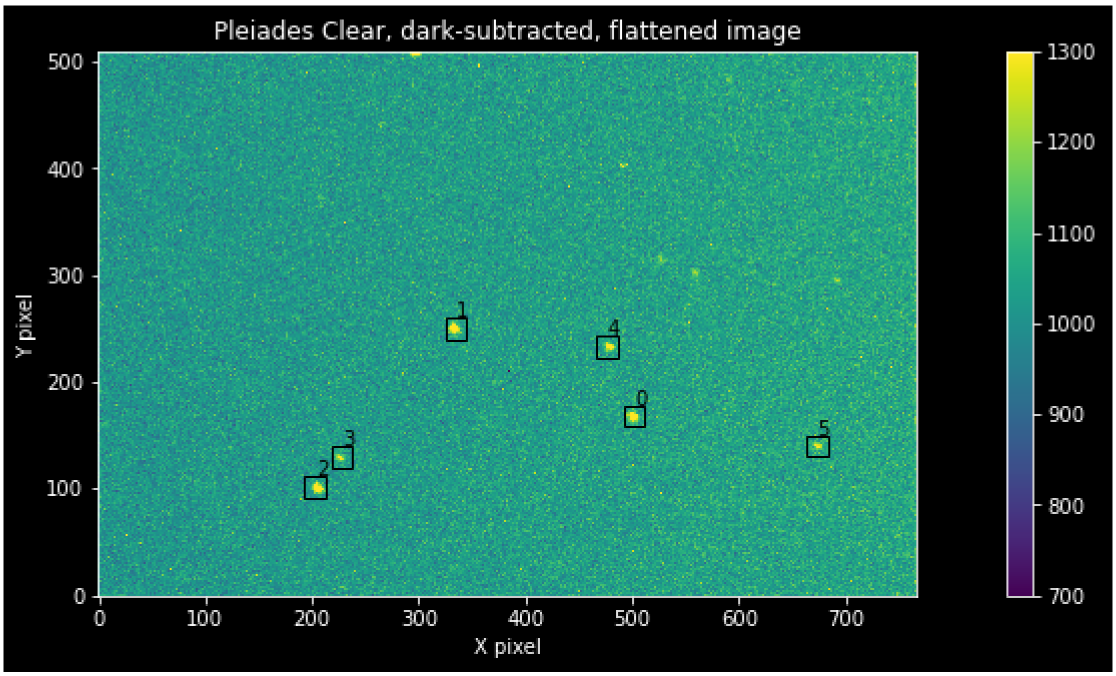
In [68]:
```
pl.figure(figsize=(16,5))
im = pl.imshow(pleiades_clear_darksub_flattened, origin='lower', interpolation='r
pl.colorbar(im)
_=pl.title("Pleiades Clear, dark-subtracted, flattened image")
_=pl.xlabel("X pixel")
_=pl.ylabel("Y pixel")
```



In [69]:
```
star_centers = [[502,168], [335,250], [203,102], [228,130], [477,233], [673,140]]
width = 20
height = 20
```

To show where we found stars, we draw boxes around each of them.

In [70]:
```
fig = pl.figure(figsize=(16,5))
ax = fig.gca()
im = pl.imshow(pleiades_clear_darksub_flattened,
               origin='lower', interpolation='none', vmax=1300, vmin=700)
pl.colorbar(im)
_=pl.title("Pleiades Clear, dark-subtracted, flattened image")
_=pl.xlabel("X pixel")
_=pl.ylabel("Y pixel")
for ii,(xcen, ycen) in enumerate(star_centers):
    rect = pl.Rectangle(xy=[xcen-width/2, ycen-height/2],
                        width=width, height=height,
                        facecolor='none', edgecolor='k')
    ax.add_patch(rect)
    ax.text(xcen, ycen+height/2, str(ii), color='k')
```



Measure Photometry

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Using the tools we made at the end of the photometry notebook (`BasicPhotometry.ipynb`), we can measure the stars' counts.

In [71]:
```
def calculate_star_flux_and_error(cutout_star, cutout_uncertainty, sky_stddev):

    mask = cutout_star > 2*sky_stddev
    masked_star_sum = cutout_star[mask].sum()
    masked_star_sum_error = ((cutout_uncertainty[mask]**2).sum() + sky_stddev**2*

    return masked_star_sum, masked_star_sum_error
```

In [72]:
```
star_centers
```

Out[72]:
```
[[502, 168], [335, 250], [203, 102], [228, 130], [477, 233], [673, 140]]
```

In [73]:
```
# the // means "divide by two, but return an integer (instead of a float)"
# single / means "divide by, then return a float"
502//2
```

Out[73]:
```
251
```

In [74]:
```
# we are going to use cutouts around the star for their measurements
for (xc, yc) in star_centers:
    slc = slice(yc-height//2,yc+height//2),slice(xc-width//2,xc+width//2)
    print(slc)
```

```
(slice(158, 178, None), slice(492, 512, None))
(slice(240, 260, None), slice(325, 345, None))
(slice(92, 112, None), slice(193, 213, None))
(slice(120, 140, None), slice(218, 238, None))
(slice(223, 243, None), slice(467, 487, None))
(slice(130, 150, None), slice(663, 683, None))
```

There are two equivalent syntaxes to make a cutout:

```
sky_subtracted_pleiades_clear[158:178, 492:512]
sky_subtracted_pleiades_clear[slice(158,178), slice(492,512)]
```

These do the same thing. The former is "syntactic sugar" for the latter (that's a technical term that you don't need to know but might be useful if you're googling)

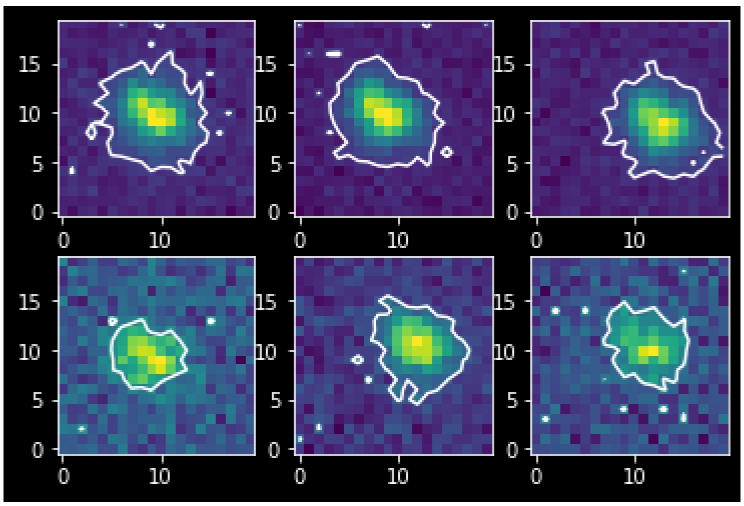
Then, we use a list comprehension (an inline for loop) to:

1. loop over the star centers
2. for each star, make a cutout around the star
3. for each star, make a cutout *of the uncertainty map* around the star
4. Pass the cutouts, along with the sky background standard deviation to `calculate_star_flux_and_error`

In [75]:
```
results = [calculate_star_flux_and_error(
    sky_subtracted_pleiades_clear[yc-height//2:yc+height//2,
                                  xc-width//2:xc+width//2],
    pleiades_clear_darksub_flattened_uncertainty[yc-height//2:yc+height//2,
                                                 xc-width//2:xc+width//2],
    sky_stddev)
           for (xc,yc) in star_centers]
```

It's a good idea to look at what we did. We use another loop to show each of the cutout stars along with a contour showing the mask we used. We are reporting the sum over pixels contained within the mask:

In [76]:
```
for ii,(xc, yc) in enumerate(star_centers):
    ax = pl.subplot(2,3,ii+1)
    cutout = sky_subtracted_pleiades_clear[yc-height//2:yc+height//2,
                                           xc-width//2:xc+width//2]
    ax.imshow(cutout)
    ax.contour(cutout, levels=[2*sky_stddev], colors=['w'])
```



We now add our results to a table to save them.

Astropy tables are useful tools for storing and displaying tabular data.

In [77]:
```
from astropy.table import Table
```

We extract the flux and uncertainty measurements from the `results` variable, which is a 2-dimensional array.

