ZTF24aahgqwk in NGC 3443

Light Curve Notebook

This notebook begins with the 36 stacked images produced by our Calibration Notebook, and produces a light curve, consisting of 18 Sloan r' and 18 Sloan g' data points.

See a least squares notebook for background for the method used below.

In [1]:
```
import os
import numpy as np
from scipy.optimize import least_squares
from astropy import units as u
from astropy.nddata import CCDData
from astropy.io import fits
from ccdproc import ImageFileCollection
import astroalign as aa
import matplotlib.pyplot as plt
%matplotlib inline
from math import log10, floor, sqrt, log, exp, pi

# THIS COMMENT IS THE LONGEST A LINE CAN BE AND STILL RENDER COMPLETELY WHEN PRINTING IN LANDSCAPE MODE.
# THIS COMMENT IS 72 CHARACTERS WITHOUT COUNTING THE NEWLINE AT THE END.

# This notebook needs to be able to find the stacked images.

home_directory = os.path.expanduser('~')
supernova_project_directory = os.path.join(home_directory, 'Projects', 'supernova-observation')
stacked_directory = os.path.join(supernova_project_directory, 'analyses', 'ZTF24aahgqwk', 'stacked')

# The 36 images are in the stacked directory. There were 18 observation sessions with 2 filters each.

# filters
```

```
filters = ['r', 'g']
filter_full_names = ["Sloan r'", "Sloan g'"]

# observation dates (UTC)

observation_dates = [
    '2024-03-20',
    '2024-03-21',
    '2024-03-23',
    '2024-03-27',
    '2024-04-02',
    '2024-04-03',
    '2024-04-04',
    '2024-04-06',
    '2024-04-10',
    '2024-04-11',
    '2024-04-13',
    '2024-04-17',
    '2024-04-21',
    '2024-04-22',
    '2024-04-23',
    '2024-04-29',
    '2024-04-30',
    '2024-05-02'
]

# We will need to specify rectangles surrounding the target and the reference stars.

# use named tuples to improve readability

from collections import namedtuple

Point = namedtuple('Point', 'x y')
Extent = namedtuple('Extent', 'width height')
Rectangle = namedtuple('Rectangle', 'center extent')

# Various utilities
```

```
def file_for_date_and_filter(date, filter):
    return os.path.join(stacked_directory, date + '-' + filter + '_stacked.fit')

def stacked_image_for_date_and_filter(date, filter):
    file = file_for_date_and_filter(date, filter)
    return CCDData.read(file, unit=u.adu)

# Log stretch utility

def log_stretch_transform(black_point, saturation_range):

    log_saturation_range = log10(saturation_range)

    def fn(pixel_value):
        pixel_value -= black_point
        if pixel_value <= 1.0:
            return 0
        else:
            log_pixel_value = log10(pixel_value)
            if log_pixel_value >= log_saturation_range:
                return 255;
            else:
                return floor(256 * log_pixel_value / log_saturation_range)

    return fn
```

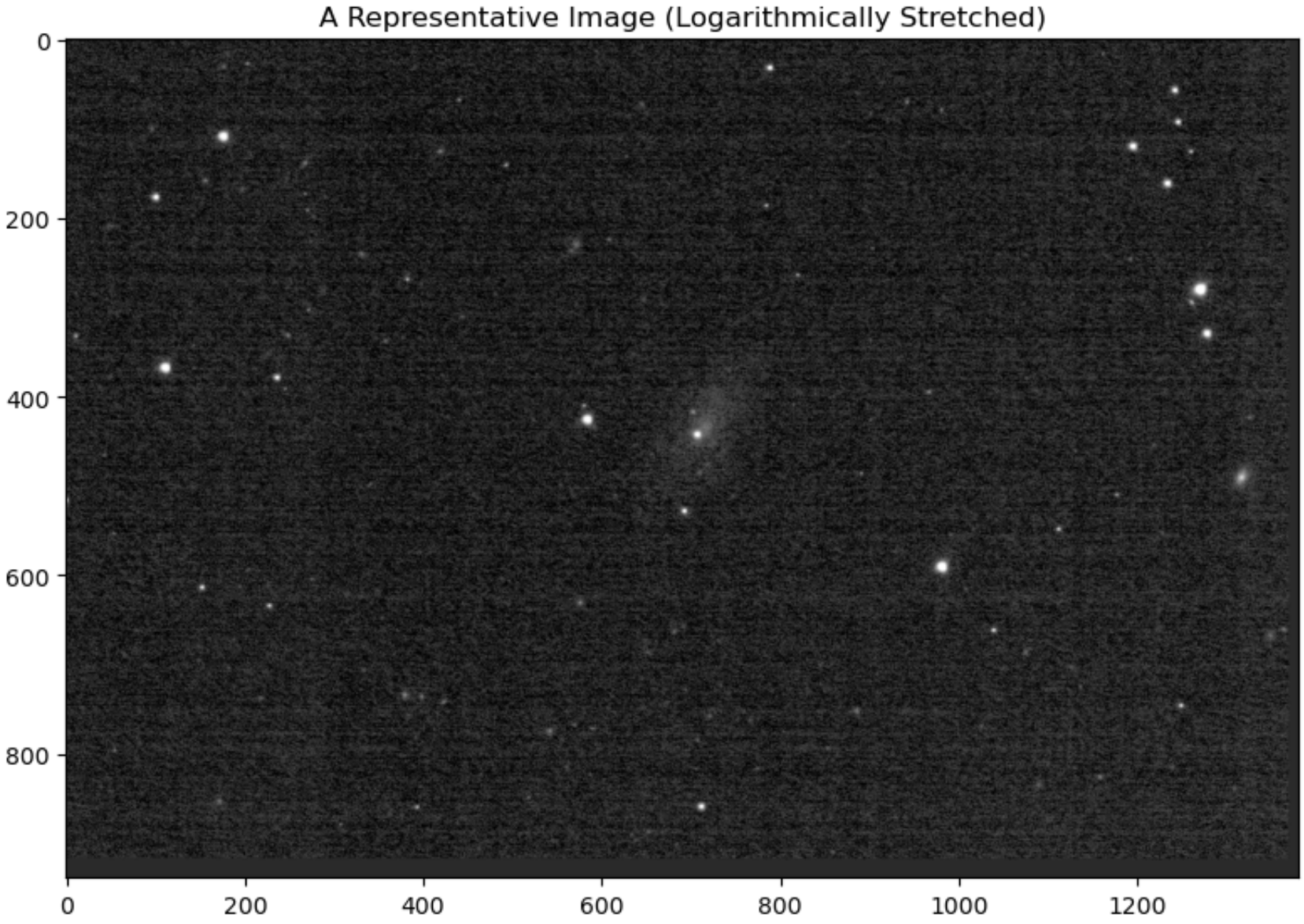
Specify the Regions of Interest for the Target and Reference Stars

In [2]:
```
# Guarantee the extent widths and heights are odd so the loops do not have to handle even and odd cases.
EXTENT_HALF_WIDTH = 10
EXTENT_WIDTH = 2 * EXTENT_HALF_WIDTH + 1
EXTENT_HEIGHT = EXTENT_WIDTH
EXTENT = Extent(EXTENT_WIDTH, EXTENT_HEIGHT)

CENTERS = [
    Point(708, 443), # target
    Point(177, 109), # reference star at far upper left
    Point(112, 368), # reference star at far left
    Point(585, 426), # reference star just left of center
    Point(982, 591), # reference star right of center
    Point(1271, 280), # reference star at far right
]

CENTER_COUNT = len(CENTERS)
```