The `.T` here means "transpose". The fluxes and uncertainties are presently in columns, e.g.:

```
[[1,2],
 [3,4],
 [5,6]]
```

But we want to put them into *rows* so we can make a table out of them. This is the transpose:

```
[[1,2,3],
 [4,5,6]]
```

In [78]:
```
fluxes, uncertainties = np.array(results).T
```

We then make a table with three columns: the star number, the fluxes, and the uncertainties

In [79]:
```
Table([np.arange(len(fluxes)), fluxes, uncertainties], names=['Star Number', 'Flu
```

Out[79]: *Table length=6*

Star Number	Flux	Uncertainty
int32	float64	float64
0	35316.171723260944	700.1730852477532
1	40898.35182370345	696.7739320352291
2	39515.09479166292	668.7418749842823
3	8163.221738016462	435.20327093367445
4	18341.568210431426	582.6446125975509
5	10853.453148936138	533.3646210877812

Finder chart matching: Look up the stars

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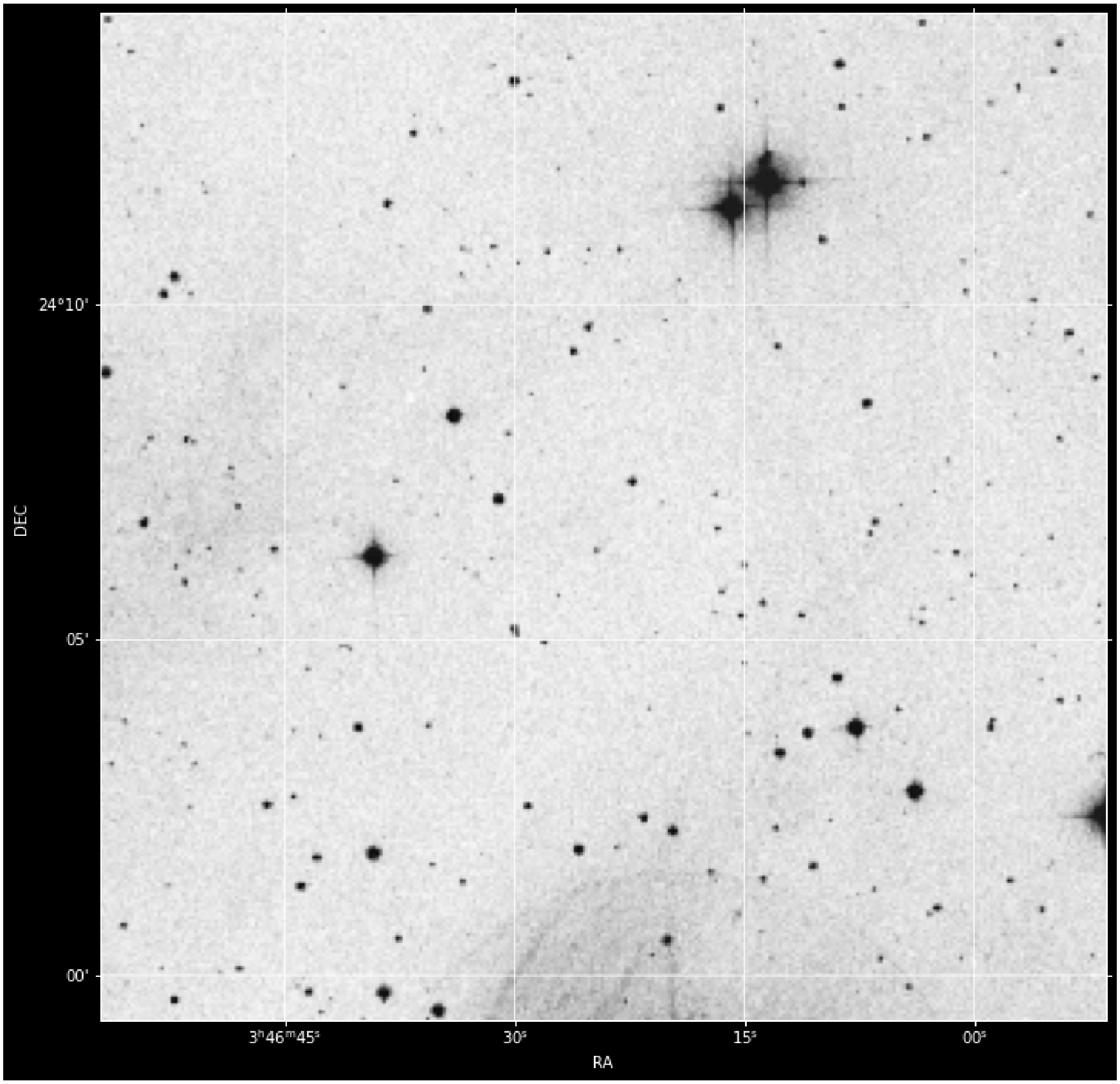
We now have measurements of 6 stars. We need to calibrate them by looking up known photometric measurements in a catalog. To do this, we have to figure out which stars they are!

This is probably best done using ds9 (demo recording [here](https://ufl.zoom.us/rec/play/Wny4jrohY1fctEe_LXqd2REM6NRtU8qr8RnaJztB7ymMd5Jj_gCYf1eAle) (https://ufl.zoom.us/rec/play/Wny4jrohY1fctEe_LXqd2REM6NRtU8qr8RnaJztB7ymMd5Jj_gCYf1eAle continueMode=true&_x_zm_rtaid=h4gsRRw_QbugEy3jXCpJFw.1616984572261.b538290e2780289 but I'll show how to do this in the notebook below.

In [80]:
```
from astroplan.plots import plot_finder_image
from astropy import units as u
from astropy.coordinates import SkyCoord
```

In [81]:
```
pl.figure(figsize=(12,12))
ax, hdu = plot_finder_image(SkyCoord.from_name('Pleiades'), survey='DSS', fov_rad
```



I found the stars by eye and matched them up to real coordinates using a finder chart loaded in ds9.

Record the stars' real coordinates:

In [82]:
```
star_coordinates = SkyCoord("""3:47:03.5093 +24:09:36.041
3:46:56.8012 +24:08:58.195
3:46:52.2998 +24:10:23.754
3:46:52.9937 +24:10:07.865
3:47:02.5002 +24:08:59.299
3:47:10.3589 +24:09:40.857""".split("\n"), frame='fk5', unit=(u.hour, u.deg))
star_coordinates
```

Out[82]:
```
<SkyCoord (FK5: equinox=J2000.000): (ra, dec) in deg
    [(56.76462208, 24.16001139), (56.73667167, 24.14949861),
     (56.71791583, 24.173265  ), (56.72080708, 24.16885139),
     (56.7604175 , 24.14980528), (56.79316208, 24.16134917)]>
```

The astropy coordinates package can understand strings like we wrote them above.

We can also enter the coordinates in other ways:

In [83]:
```
SkyCoord("3:47:03.59", "24:09:36", unit=(u.hour, u.deg))
```

Out[83]:
```
<SkyCoord (ICRS): (ra, dec) in deg
    (56.76495833, 24.16)>
```

We could even do the math ourselves:

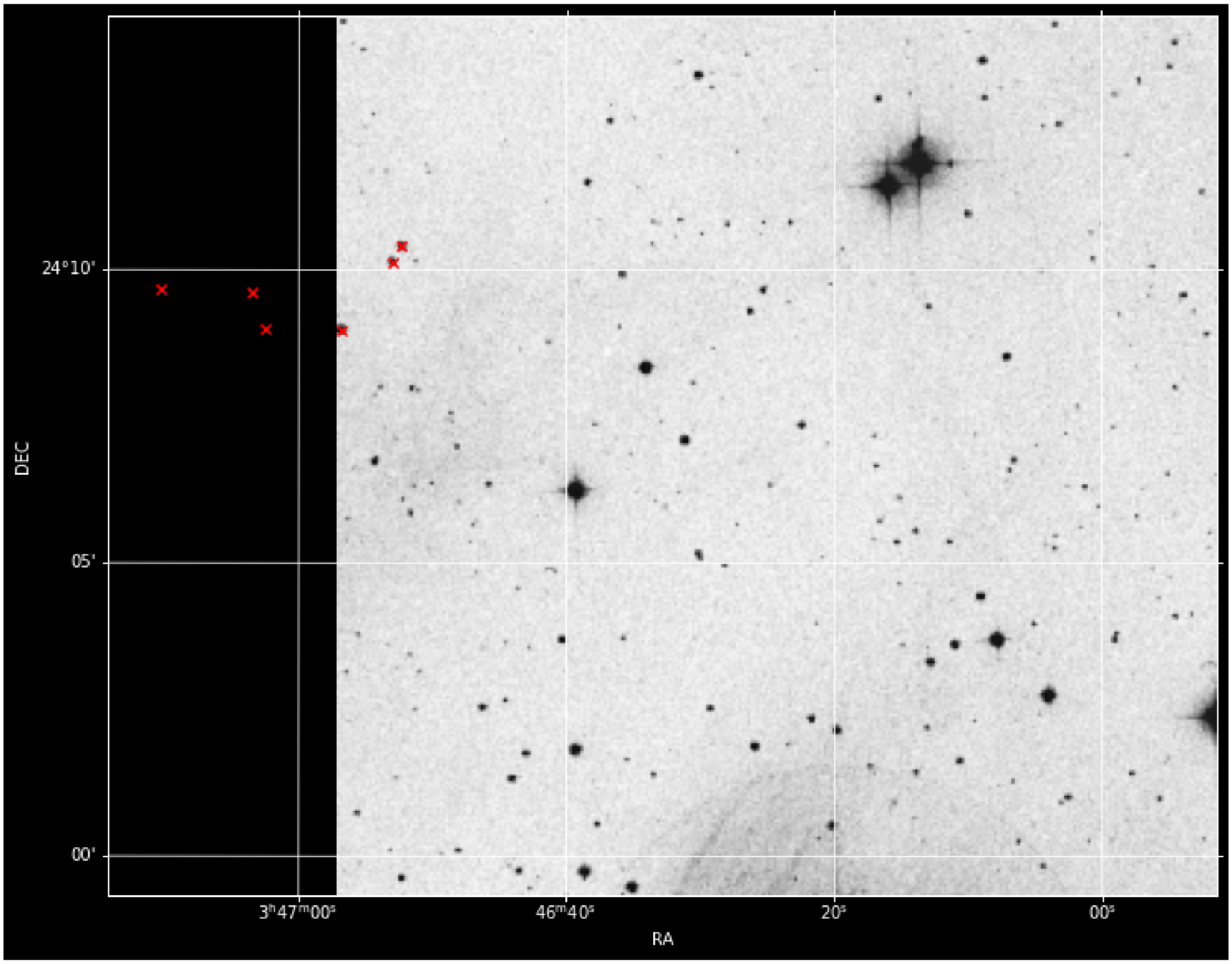
In [84]:
```
SkyCoord(3+47/60+3.59/3600, "24:09:36", unit=(u.hour, u.deg)).to_string('hmsdms')
```

Out[84]:
```
'03h47m03.59s +24d09m36s'
```

We can plot the stars' coordinates on top of the finder chart to prove we got them right:

In [85]:
```
pl.figure(figsize=(12,12))
ax, hdu = plot_finder_image(SkyCoord.from_name('Pleiades'), survey='DSS', fov_rad
ax.scatter(star_coordinates.ra.deg, star_coordinates.dec.deg, transform=ax.get_tr
```

Out[85]: <matplotlib.collections.PathCollection at 0x1af6a5b96a0>



Add star coordinates to our table

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Now that we've identified the stars, we want to make a new table that includes the stars' true coordinates as one of the columns:

In [86]:
```
Table([np.arange(len(fluxes)), fluxes, uncertainties, star_coordinates.ra, star_c
      names=['Star Number', 'Flux', 'Uncertainty', 'RA', 'Dec'])
```

Out[86]: *Table length=6*

Star Number	Flux	Uncertainty	RA	Dec
			deg	deg
int32	float64	float64	float64	float64
0	35316.171723260944	700.1730852477532	56.76462208333332	24.160011388888886
1	40898.35182370345	696.7739320352291	56.73667166666666	24.14949861111111
2	39515.09479166292	668.7418749842823	56.71791583333332	24.173265
3	8163.221738016462	435.20327093367445	56.72080708333333	24.16885138888889
4	18341.568210431426	582.6446125975509	56.76041749999999	24.149805277777777
5	10853.453148936138	533.3646210877812	56.79316208333332	24.161349166666664

Look up stars: SIMBAD

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Now we can look up the stars.

This process is similar to what we did in the Observation Planning notebooks.

In [87]:
```
from astroquery.simbad import Simbad
```

In [88]:
```
Simbad.reset_votable_fields()
Simbad.add_votable_fields('flux(B)', 'flux(V)', 'flux(I)')
```

In [89]:
```
simbad_rslt = Simbad.query_region(star_coordinates[0], radius=2*u.arcsec)
simbad_rslt
```

Out[89]: *Table length=1*

MAIN_ID	RA	DEC	RA_PREC	DEC_PREC	COO_ERR_MAJA	COO_ERR_MINA	COO_ERR_A
	"h:m:s"	"d:m:s"			mas	mas	
object	str13	str13	int16	int16	float32	float32	
V* V535 Tau	03 47 03.5821	+24 09 34.871	14	14	0.039	0.021	

In [90]:
```
mags_star0 = simbad_rslt[['FLUX_B','FLUX_V','FLUX_I']]
mags_star0
```

Out[90]: *Table length=1*

FLUX_B	FLUX_V	FLUX_I
mag	mag	mag
float32	float32	float32
15.93	14.58	12.72

The second star doesn't have fluxes in the SIMBAD catalog:

In [91]:
```
Simbad.query_region(star_coordinates[1], radius=2*u.arcsec)
```

Out[91]: *Table length=1*

MAIN_ID	RA	DEC	RA_PREC	DEC_PREC	COO_ERR_MAJA	COO_ERR_MINA	COO_ERR_A
	"h:m:s"	"d:m:s"			mas	mas	
object	str13	str13	int16	int16	float32	float32	
HAT 260-09130	03 46 56.8043	+24 08 58.151	14	14	0.130	0.086	

Look up stars: Vizier

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We can try a specific Vizier catalog:

In [92]:
```
from astroquery.vizier import Vizier
```

In [93]:
```
viz_result = Vizier.query_region(star_coordinates[1], radius=2*u.arcsec, catalog=
viz_result
```

Out[93]:
```
TableList with 1 tables:
	'0:I/322A/out' with 24 column(s) and 1 row(s)
```

In [94]:
```
viz_result = Vizier.query_region('V1073 Ori', radius=15*u.arcsec, catalog='I/322A
viz_result
```

Out[94]:
```
TableList with 1 tables:
	'0:I/322A/out' with 24 column(s) and 1 row(s)
```

In [95]:
```
viz_result[0]
```

Out[95]: *Table length=1*

UCAC4	RAJ2000	DEJ2000	ePos	f.mag	of	db	pmRA	pmDE	Jmag	Kmag	Bmag
	deg	deg	mas	mag			mas / yr	mas / yr	mag	mag	mag
str10	float64	float64	int16	float32	uint8	int16	float64	float64	float32	float32	float32
423-010230	83.8684242	-5.4389753	55	9.921	1	0	-2.7	-2.8	9.386	9.315	9.711

In [96]:
```
mags_star1 = viz_result[0][['Bmag','Vmag','imag']]
mags_star1
```

Out[96]: *Table length=1*

Bmag	Vmag	imag
mag	mag	mag
float32	float32	float32
9.711	9.712	9.757

Rinse & repeat:

In [97]:
```
mags_for_stars = {}
for starnum in (0,1,2,3,4,5):
    viz_result = Vizier.query_region(star_coordinates[starnum], radius=2*u.arcse
    mags_for_stars[starnum] = viz_result[0][['Bmag','Vmag','imag']]
```

In [98]:
```
mags_for_stars
```

Out[98]:
```
{0: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  16.022  14.658  13.308,
 1: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  15.237  14.081  13.158,
 2: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  14.591  13.887  13.350,
 3: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
      --      --      --,
 4: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  15.093  14.623  14.338,
 5: <Table length=1>
   Bmag    Vmag    imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
      --      --      --}
```

Not all of the stars had good measurements. We will ignore the stars that don't have measurements (that are masked) because we can't use them.