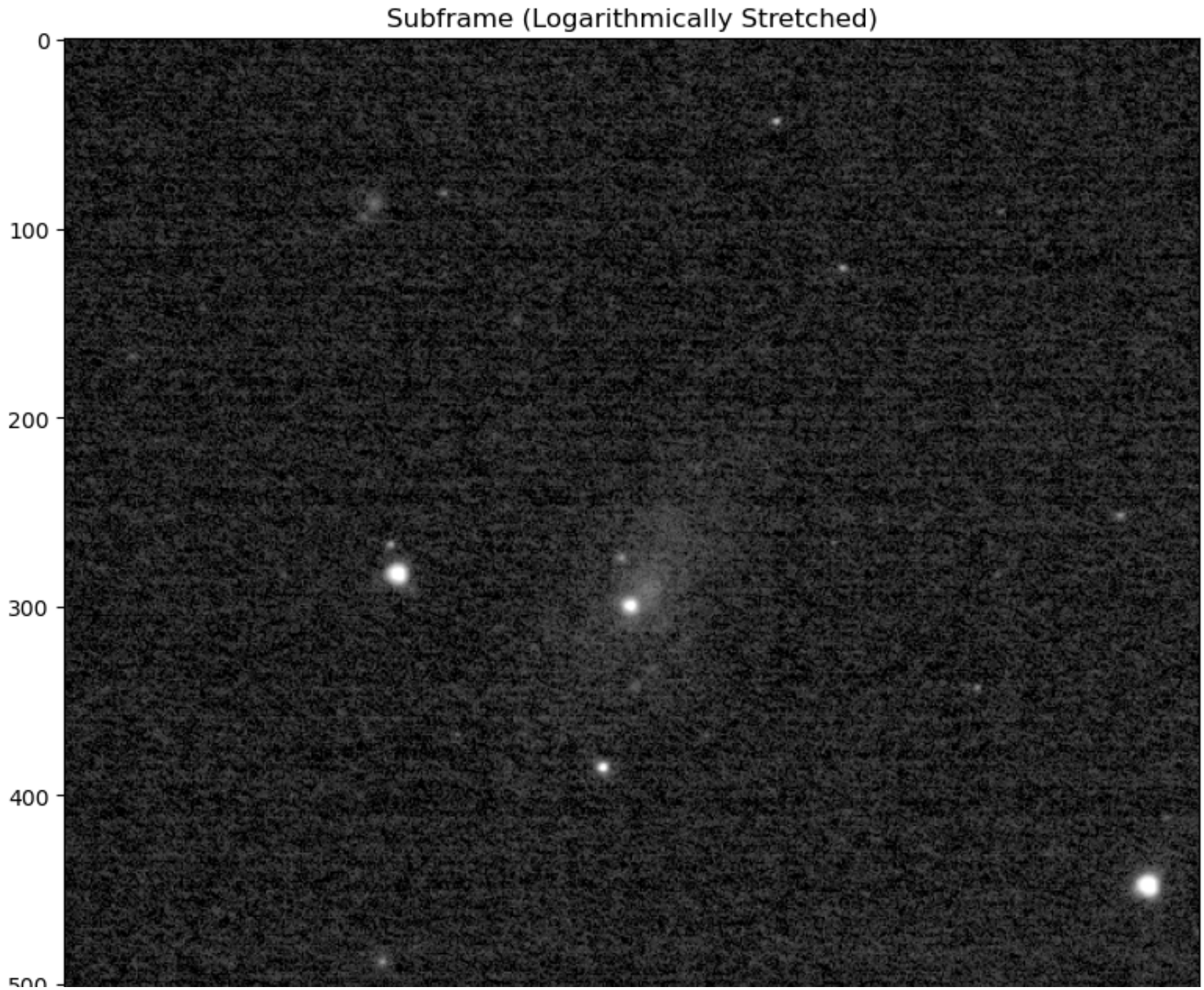
Display a Representative Image

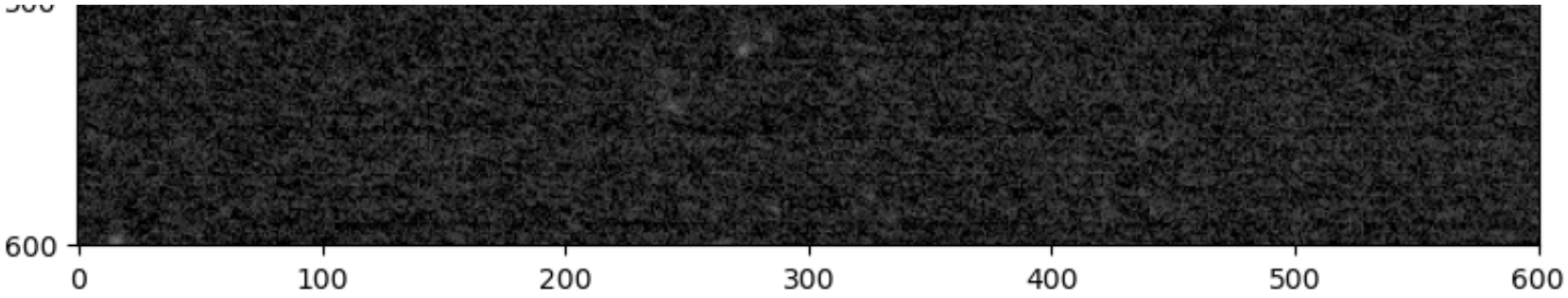
In [3]:
```
first_image = stacked_image_for_date_and_filter('2024-04-03', 'r')

# Log stretch

stretch_function = log_stretch_transform(8, 50)
stretch_transform = np.vectorize(stretch_function)

stretched_image = stretch_transform(first_image.data)

# Display the image

fig, axes = plt.subplots(1, 1, figsize=(8, 8))

axes.imshow(stretched_image, cmap='gray')
axes.set_title("A Representative Image (Logarithmically Stretched)")

plt.tight_layout()
plt.show()
```

```
WARNING: FITSFixedWarning: 'datfix' made the change 'Set MJD-OBS to 60403.212974 from DATE-OBS'. [astrop
y.wcs.wcs]
WARNING: FITSFixedWarning: 'obsfix' made the change 'Set OBSGEO-X to -2381449.053 from OBSGEO-[LBH].
Set OBSGEO-Y to -4483194.922 from OBSGEO-[LBH].
Set OBSGEO-Z to  3851220.317 from OBSGEO-[LBH]'. [astropy.wcs.wcs]
```