In [99]:
```
b_mags = [mags_for_stars[starnum]['Bmag'][0] for starnum in (0,1,2,3,4,5,)]
b_mags
```

Out[99]:
```
[16.022, 15.237, 14.591, masked, 15.093, masked]
```

In [100]:
```
v_mags = [mags_for_stars[starnum]['Vmag'][0] for starnum in (0,1,2,3,4,5,)]
v_mags
```

Out[100]:
```
[14.658, 14.081, 13.887, masked, 14.623, masked]
```

In [101]:
```
i_mags = [mags_for_stars[starnum]['imag'][0] for starnum in (0,1,2,3,4,5,)]
i_mags
```

Out[101]:
```
[13.308, 13.158, 13.35, masked, 14.338, masked]
```

Build Calibration Table

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In [102]:
```
cal_table = Table([np.arange(len(fluxes)), fluxes*u.electron, uncertainties*u.ele
        v_mags, b_mags, i_mags],
       names=['Star Number', 'Flux', 'Uncertainty', 'RA', 'Dec', 'Vmag', 'Bmag', '
cal_table
```

Out[102]: *Table length=6*

Star Number	Flux	Uncertainty	RA	Dec	
	electron	electron	deg	deg	
int32	float64	float64	float64	float64	
0	35316.171723260944	700.1730852477532	56.76462208333332	24.160011388888886	14.65799
1	40898.35182370345	696.7739320352291	56.73667166666666	24.14949861111111	14.08100
2	39515.09479166292	668.7418749842823	56.71791583333332	24.173265	13.8870
3	8163.221738016462	435.20327093367445	56.72080708333333	24.16885138888889	
4	18341.568210431426	582.6446125975509	56.76041749999999	24.149805277777777	14.62300
5	10853.453148936138	533.3646210877812	56.79316208333332	24.161349166666664	

From http://svo2.cab.inta-csic.es/theory/fps/index.php?id=Generic/Bessell.V&&mode=browse&gname=Generic&gname2=Bessell#filter (http://svo2.cab.inta-csic.es/theory/fps/index.php?id=Generic/Bessell.V&&mode=browse&gname=Generic&gname2=Bessell#filter), we get the Bessel-V zero-magnitude flux 3579.76 Jy.

In [103]:
```
bessel_v_mag0 = 3579.76*u.Jy
```

For star 0, then, we have:

In [104]:
```
mag_v_0 = cal_table['Vmag'][0]
flux_v_0 = 10**(-mag_v_0/2.5) * bessel_v_mag0
mag_v_0,flux_v_0
```

Out[104]:
```
(14.657999992370605, <Quantity 0.00490517 Jy>)
```

The same star produces a count rate calculated by dividing the total counts by the exposure time:

In [105]:
```
exptime = fits.getheader('pleiades_30s_C_other_001_darksub_flattened.fits')['EXPT
exptime
```

Out[105]: 30 s

In [106]:
```
star_0_electron_counts = cal_table['Flux'].quantity[0]
star_0_countrate = star_0_electron_counts / exptime
star_0_countrate
```

Out[106]: $1177.2057 \ \frac{\mathrm{e^-}}{\mathrm{s}}$

So we end up with star 0 has flux 0.005 Jy (5 mJy) and produces 1200 counts/second.

Magnitude Zero Point

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To get the zeropoint, we want the magnitude that produces 1 electron (1 count) per second:

We define this by setting the zero point based on the flux received in one second:

$$m_{inst} \equiv m_{*,observed\ in\ 1s} \equiv -2.5 \log \frac{counts}{t_{exp}}$$

We can then derive the zero-point by relating our *instrumental magnitude* ($m_{inst} = m_{*,observed\ in\ 1s}$) to the catalogued, "known" magnitude

$$m_{*,catalog} = m_{*,observed\ in\ 1s} + m_{zp}$$

We then solve for the zero-point magnitude m_{zp}

In [107]:
```
# first we calculate the instrumental magnitude in two different, equivalent ways
-2.5*np.log10(star_0_countrate.value), -2.5*np.log10(star_0_electron_counts.value
```

Out[107]: (-7.6771309129241345, -7.6771309129241345)

In [108]:
```
# solve for the zero point
star_0_instrumental_mag = -2.5*np.log10(star_0_countrate.value)
zeropoint = mag_v_0 - star_0_instrumental_mag
star_0_instrumental_mag, zeropoint
```

Out[108]: (-7.6771309129241345, 22.33513090529474)

We repeat for the other stars:

In [109]:
```
zeropoint_measurements = []
for row in cal_table:
    mag_v = row['Vmag']
    if mag_v:
        star_countrate = row['Flux'] / exptime
        star_instrumental_mag = -2.5*np.log10(star_countrate.value)
        zeropoint = mag_v - star_instrumental_mag
        print(f"Instrumental magnitude of star {row['Star Number']}={star_instrum
        zeropoint_measurements.append(zeropoint)
```

```
Instrumental magnitude of star 0=-7.7, m_zp=22.3
Instrumental magnitude of star 1=-7.8, m_zp=21.9
Instrumental magnitude of star 2=-7.8, m_zp=21.7
Instrumental magnitude of star 4=-7.0, m_zp=21.6
```

The zero-point should be the same for all stars. It isn't in this case, but it's pretty close for the first two stars.

There are several reasons some stars could give incorrect zero-points:

- Some sort of problem with the flux measurement for that star (hot pixel, cosmic ray, etc)
- The star may be variable
- We could have mis-matched the star to the catalog
- There could be differences between the star and the catalog

Zero-point uncertainty

Because we have multiple measurements, we can use the standard deviation of the measurements as a quantitative estimate of our uncertainty.

In [110]:
```
avg_zp, std_zp = np.mean(zeropoint_measurements),np.std(zeropoint_measurements)
print(f"Zero-point is estimated to be {avg_zp:0.1f}+/-{std_zp:0.1f}")
```

```
Zero-point is estimated to be 21.9+/-0.3
```

Estimate the Sky Background

Index

We already determined the average sky background in electrons:

In [111]:
```
sky_mean
```

Out[111]:
```
1035.2701922573067
```

The magnitude, per pixel, is then:

In [112]:
```
mag_sky_inst = -2.5 * np.log10(sky_mean / exptime.value)
mag_sky_inst
```

Out[112]: -3.8448311379067563

In [113]:
```
mag_sky = mag_sky_inst + avg_zp
print(f"Sky magnitude is {mag_sky:0.1f} per pixel")
```

```
Sky magnitude is 18.0 per pixel
```

If we know our pixel scale, which we can measure from comparing star locations in the finder chart to those in the image, we can get the surface brightness in magnitudes per square arcsecond.

$$m_{per\ arcsec} - m_{per\ pix} = -2.5 \log \frac{1 arcsec^2}{pixel\ area}$$

In [114]:
```
pixscale = 0.55*u.arcsec # 1-dimensional pixel scale
```

In [115]:
```
sky_brightness = mag_sky + 2.5*np.log10(pixscale**2 / u.arcsec**2)
print(f"The sky surface brightness is {sky_brightness:0.1f} magnitudes per square
```

```
The sky surface brightness is 16.7 magnitudes per square arcsecond
```

Exercise

Do these calculations for your data on the star cluster:

- Select stars
- Measure Photometry
- Finder Chart Matching
- Add coordinates to table
- Look up stars: SIMBAD
- Look up stars: Vizier
- Build Calibration Table
- Magnitude Zero Point
- Sky Brightness

End

Index

In [116]:
```
import os
```

In [117]:
```
os.chdir("C:\\Users\\Sydnee O'Donnell\\OneDrive\\UF\\Obs Tech 1\\AST3722-Fall-202
```

In [7]:
```
import glob

biases = glob.glob("Darks\\dark_40ms*.FIT")
dark_40ms = [fits.getdata(x)*fits.getheader(x)['EGAIN'] for x in biases]
average_40ms_dark = np.mean(dark_40ms, axis=0)
stddev_40ms_dark = np.std(dark_40ms, axis=0)
del dark_40ms
```

In [8]:
```
bias_timestream = [fits.getdata(x)*fits.getheader(x)['EGAIN'] for x in biases]
mean_bias = np.mean(bias_timestream, axis=0)
stddev_bias = np.std(bias_timestream, axis=0)
readnoise = np.mean(stddev_bias)
del bias_timestream
```

In [9]:
```
dark20s = glob.glob("Darks\\dark_20s*.FIT")
dark_20s = [fits.getdata(x)*fits.getheader(x)['EGAIN'] for x in dark20s]
average_20s_dark = np.mean(dark_20s, axis=0)
stddev_20s_dark = np.std(dark_20s, axis=0)
del dark_20s
```

In [10]:
```
clear_flat = glob.glob("Twighlight Flats\\flat_15s_Clear*FIT")
I_flat = glob.glob("Twighlight Flats\\flat_10s_I*FIT")
B_flat = glob.glob("Twighlight Flats\\flat_15s_B*FIT")
V_flat = glob.glob("Twighlight Flats\\flat_15s_V*FIT")
```

In [11]:
```
#Clear, B , V , I
flat = [clear_flat]
flat_timestream = []
mean_flat = []
bias_subtracted_flat = []
normed_flat = []

for i in range(1):
    flat_timestream.append([fits.getdata(x)*fits.getheader(x)['EGAIN'] for x in f
    mean_flat.append(np.mean(flat_timestream[i], axis=0))
    bias_subtracted_flat.append(mean_flat[i] - mean_bias)
    normed_flat.append(bias_subtracted_flat[i]/bias_subtracted_flat[i].mean())

del flat_timestream
```

In [12]:
```
mean_bias_noise = readnoise / np.sqrt(len(biases))
mean_bias_noise
```

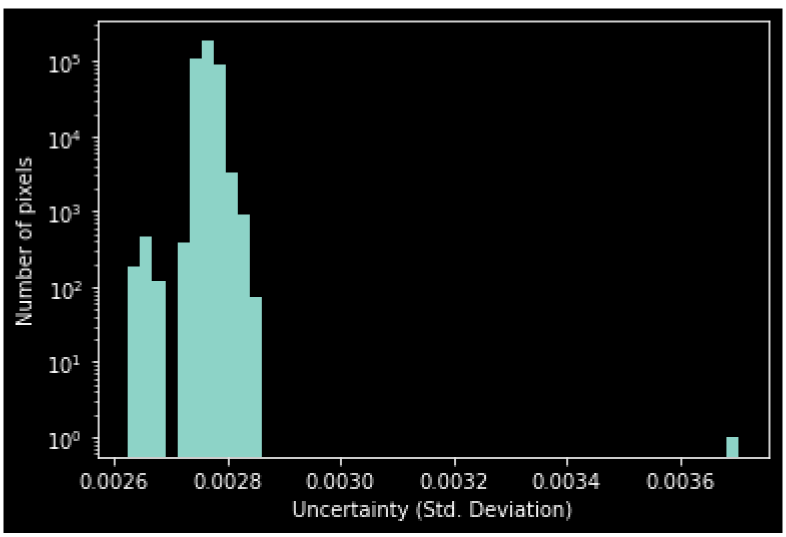
Out[12]:
```
6.321659545083941
```

In [13]:
```
gain = fits.getheader("Twighlight Flats\\flat_15s_Clear001.FIT")['EGAIN']
flat_poisson_uncertainty = []
flat_singleframe_uncertainty = []
flat_total_uncertainty = []
normalized_mean_flat = []

for i in range(1):
    flat_poisson_uncertainty.append((bias_subtracted_flat[i])**0.5)
    flat_singleframe_uncertainty.append((flat_poisson_uncertainty[i]**2 + readnoi
    flat_total_uncertainty.append(((flat_singleframe_uncertainty[i]/np.sqrt(len(f
    mean_of_flat = np.mean(bias_subtracted_flat[i])
    normalized_mean_flat.append(bias_subtracted_flat[i] / mean_of_flat)
```

In [14]:
```
uncertainty_on_20s_mean_dark = stddev_20s_dark / np.sqrt(len(dark20s))
```

In [15]:
```
M13_shift = fits.getdata('M13\\M13_20s_Clear001.FIT')*fits.getheader('M13\\M13_20
```

In [16]:
```
normalized_flat_uncertainty = []
for i in range(1):
    pl.figure()
    normalized_flat_uncertainty.append(flat_total_uncertainty[i] / mean_of_flat)
    pl.xlabel("Uncertainty (Std. Deviation)")
    pl.ylabel("Number of pixels")
    _=pl.hist(normalized_flat_uncertainty[i].ravel(), bins=50, log=True)
```



In [17]:
```
M13_darksub = (M13_shift - average_40ms_dark)
M13_darksub_uncertainty = ((M13_darksub + readnoise**2 + uncertainty_on_20s_mean_
M13_darksub_flattened = ( M13_darksub / normalized_mean_flat[0])
M13_darksub_flattened_uncertainty = (((M13_darksub_uncertainty**2 / M13_darksub**
```

In [18]:
```
M13_darksub_flattened.shape
```

Out[18]:
```
(510, 765)
```

In [19]:
```
header = fits.getheader('M13\\M13_20s_B001.FIT')

fh = fits.PrimaryHDU(data = M13_darksub_flattened, header=header)
fh.writeto('M13_darksub_C1_flattened.FIT', overwrite=True)
```

In [20]:
```
fh = fits.PrimaryHDU(data = M13_darksub_flattened_uncertainty, header=header)
fh.writeto('M13_darksub_C1_flattened_uncertainty.FIT', overwrite=True)
```

In [21]:
```
M13_darksub_C_flattened = fits.getdata('M13_darksub_C1_flattened.FIT')
M13_darksub_C_flattened_uncertainty = fits.getdata('M13_darksub_C1_flattened_unce
```

In [118]:
```
sky_mean = M13_darksub_C_flattened.mean()
sky_median = np.median(M13_darksub_C_flattened)
print(sky_mean, sky_median)
```

```
770.7818516752839 698.2592005869254
```

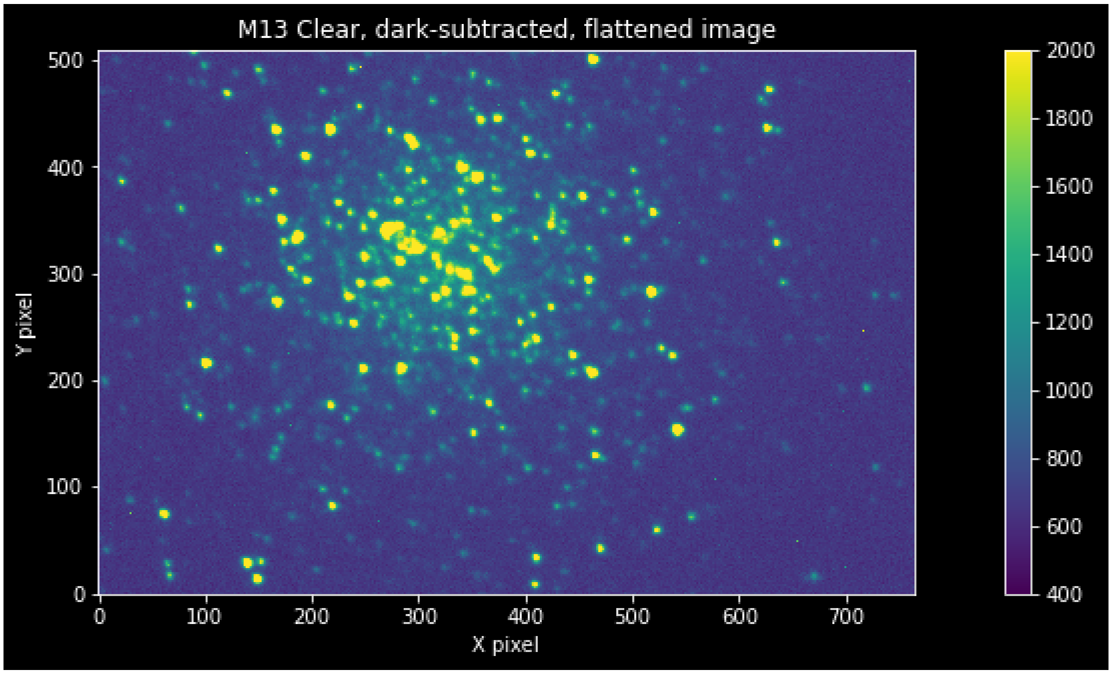
In [119]:
```
sky_stddev = M13_darksub_C_flattened.std() # estimate of the per-pixel error
print(f"Standard deviation of the data: {sky_stddev:0.1f}")
print(f"Average of the per-pixel uncertainty from error propagation: {M13_darksub
```

```
Standard deviation of the data: 293.8
Average of the per-pixel uncertainty from error propagation: 31.8
```

In [120]:
```
sky_subtracted_M13_clear = M13_darksub_C_flattened - sky_mean
sky_subtracted_M13_clear
```