A Representative Image (Logarithmically Stretched)
0
200
400
600
800
0
200
400
600
800
1000
1200

In [4]:
```
DISPLAY_WHICH_CENTER = 0

display_extent_half = 300
display_extent_width = 2 * display_extent_half + 1
display_extent_height = display_extent_width
display_extent = Extent(display_extent_width, display_extent_height)

display_center = CENTERS[DISPLAY_WHICH_CENTER]
display_left = display_center.x - display_extent_half
display_right = display_left + display_extent_width
display_top = display_center.y - display_extent_half
display_bottom = display_top + display_extent_height

subframe = stretched_image[display_top:display_bottom, display_left:display_right]

# Display the representative subtracted dark

fig, axes = plt.subplots(1, 1, figsize=(8, 8))

axes.imshow(subframe, cmap='gray')
axes.set_title("Subframe (Logarithmically Stretched)")

plt.tight_layout()
plt.show()
```


Subframe (Logarithmically Stretched)
0
100
200
300
400
500



Code for Least Squares Fit

In [5]:
```
def sigma_squared_for_fwhm(fwhm):
    return fwhm**2 / (8 * log(2))

def make_gaussian_with_flux(fwhm, flux, center_x, center_y):
    sigma_squared = sigma_squared_for_fwhm(fwhm)
    flux_factor = flux / (2 * pi * sigma_squared)
    def gaussian(x, y):
        delta_x = x - center_x
        delta_y = y - center_y
        return flux_factor * exp(-(delta_x**2 + delta_y**2) / 2 / sigma_squared)
    return gaussian

def model_data_for_parameters(extent, total_background, fwhm, flux, center_x, center_y):
    model_data = np.zeros([extent.height, extent.width])  # height goes before width in the array shape
    model_data.fill(total_background)
    gaussian = make_gaussian_with_flux(fwhm, flux, center_x, center_y)
    for j in range(EXTENT_HEIGHT):
        for i in range(EXTENT_WIDTH):
            model_data[j, i] += gaussian(i, j)
    return model_data

# IS THERE A WAY TO USE NP.VECTORIZE?

PINDEX_TARGET_BACKGROUND = 0  # NB: THE TARGET BACKGROUND IS IN ADDITION TO THE GENERAL_BACKGROUND
PINDEX_GENERAL_BACKGROUND = 1
```

```
PINDEX_FWHM = 2

POFFSETINDEX_FLUX = 0
POFFSETINDEX_CENTER_X = 1
POFFSETINDEX_CENTER_Y = 2

def roi_residuals(image_data, target_index, center, extent, parameter_vector):
    left = center.x - extent.width // 2
    right = left + extent.width
    top = center.y - extent.height // 2
    bottom = top + extent.height
    roi_data = image_data[top:bottom, left:right]
    target_background = parameter_vector[PINDEX_TARGET_BACKGROUND]
    general_background = parameter_vector[PINDEX_GENERAL_BACKGROUND]
    total_background = target_background + general_background if target_index==0 else general_background
    fwhm = parameter_vector[PINDEX_FWHM]
    base_index = 3 + 3 * target_index
    flux = parameter_vector[base_index + POFFSETINDEX_FLUX]
    center_x = parameter_vector[base_index + POFFSETINDEX_CENTER_X]
    center_y = parameter_vector[base_index + POFFSETINDEX_CENTER_Y]
    model_data = model_data_for_parameters(extent, total_background, fwhm, flux, center_x, center_y)
    return roi_data - model_data

def make_residuals_function(image_data, centers, extent):
    def residuals_function(parameter_vector):
        all_roi_residuals = [
            roi_residuals(image_data, i, center, extent, parameter_vector)
            for i, center in enumerate(centers)
        ]
        return np.concatenate(all_roi_residuals).ravel()

    return residuals_function
```

Testing

We test the least squares fitting code above with generated data.