Out[120]:
```
array([[-104.73145688,  -61.18083853,  -68.99133244, ...,  -77.0268335 ,
        -138.24230854, -120.02471857],
       [ -19.53240195,  -64.34239917,  -52.70130533, ..., -158.07892519,
        -160.3704669 , -130.40802924],
       [ -50.82446998,  -74.75655273,   -4.45535041, ..., -109.02323886,
         -62.12628983, -145.43330766],
       ...,
       [-162.40966958, -155.53360229,  -97.46276775, ..., -100.42273696,
        -100.50558818, -103.3110619 ],
       [-134.16121826, -101.24930919,  -92.922281  , ...,  -52.30881427,
        -118.37581347,  -91.51678981],
       [-104.8501044 , -128.56324206, -116.75000474, ..., -131.15902401,
        -184.93183576, -163.83296872]])
```

In [121]:
```
pl.figure(figsize=(16,5))
im = pl.imshow(M13_darksub_C_flattened, origin='lower', interpolation='none', vma
pl.colorbar(im)
_=pl.title("M13 Clear, dark-subtracted, flattened image")
_=pl.xlabel("X pixel")
_=pl.ylabel("Y pixel")
```



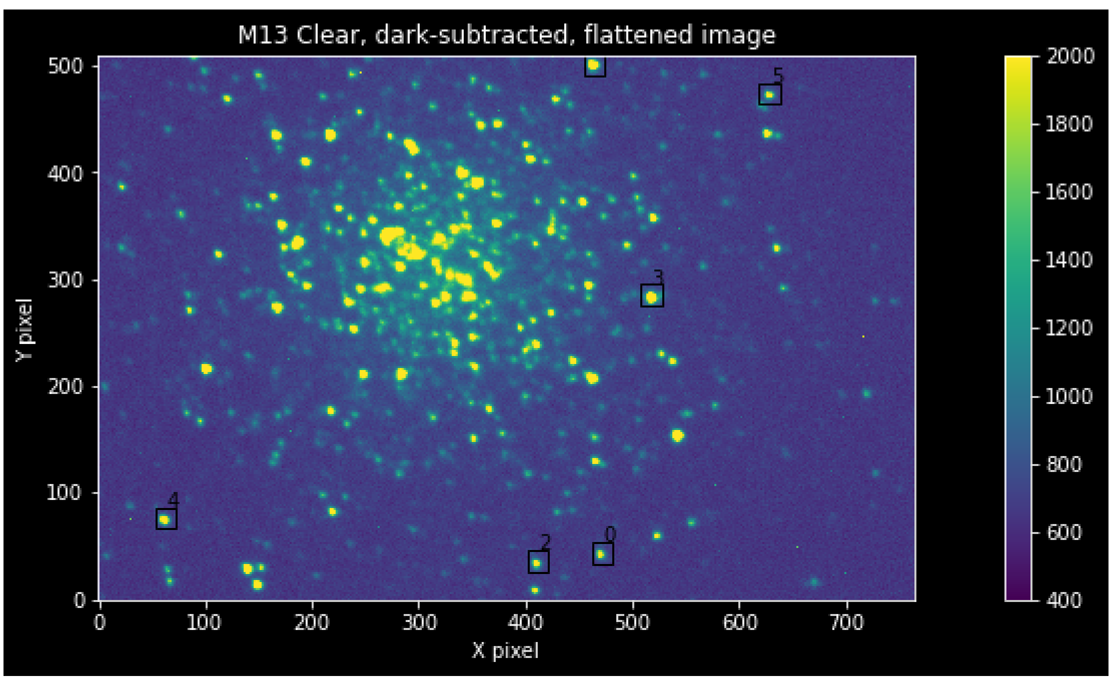
In [122]:
```
star_centers = [[472,43], [464,501], [412,36], [518,285], [63,76], [629,474]]
width = 20
height = 20
##[[64.6,75.8], [627.4,439.6], [629.8,474.88], [140.2,29.92], [150,15], [412,36]]
## [411,35], [471,44]]
```

16:41:48.4526, +36:25:47.714 16:41:47.9901, +36:29:54.351 16:41:48.4526, +36:25:47.714 16:41:47.9901, +36:29:54.351 16:41:30.3895, +36:29:42.752 16:41:53.9756, +36:26:08.733

In [123]:
```
def calculate_star_flux_and_error(cutout_star, cutout_uncertainty, sky_stddev):

    mask = cutout_star > 2*sky_stddev
    masked_star_sum = cutout_star[mask].sum()
    masked_star_sum_error = ((cutout_uncertainty[mask]**2).sum() + sky_stddev**2*

    return masked_star_sum, masked_star_sum_error

star_centers
```

Out[123]:
```
[[472, 43], [464, 501], [412, 36], [518, 285], [63, 76], [629, 474]]
```

In [124]:
```
fig = pl.figure(figsize=(16,5))
ax = fig.gca()
im = pl.imshow(M13_darksub_C_flattened,
               origin='lower', interpolation='none', vmax=2000, vmin=400)
pl.colorbar(im)
_=pl.title("M13 Clear, dark-subtracted, flattened image")
_=pl.xlabel("X pixel")
_=pl.ylabel("Y pixel")
for ii,(xcen, ycen) in enumerate(star_centers):
    rect = pl.Rectangle(xy=[xcen-width/2, ycen-height/2],
                         width=width, height=height,
                     facecolor='none', edgecolor='k')
    ax.add_patch(rect)
    ax.text(xcen, ycen+height/2, str(ii), color='k')
```

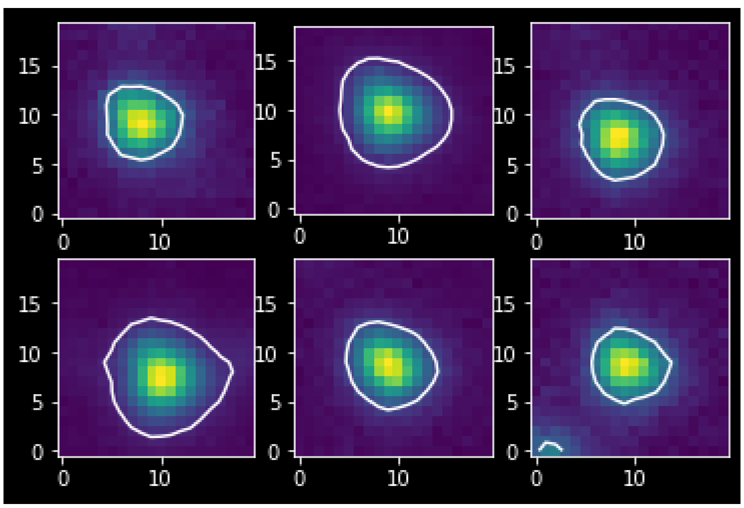


In [125]:
```
for (xc, yc) in star_centers:
    slc = slice(yc-height//2,yc+height//2),slice(xc-width//2,xc+width//2)
    print(slc)
```

```
(slice(33, 53, None), slice(462, 482, None))
(slice(491, 511, None), slice(454, 474, None))
(slice(26, 46, None), slice(402, 422, None))
(slice(275, 295, None), slice(508, 528, None))
(slice(66, 86, None), slice(53, 73, None))
(slice(464, 484, None), slice(619, 639, None))
```

In [126]:
```
results = [calculate_star_flux_and_error(
    sky_subtracted_M13_clear[yc-height//2:yc+height//2,
                              xc-width//2:xc+width//2],
    M13_darksub_C_flattened_uncertainty[yc-height//2:yc+height//2,
                                       xc-width//2:xc+width//2],
    sky_stddev)
        for (xc,yc) in star_centers]
```

In [127]:
```
for ii,(xc, yc) in enumerate(star_centers):
    ax = pl.subplot(2,3,ii+1)
    cutout = sky_subtracted_M13_clear[yc-height//2:yc+height//2,
                                      xc-width//2:xc+width//2]
    ax.imshow(cutout)
    ax.contour(cutout, levels=[2*sky_stddev], colors=['w'])
```

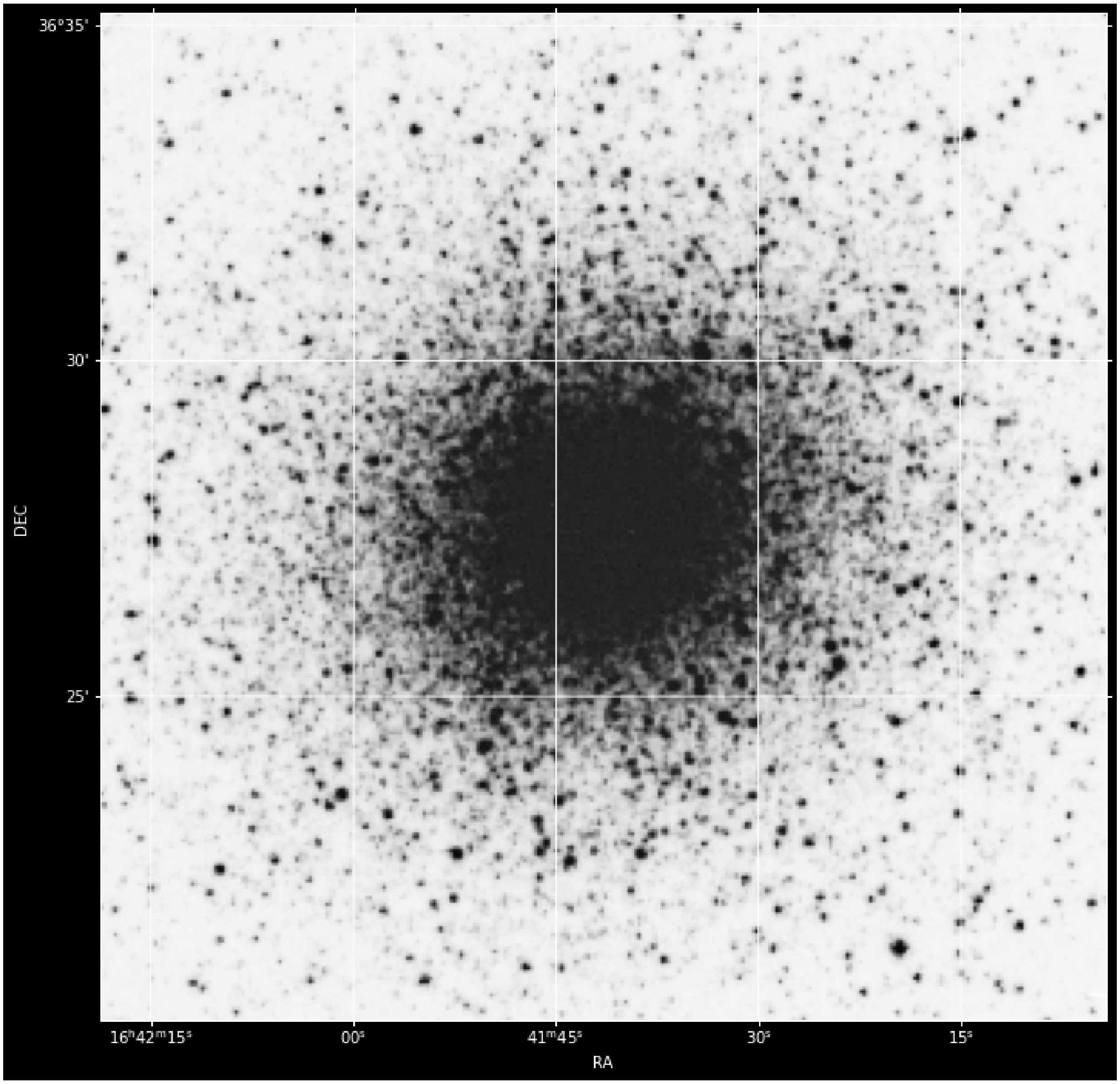


In [128]:
```
fluxes, uncertainties = np.array(results).T

Table([np.arange(len(fluxes)), fluxes, uncertainties], names=['Star Number', 'Flu
```

Out[128]: *Table length=6*

Star Number	Flux	Uncertainty
int32	float64	float64
0	54887.73220635183	2018.569093005021
1	202038.45824647456	2901.833675477675
2	70872.40259784479	2188.507085326111
3	229056.80292245708	3124.621995834513
4	90111.52391605178	2290.2877815407523
5	54272.866991865056	2061.567696973357

In [129]:
```
pl.figure(figsize=(12,12))
ax, hdu = plot_finder_image(SkyCoord.from_name('M13'), survey='DSS', fov_radius=1
```



In [ ]:

In [130]:
```
star_coordinates = SkyCoord("""16:41:48.4526 +36:25:47.714
                              16:41:47.9901 +36:29:54.351
                              16:41:48.4526 +36:25:47.714
                              16:41:47.9901 +36:29:54.351
                              16:41:30.3895 +36:29:42.752
                              16:41:53.9756 +36:26:08.733""".split("\n"), frame=
star_coordinates
```

Out[130]:
```
<SkyCoord (FK5: equinox=J2000.000): (ra, dec) in deg
    [(250.45188583, 36.42992056), (250.44995875, 36.49843083),
     (250.45188583, 36.42992056), (250.44995875, 36.49843083),
     (250.37662292, 36.49520889), (250.47489833, 36.43575917)]>
```

In [131]:
```
Simbad.reset_votable_fields()
Simbad.add_votable_fields('flux(B)', 'flux(V)', 'flux(I)')

Table([np.arange(len(fluxes)), fluxes, uncertainties, star_coordinates.ra, star_c
      names=['Star Number', 'Flux', 'Uncertainty', 'RA', 'Dec'])
```

Out[131]: *Table length=6*

Star Number	Flux	Uncertainty	RA	Dec
			deg	deg
int32	float64	float64	float64	float64
0	54887.73220635183	2018.569093005021	250.45188583333328	36.429920555555555
1	202038.45824647456	2901.833675477675	250.44995874999995	36.49843083333334
2	70872.40259784479	2188.507085326111	250.45188583333328	36.429920555555555
3	229056.80292245708	3124.621995834513	250.44995874999995	36.49843083333334
4	90111.52391605178	2290.2877815407523	250.37662291666663	36.49520888888889
5	54272.866991865056	2061.567696973357	250.47489833333333	36.435759166666664

In [132]:
```
simbad_rslt = Simbad.query_region(star_coordinates[0], radius=2*u.arcsec)
simbad_rslt
```

Out[132]: *Table length=1*

MAIN_ID	RA	DEC	RA_PREC	DEC_PREC	COO_ERR_MAJA	COO_ERR_MINA	COO_ERR_A
	"h:m:s"	"d:m:s"			mas	mas	
object	str13	str13	int16	int16	float32	float32	
NGC 6205 890	16 41 48.46	+36 25 47.4	6	6	70.000	60.000	

In [133]:
```
viz_result = Vizier.query_region(star_coordinates[1], radius=2*u.arcsec, catalog=
viz_result
```

Out[133]:
```
TableList with 1 tables:
	'0:J/MNRAS/485/3042/table4' with 25 column(s) and 1 row(s)
```

In [134]:
```
viz_result[0]
```

Out[134]:

Table length=1

Cluster	Star	Xpos	Ypos	Umag	e_Umag	o_Umag	Bmag	e_Bmag	o_Bmag	Vmag	e_
		arcsec	arcsec	mag	mag		mag	mag		mag	
str7	int32	float64	float64	float32	float32	int16	float32	float32	int16	float32	fl
NGC6205	83107	78.251	136.009	14.816	0.0014	27	14.117	0.0028	48	13.039	0

In [135]:
```
mags_star1 = viz_result[0]['Bmag','Vmag','Imag']
mags_star1
```

Out[135]:

Table length=1

Bmag	Vmag	Imag
mag	mag	mag
float32	float32	float32
14.117	13.039	11.861

In [136]:
```
mags_for_stars_my = {}
for i in (1, 2, 3, 5):
    viz_result = Vizier.query_region(star_coordinates[i], radius=2*u.arcsec, cata
    mags_for_stars_my[i] = viz_result[0]['Bmag','Vmag','Imag']
mags_for_stars_my
```

Out[136]:
```
{1: <Table length=1>
   Bmag    Vmag    Imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  14.117  13.039  11.861,
 2: <Table length=3>
   Bmag    Vmag    Imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  15.031  14.836  14.534
  15.461  15.380  15.341
  17.649  16.989  16.178,
 3: <Table length=1>
   Bmag    Vmag    Imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  14.117  13.039  11.861,
 5: <Table length=1>
   Bmag    Vmag    Imag
   mag     mag     mag
 float32 float32 float32
 ------- ------- -------
  14.121  13.047  11.859}
```

In [137]:
```
b_mags = [mags_for_stars_my[i]['Bmag'][0] for i in (1, 2, 3, 5)]

v_mags = [mags_for_stars_my[i]['Vmag'][0] for i in (1, 2, 3, 5)]

i_mags = [mags_for_stars_my[i]['Imag'][0] for i in (1, 2, 3, 5)]

b_mags, v_mags, i_mags
```