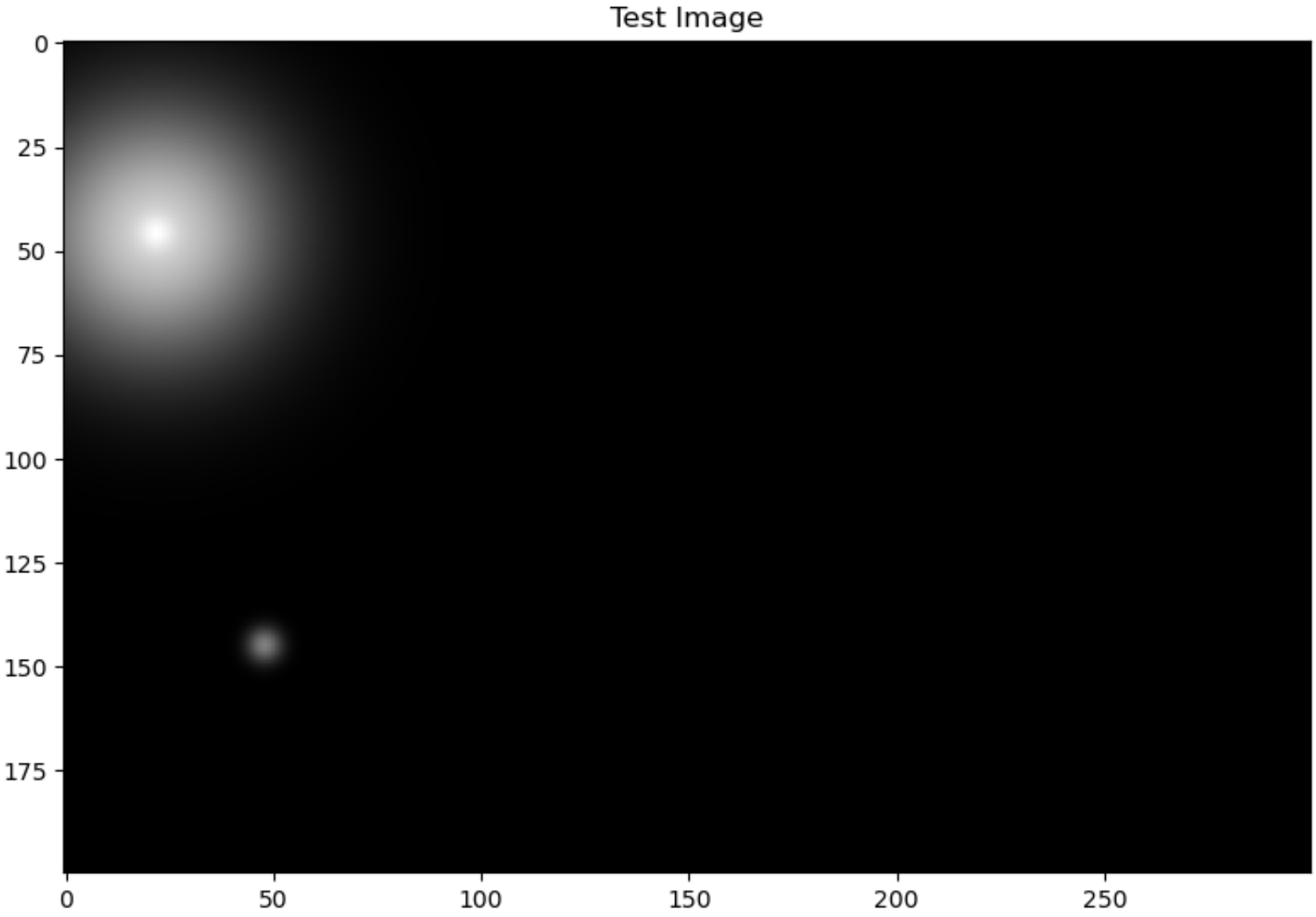
Generate the Data

In [6]:
```
TEST_DATA_WIDTH = 300
TEST_DATA_HEIGHT = 200

TEST_EXTENT_HALF_WIDTH = 10
TEST_EXTENT_WIDTH = 2 * TEST_EXTENT_HALF_WIDTH + 1
TEST_EXTENT_HEIGHT = TEST_EXTENT_WIDTH
TEST_EXTENT = Extent(TEST_EXTENT_WIDTH, TEST_EXTENT_HEIGHT)

TEST_CENTERS = [
    Point(20, 40), # test target
    Point(50, 150), # test reference star
]

TEST_CENTER_OFFSETS = [
    Point(2, 6), # test target
    Point(-2, -5), # test reference star
]

TEST_CENTERS_WITH_OFFSETS = [
    Point(TEST_CENTERS[i].x + TEST_CENTER_OFFSETS[i].x, TEST_CENTERS[i].y + TEST_CENTER_OFFSETS[i].y)
    for i in range(len(TEST_CENTERS))
]

TEST_CENTERS_COUNT = 2

TEST_FLUXES = [
    100.0,
    300.0
]
```

```
TEST_FWHM = 7.0

TEST_TARGET_GAUSSIAN =  make_gaussian_with_flux(TEST_FWHM, TEST_FLUXES[0],
                                                TEST_CENTERS_WITH_OFFSETS[0].x,
                                                TEST_CENTERS_WITH_OFFSETS[0].y)
TEST_TARGET_BACKGROUND = make_gaussian_with_flux(50, 2500 * 10.0,
                                                 TEST_CENTERS_WITH_OFFSETS[0].x,
                                                 TEST_CENTERS_WITH_OFFSETS[0].y)
TEST_REFERENCE_GAUSSIAN =  make_gaussian_with_flux(TEST_FWHM, TEST_FLUXES[1],
                                                   TEST_CENTERS_WITH_OFFSETS[1].x,
                                                   TEST_CENTERS_WITH_OFFSETS[1].y)
TEST_REFERENCE_BACKGROUND = make_gaussian_with_flux(500, 0 * 250000 * 5.0,
                                                    TEST_CENTERS_WITH_OFFSETS[1].x,
                                                    TEST_CENTERS_WITH_OFFSETS[1].y)


TEST_IMAGE_DATA = np.zeros([TEST_DATA_HEIGHT, TEST_DATA_WIDTH])  # height goes before width in the array

for j in range(TEST_DATA_HEIGHT):
        for i in range(TEST_DATA_WIDTH):
            TEST_IMAGE_DATA[j, i] += \
                TEST_TARGET_GAUSSIAN(i, j) + \
                TEST_REFERENCE_GAUSSIAN(i, j) + \
                TEST_TARGET_BACKGROUND(i, j) + \
                TEST_REFERENCE_BACKGROUND(i, j)
```

Display the Test Image

In [7]:
```
# Display the representative subtracted dark

fig, axes = plt.subplots(1, 1, figsize=(8, 8))

axes.imshow(TEST_IMAGE_DATA, cmap='gray')
axes.set_title("Test Image")

plt.tight_layout()
plt.show()
```



Fit the Test Image

In [8]:
```
TEST_INITIAL_GUESS_FOR_TARGET_BACKGROUND = 0.0
TEST_INITIAL_GUESS_FOR_GENERAL_BACKGROUND = 0.0
TEST_INITIAL_GUESS_FOR_FWHM = 5.0

TEST_INITIAL_PARAMETER_VECTOR = [
    TEST_INITIAL_GUESS_FOR_GENERAL_BACKGROUND,
    TEST_INITIAL_GUESS_FOR_GENERAL_BACKGROUND,
    TEST_INITIAL_GUESS_FOR_FWHM
]

for index in range(TEST_CENTERS_COUNT):
    TEST_INITIAL_PARAMETER_VECTOR.append(10.0)  # Initial guess for flux
    TEST_INITIAL_PARAMETER_VECTOR.append(0.0)   # Initial guess for center_x
    TEST_INITIAL_PARAMETER_VECTOR.append(0.0)   # Initial guess for center_y


TEST_RESIDUALS_FUNCTION = make_residuals_function(TEST_IMAGE_DATA, TEST_CENTERS, TEST_EXTENT)

TEST_result = least_squares(TEST_RESIDUALS_FUNCTION, np.array(TEST_INITIAL_PARAMETER_VECTOR))
```

In [9]:
```
TEST_result.x
```

Out[9]:
```
array([ 8.03219575e+00,  2.38082030e-05,  7.00016108e+00, -3.22978131e+02,
        5.63367294e+01,  1.17897959e+03,  3.00014164e+02,  7.99996931e+00,
        4.99990495e+00])
```

Fit the Real Data