Out[137]:
```
([14.117, 15.031, 14.117, 14.121],
 [13.039, 14.836, 13.039, 13.047],
 [11.861, 14.534, 11.861, 11.859])
```

In [138]:
```
indices = [1, 2, 3, 5]
a = np.array(fluxes)
b = a[indices]
fluxes_my = list(b)

c = np.array(uncertainties)
d = c[indices]
uncertainties_my = list(d)

x = np.array(star_coordinates.ra)
y = x[indices]
star_coordinates_ra = list(y)

z = np.array(star_coordinates.dec)
t = z[indices]
star_coordinates_dec = list(t)

fluxes_my, uncertainties_my, star_coordinates_ra, star_coordinates_dec
```

Out[138]:
```
([202038.45824647456,
  70872.40259784479,
  229056.80292245708,
  54272.866991865056],
 [2901.833675477675, 2188.507085326111, 3124.621995834513, 2061.567696973357],
 [250.44995874999995,
  250.45188583333328,
  250.44995874999995,
  250.47489833333333],
 [36.49843083333334,
  36.429920555555555,
  36.49843083333334,
  36.435759166666664])
```

In [139]:
```
cal_table_my = Table([np.arange(len(fluxes_my)), fluxes_my*u.electron, uncertaint
       v_mags, b_mags, i_mags],
      names=['Star Number', 'Flux', 'Uncertainty', 'RA', 'Dec', 'Vmag', 'Bmag', '
cal_table_my
```

Out[139]: *Table length=4*

Star Number	Flux	Uncertainty	RA	Dec	Vmag
	electron	electron			
int32	float64	float64	float64	float64	float32
0	202038.45824647456	2901.833675477675	250.44995874999995	36.49843083333334	13.039
1	70872.40259784479	2188.507085326111	250.45188583333328	36.429920555555555	14.836
2	229056.80292245708	3124.621995834513	250.44995874999995	36.49843083333334	13.039
3	54272.866991865056	2061.567696973357	250.47489833333333	36.435759166666664	13.047

In [141]:
```
exptime = fits.getheader('M13_darksub_C1_flattened.FIT')['EXPTIME'] * u.s
exptime
```

Out[141]: 20 s

In [142]:
```
star_0_electron_counts = cal_table['Flux'].quantity[0]
star_0_countrate = star_0_electron_counts / exptime
star_0_countrate
```

Out[142]: $1765.8086 \ \frac{e^-}{s}$

In [143]:
```
-2.5*np.log10(star_0_countrate.value), -2.5*np.log10(star_0_electron_counts.value

star_0_instrumental_mag = -2.5*np.log10(star_0_countrate.value)
zeropoint = mag_v_0 - star_0_instrumental_mag
star_0_instrumental_mag, zeropoint
```

Out[143]: (-8.117359060563338, 22.775359052933943)

In [144]:
```
zeropoint_measurements = []
for row in cal_table:
    mag_v = row['Vmag']
    if mag_v:
        star_countrate = row['Flux'] / exptime
        star_instrumental_mag = -2.5*np.log10(star_countrate.value)
        zeropoint = mag_v - star_instrumental_mag
        print(f"Instrumental magnitude of star {row['Star Number']}={star_instrum
        zeropoint_measurements.append(zeropoint)
```

```
Instrumental magnitude of star 0=-8.1, m_zp=22.8
Instrumental magnitude of star 1=-8.3, m_zp=22.4
Instrumental magnitude of star 2=-8.2, m_zp=22.1
Instrumental magnitude of star 4=-7.4, m_zp=22.0
```

In [145]:
```
mag_sky_inst = -2.5 * np.log10(sky_mean / exptime.value)
mag_sky_inst
```

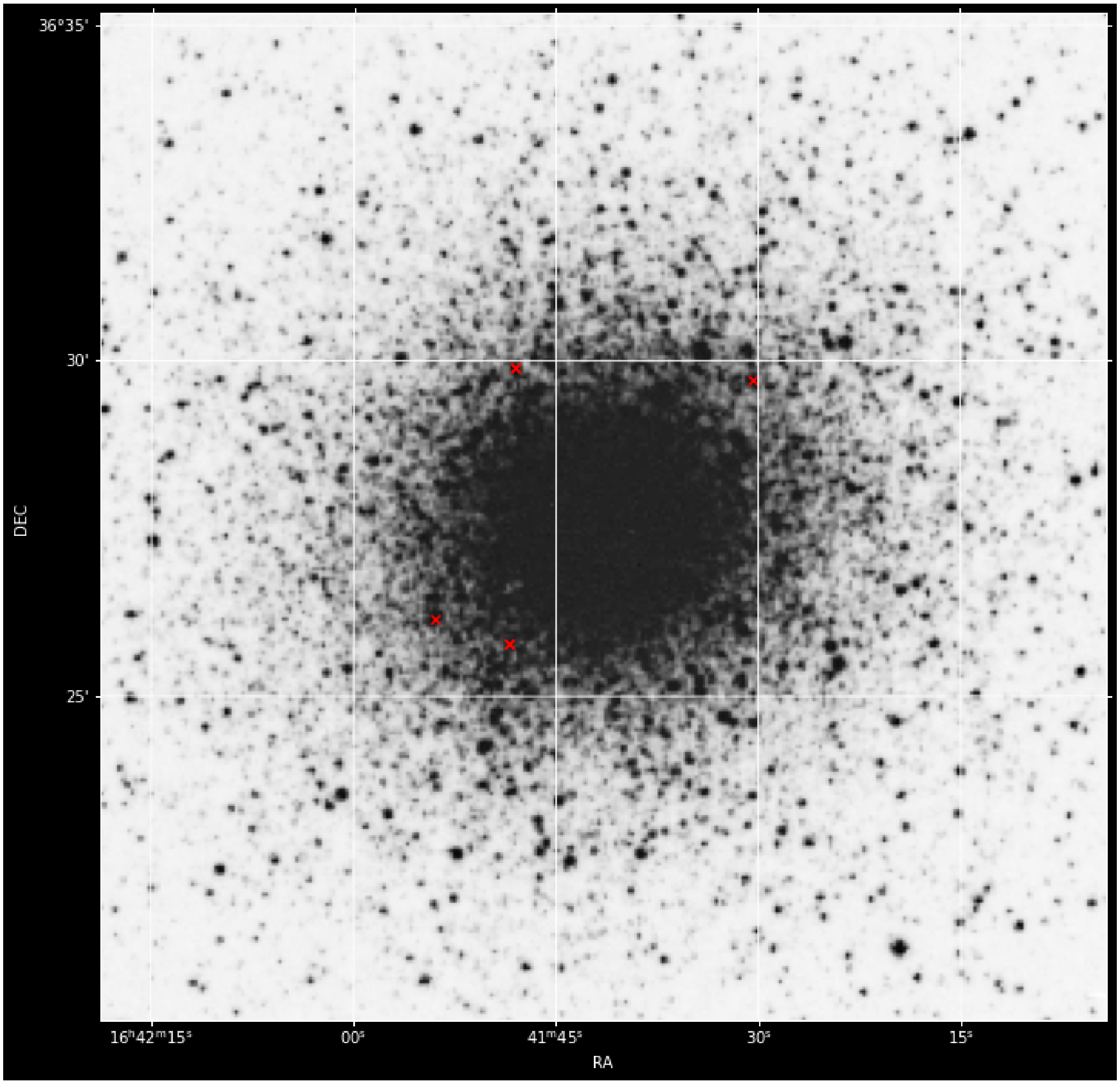
Out[145]: -3.9647537120658787

In [146]:
```
mag_sky = mag_sky_inst + avg_zp
print(f"Sky magnitude is {mag_sky:0.1f} per pixel")

pixscale = 0.55*u.arcsec

sky_brightness = mag_sky + 2.5*np.log10(pixscale**2 / u.arcsec**2)
print(f"The sky surface brightness is {sky_brightness:0.1f} magnitudes per square
```

```
Sky magnitude is 17.9 per pixel
The sky surface brightness is 16.6 magnitudes per square arcsecond
```

In [147]:
```
pl.figure(figsize=(12,12))
ax, hdu = plot_finder_image(SkyCoord.from_name('M13'), survey='DSS', fov_radius=1
ax.scatter(star_coordinates.ra.deg, star_coordinates.dec.deg, transform=ax.get_tr
```

Out[147]: <matplotlib.collections.PathCollection at 0x1af6ac35af0>



In [ ]: