Appendix 1 - Python Code

November 14, 2022

[1]:
```python
# Importing packages

from astropy.io import fits # For handling fits files
from astropy.wcs import WCS # Applying coordinates to images
from astropy.coordinates import SkyCoord
from glob import glob # to search for file paths under similar names
from astropy.coordinates import Angle
from astropy import units as u

import numpy as np
from matplotlib import pyplot as plt
from matplotlib.ticker import FormatStrFormatter
# The below commands make the font and image size bigger
plt.rcParams.update({'font.size': 16})
plt.rcParams["figure.figsize"] = (8,8)

# Photometry
from photutils import DAOStarFinder
from astropy.stats import mad_std
from photutils import aperture_photometry, CircularAperture, CircularAnnulus

from dataclasses import dataclass

from scipy.optimize import curve_fit
```

1 Importing all data

[2]:
```python
rootPath = r"/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis"
```

1.1 M91

[3]:
```python
# Note each group of files is a list for each band

# Bias
biasFiles_M91 = [glob(rootPath + r"/data_2019/M91/bias/*.fits")]

# Flats
```

```
flatsFiles_M91 = [
    glob(rootPath + r"/data_2019/M91/flats/B/*.fits"),
    glob(rootPath + r"/data_2019/M91/flats/V/*.fits"),
    glob(rootPath + r"/data_2019/M91/flats/Halpha_NII/*.fits")
]

# Object
objectFiles_M91 = [
    glob(rootPath + r"/data_2019/M91/object/B/*.fits"),
    glob(rootPath + r"/data_2019/M91/object/V/*.fits"),
    glob(rootPath + r"/data_2019/M91/object/Halpha_NII/*.fits")
]
```

[4]:
```
# Load files using astropy.fits

biasFITS_M91 = [fits.open(el) for el in biasFiles_M91[0]]

flatFITS_M91 = [[fits.open(el) for el in flatsFiles_M91[0]], \
                [fits.open(el) for el in flatsFiles_M91[1]], \
                [fits.open(el) for el in flatsFiles_M91[2]]]

objectFITS_M91 = [[fits.open(el) for el in objectFiles_M91[0]], \
                [fits.open(el) for el in objectFiles_M91[1]], \
                [fits.open(el) for el in objectFiles_M91[2]]]
```

1.2 NNSer

[5]:
```
# Note, only frames of NNSer in the clear band.
import re
# Bias
biasFiles_NNSer = [glob(rootPath + r"/data_2019/NNSer/bias/*.fits")]

# Flats
flatsFiles_NNSer = [glob(rootPath + r"/data_2019/NNSer/flats/clear/*.fits")]

# Object - weird sorting function was required as glob was misbehaving.
objectFiles_NNSer = [sorted(glob(rootPath + r"/data_2019/NNSer/object/clear/*.
↪fits"), key=lambda x: tuple(map(int, re.findall(r'\d+', x))))]
print(objectFiles_NNSer)
```

```
[['/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/
NNSer/object/clear/0120308_0175.fits', '/home/daraghhollman/jupyter/UCD_PASS_Lab
s/Astronomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_0176.fits', '/ho
me/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/
object/clear/0120308_0177.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astr
onomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_0178.fits', '/home/dar
aghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/object
/clear/0120308_0179.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_
```

Image_Analysis/data_2019/NNSer/object/clear/0120308_0180.fits', '/home/daraghhol
lman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/object/clear
/0120308_0181.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_
Analysis/data_2019/NNSer/object/clear/0120308_0182.fits', '/home/daraghhollman/j
upyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/object/clear/01203
08_0183.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analys
is/data_2019/NNSer/object/clear/0120308_0184.fits', '/home/daraghhollman/jupyter
/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_018
5.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/dat
a_2019/NNSer/object/clear/0120308_0186.fits', '/home/daraghhollman/jupyter/UCD_P
ASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_0187.fits
', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019
/NNSer/object/clear/0120308_0188.fits', '/home/daraghhollman/jupyter/UCD_PASS_La
bs/Astronomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_0189.fits', '/h
ome/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer
/object/clear/0120308_0190.fits', '/home/daraghhollman/jupyter/UCD_PASS_Labs/Ast
ronomy_Image_Analysis/data_2019/NNSer/object/clear/0120308_0191.fits', '/home/da
raghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_Analysis/data_2019/NNSer/objec
t/clear/0120308_0192.fits']]

[6]:
```
biasFITS_NNSer = [fits.open(el) for el in biasFiles_NNSer[0]]

flatFITS_NNSer = [fits.open(el) for el in flatsFiles_NNSer[0]]

objectFITS_NNSer = [fits.open(el) for el in objectFiles_NNSer[0]]
```

2 Data Reduction

2.1 Create Master Bias and Flat files

[7]:
```
# Read in the pixel values of each bias into an np array.
# Find the average value of each pixel across all bias frames.
# Assign each average pixel to a new file: masterBias.fits



# Takes a list of arrays and returns an array with each element being
# the average element of the list
def createAvgArray(arraysList):

    arraySum = np.empty(np.shape(arraysList[0]))

    for array in arraysList:
        arraySum += array

    return arraySum / len(arraysList)
```

```
# Converts a list of fits files into a list of arrays and passes it to the␣
↪createAvgArray
# function to get the masterBias
def createMasterBias(biasList):

    arraysList = list()

    for el in biasList:
        arraysList.append(el[0].data)

    avg = createAvgArray(arraysList)

    return avg

# Converts a list of fits files into a list of arrays, subtacting the␣
↪masterBias,
# and passes it to the createAvgArray function to get the masterFlat
def createMasterFlat(flatsList, masterBias):

    arraysList = list()

    for el in flatsList:
        arraysList.append(el[0].data - masterBias)

    avgArray = createAvgArray(arraysList)

    # normalisation, find the value at the centre and divide by it
    xLength, yLength = np.shape(avgArray)

    normFac = avgArray[int(xLength/2)][int(yLength/2)]

    return avgArray / normFac
```

[8]:
```
masterBias_M91 = createMasterBias(biasFITS_M91)
masterBias_NNSer = createMasterBias(biasFITS_NNSer)
```

[9]:
```
masterFlats_M91_B = createMasterFlat(flatFITS_M91[0], masterBias_M91)
masterFlats_M91_V = createMasterFlat(flatFITS_M91[1], masterBias_M91)
masterFlats_M91_Ha = createMasterFlat(flatFITS_M91[2], masterBias_M91)

# masterFlats_M91 is a list of 3 master flats, one for each band.
masterFlats_M91 = [masterFlats_M91_B, masterFlats_M91_V, masterFlats_M91_Ha]

masterFlat_NNSer = createMasterFlat(flatFITS_NNSer, masterBias_NNSer)
```

[10]:
```
def writeFITS(array, newPath):
    hdu = fits.PrimaryHDU(array)
```

```
    hdu.writeto(newPath, overwrite=True)
    print(f"FITS image saved to: {newPath}")
```

[11]:
```
writeFITS(masterBias_M91, rootPath + r"/output/masterFiles/masterBias_M91.fits")
writeFITS(masterBias_NNSer, rootPath + r"/output/masterFiles/masterBias_NNSer.
 ↪fits")

writeFITS(masterFlats_M91_B, rootPath + r"/output/masterFiles/masterFlat_M91_B.
 ↪fits")
writeFITS(masterFlats_M91_V, rootPath + r"/output/masterFiles/masterFlat_M91_V.
 ↪fits")
writeFITS(masterFlats_M91_Ha, rootPath + r"/output/masterFiles/
 ↪masterFlat_M91_Ha.fits")

writeFITS(masterFlat_NNSer, rootPath + r"/output/masterFiles/masterFlat_NNSer.
 ↪fits")
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterBias_M91.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterBias_NNSer.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterFlat_M91_B.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterFlat_M91_V.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterFlat_M91_Ha.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/masterFiles/masterFlat_NNSer.fits
```

2.2 Reduce Images

[12]:
```
def reduceImage(fitsFile, masterBias, masterFlat, newPath):
    # Reduces the image by subtracting the masterBias file and dividing by the␣
 ↪masterFlat.
    # Note that the first 50 pixels are deleted. This is due to the bias = the␣
 ↪flat and hence they observe no light

    fitsFile = np.delete(fitsFile[0].data, np.arange(0, 50, 1), 1)
    masterBias = np.delete(masterBias[0].data, np.arange(0, 50, 1), 1)
    masterFlat = np.delete(masterFlat[0].data, np.arange(0, 50, 1), 1)

    fileArray = fitsFile

    np.subtract(fileArray, masterBias)
    fileArray = fileArray / masterFlat
```

```
    writeFITS(fileArray, newPath)
```

2.2.1 M91

[13]:
```
# B Band
count=1
for el in objectFITS_M91[0]:
    image = reduceImage(el, fits.open(rootPath + r"/output/masterFiles/
 ↪masterBias_M91.fits"),\
                        fits.open(rootPath + r"/output/masterFiles/
 ↪masterFlat_M91_B.fits"), \
                        rootPath+f"/output/M91/B/M91_B_{count:02}.fits")

    count+=1
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/B/M91_B_01.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/B/M91_B_02.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/B/M91_B_03.fits
```

[14]:
```
# V Band
count=1
for el in objectFITS_M91[1]:
    image = reduceImage(el, fits.open(rootPath + r"/output/masterFiles/
 ↪masterBias_M91.fits"),\
                        fits.open(rootPath + r"/output/masterFiles/
 ↪masterFlat_M91_V.fits"), \
                        rootPath+f"/output/M91/V/M91_V_{count:02}.fits")

    count+=1
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/V/M91_V_01.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/V/M91_V_02.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/V/M91_V_03.fits
```

[15]:
```
# Halpha Band
count=1
for el in objectFITS_M91[2]:
    image = reduceImage(el, fits.open(rootPath + r"/output/masterFiles/
 ↪masterBias_M91.fits"),\
                        fits.open(rootPath + r"/output/masterFiles/
 ↪masterFlat_M91_Ha.fits"), \
                        rootPath+f"/output/M91/Halpha/M91_Ha_{count:02}.fits")
```

```
    count+=1
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/Halpha/M91_Ha_01.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/Halpha/M91_Ha_02.fits
```

2.2.2 NNSer

[16]:
```
# Clear Band
count=1
for el in objectFITS_NNSer:
    image = reduceImage(el, fits.open(rootPath + r"/output/masterFiles/
 ↪masterBias_NNSer.fits"),\
                        fits.open(rootPath + r"/output/masterFiles/
 ↪masterFlat_NNSer.fits"), \
                        rootPath+f"/output/NNSer/clear/NNSer_{count:02}.fits")

    count+=1
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_01.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_02.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_03.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_04.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_05.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_06.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_07.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_08.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_09.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_10.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_11.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_12.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_13.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
```

```
nalysis/output/NNSer/clear/NNSer_14.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_15.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_16.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_17.fits
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/NNSer/clear/NNSer_18.fits
```

3 Combining Bands

[17]:
```
# We combine the bands for each set of images.

def CombineBands(listOfFitsLists, newPath):
    # takes a list of lists of fits files as an input and outputs a single fits␣
 ↪file

    outputArray = np.empty((2048, 2048))

    for fitsList in listOfFitsLists:
        arraysList = list()

        for file in fitsList:
            arraysList.append(file[0].data)

        avgArray = createAvgArray(arraysList)
        outputArray += avgArray

    writeFITS(outputArray, newPath)
```

[18]:
```
M91_combinedList = [[fits.open(file) for file in glob(rootPath + r"/output/M91/
 ↪B/M91_B_*.fits")], \
                    [fits.open(file) for file in glob(rootPath + r"/output/M91/
 ↪V/M91_V_*.fits")], \
                    [fits.open(file) for file in glob(rootPath + r"/output/M91/
 ↪Halpha/M91_Ha_01.fits")]]

CombineBands(M91_combinedList, rootPath + r"/output/M91/M91_combined.fits")
```

```
FITS image saved to: /home/daraghhollman/jupyter/UCD_PASS_Labs/Astronomy_Image_A
nalysis/output/M91/M91_combined.fits
```

4 Measurement of Angular Size of M91

[19]:
```
def averagePixelCount(array):
    areaCounts=0
    divisor=0
    for line in array:
        for el in line:
            areaCounts += el
            divisor+=1
    return areaCounts / divisor

def angularSize(fits, bucketSize, tol, vMin, vMax, showPlot=False,␣
 ↪color="grey", label="Ellipse"):
    # Function takes fits file as input, plots image with plt.imshow with the␣
 ↪angular sizes displayed and returned
    # Returns angular size in arcseconds
    image = fits[0].data

    backgroundAvg = averagePixelCount(image[0:250][:,500:750])
    print(backgroundAvg)

    # Find Y
    sequence = 0
    angularSizeY = 0
    i=0
    while i < len(image[:,0]):
        j=0
        while j < len(image[0]):

            smallAreaAvg = averagePixelCount(image[i:i+bucketSize][:,j:
 ↪j+bucketSize])

            if smallAreaAvg -tol > backgroundAvg:
                sequence += 1
            else:
                if sequence > angularSizeY:angularSizeY = sequence
                sequence = 0

            j+=bucketSize
        i+=bucketSize

    # Find X
    sequence = 0
    angularSizeX = 0
    i=0
    while i < len(image[0]):
        j=0
```

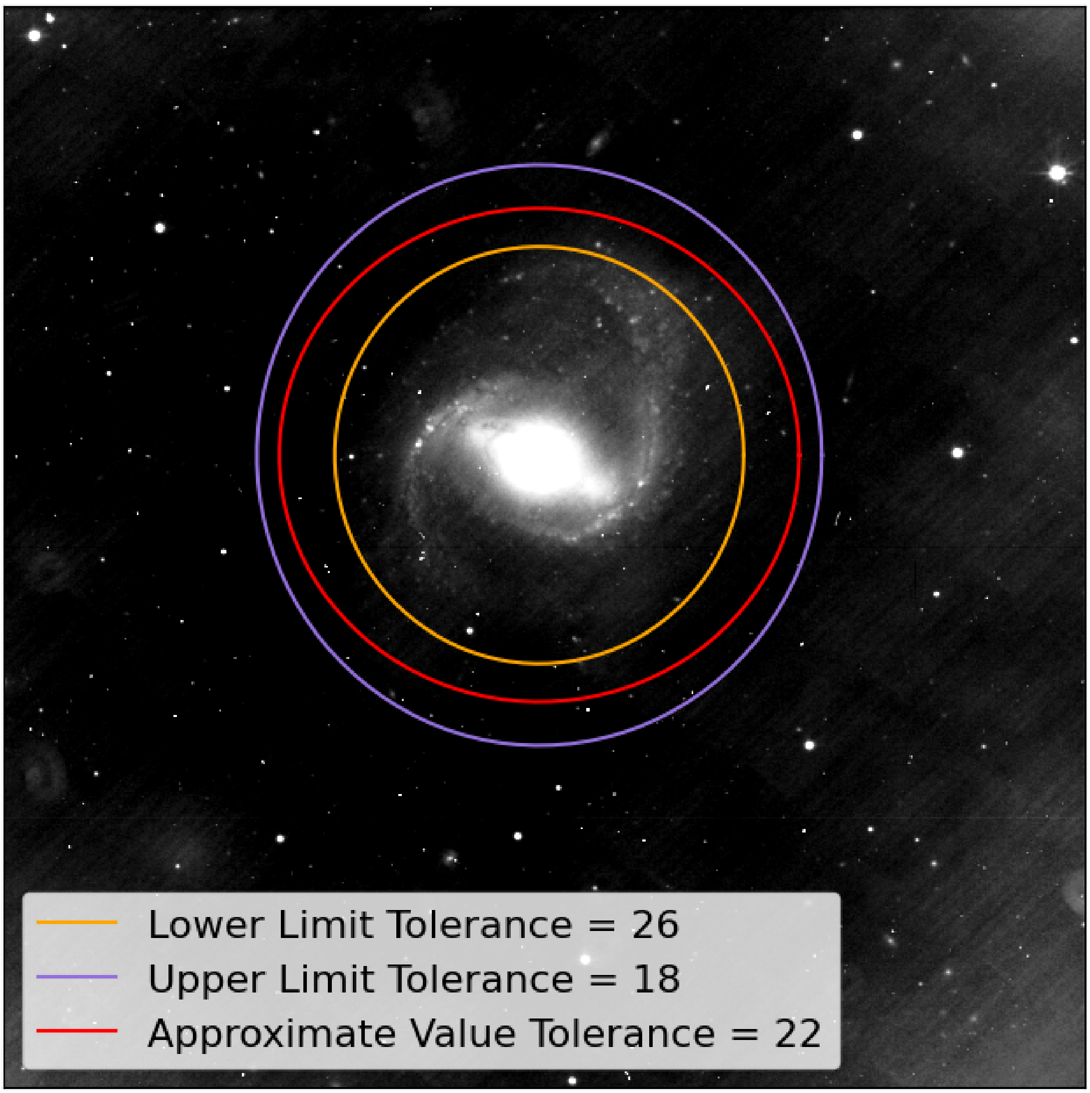
```
        while j < len(image[:,0]):

            smallAreaAvg = averagePixelCount(image[:,i:i+bucketSize][j:
↪j+bucketSize])

            if smallAreaAvg -tol > backgroundAvg:
                sequence += 1
            else:
                if sequence > angularSizeX:
                    angularSizeX = sequence
                sequence = 0

            j+=bucketSize
        i+=bucketSize

    # Convert to pixels: * bucketSize
    angularSizeX *= bucketSize
    angularSizeY *= bucketSize
    print(f"Angular Size X: {angularSizeX} pixels, {angularSizeX*0.304}␣
↪arcseconds")
    print(f"Angular Size Y: {angularSizeY} pixels, {angularSizeY*0.304}␣
↪arcseconds")

    if showPlot:
        plt.imshow(image, vmin=vMin, vmax=vMax, cmap="Greys_r")
        #plt.colorbar()

        centre = [1015, 850]
        t = np.linspace(0, 2*np.pi, 100)
        plt.plot( centre[0]+angularSizeX/2*np.cos(t) , centre[1]+angularSizeY/
↪2*np.sin(t), color=color, label=label+f" Tolerance = {tol}")
        plt.legend()
        plt.xticks([])
        plt.yticks([])

    return [angularSizeX*0.304, angularSizeY*0.304]
```

[20]:

```
angSizeU1 = angularSize(fits.open(rootPath + r"/output/M91/M91_combined.fits"),␣
↪5, tol=26, showPlot=True, \
                        label="Lower Limit", vMin=1507, vMax=1700,␣
↪color="orange")
angSizeU2 = angularSize(fits.open(rootPath + r"/output/M91/M91_combined.fits"),␣
↪5, tol=18, showPlot=True, \
                        label="Upper Limit", vMin=1507, vMax=1700,␣
↪color="mediumpurple")
```

```
angSize = angularSize(fits.open(rootPath + r"/output/M91/M91_combined.fits"),␣
↪5, tol=22, showPlot=True, color="red", \
                    label="Approximate Value", vMin=1507, vMax=1700)
```

```
1506.651890933726
Angular Size X: 775 pixels, 235.6 arcseconds
Angular Size Y: 790 pixels, 240.16 arcseconds
1506.651890933726
Angular Size X: 1070 pixels, 325.28 arcseconds
Angular Size Y: 1100 pixels, 334.4 arcseconds
1506.651890933726
Angular Size X: 985 pixels, 299.44 arcseconds
Angular Size Y: 935 pixels, 284.24 arcseconds
```



[21]:
```python
def apparentSize(angSize, dist):
    return angSize / 206265 * dist # by the small angle approximation, 206265␣
 ↪arcseconds in a radian

# Galaxy at distance (15 ± 0.8) Mpc
major = apparentSize(angSize[0], 15000)
uMajor = (apparentSize(angSizeU2[0], 15000 +800) - apparentSize(angSizeU1[0],␣
 ↪15000-800)) / 2
minor = apparentSize(angSize[1], 15000)
uMinor = (apparentSize(angSizeU2[1], 15000+800) - apparentSize(angSizeU1[1],␣
 ↪15000-800)) / 2

print(f"M91 Diameter X: ({major:0.1f} ± {uMajor:0.1f}) kpc ")
print(f"M91 Diameter Y: ({minor:0.1f} ± {uMinor:0.1f}) kpc")
```

```
M91 Diameter X: (21.8 ± 4.3) kpc
M91 Diameter Y: (20.7 ± 4.5) kpc
```

[22]:
```python
# reference values of 5.4 by 4.3 arcminutes = 324 by 258 arcseconds

print(f"Reference Size Major: {apparentSize(5.37*60, 15000):0.1f} u:␣
 ↪{apparentSize(0.05*60, 15000):0.1f}")
print(f"Reference Size Minor: {apparentSize(4.47*60, 15000):0.1f} u:␣
 ↪{apparentSize(0.05*60, 15000):0.1f}")
```

```
Reference Size Major: 23.4 u: 0.2
Reference Size Minor: 19.5 u: 0.2
```

[23]:
```python
# Adjust for inclination and position angle

# Adjusting for inclination:
# newDiameter = diameter / cos(inclination) (correcting for inclination)

def AngularAdjustments(size, inclination, posiitonAngle):
    dRA = size[0]
    dDEC = size[1]

    adjRA = 1 / np.sin(np.pi - posiitonAngle)
    adjDEC = 1 / np.cos(inclination)

    sizeRA = dRA * adjRA * adjDEC
    sizeDEC = dDEC * adjDEC * adjRA

    return [sizeRA, sizeDEC]

print(f"Physical Size: {AngularAdjustments([major, minor], 36.9 * np.pi/180,␣
 ↪150 * np.pi/180)}")
```

```
print(f"Uncertainty on physcial Size: {AngularAdjustments([uMajor, uMinor], 36.
 ↪9 * np.pi/180, 150 * np.pi/180)}")
```

```
Physical Size: [54.46114443899442, 51.6966193405683]
Uncertainty on physcial Size: [10.875641737208324, 11.356669104334465]
```

5 NNSer

[24]:
```
def wcsToPixel(RA, DEC, wcsPath):
    hdu = fits.open(wcsPath)[0]
    wcs = WCS(hdu.header)

    pixelX, pixelY = wcs.wcs_world2pix(RA*15, DEC, 1)

    return [[pixelX, pixelY], wcs]

def pixelToWCS(pixelX, pixelY, wcsPath):
    hdu = fits.open(wcsPath)[0]
    wcs = WCS(hdu.header)

    RA, DEC = wcs.wcs_pix2world(pixelX, pixelY, 1)

    return [[RA/15, DEC], wcs]
```

5.1 Plot Lightcurve

5.1.1 Identify ZP stars

[25]:
```
starNNSer = wcsToPixel(15.8822, 12.9125, rootPath + r"/output/NNSer/nnserWCS.
 ↪fits")[0]
print(starNNSer)
```

```
[array(1439.7217362), array(1150.9583329)]
```

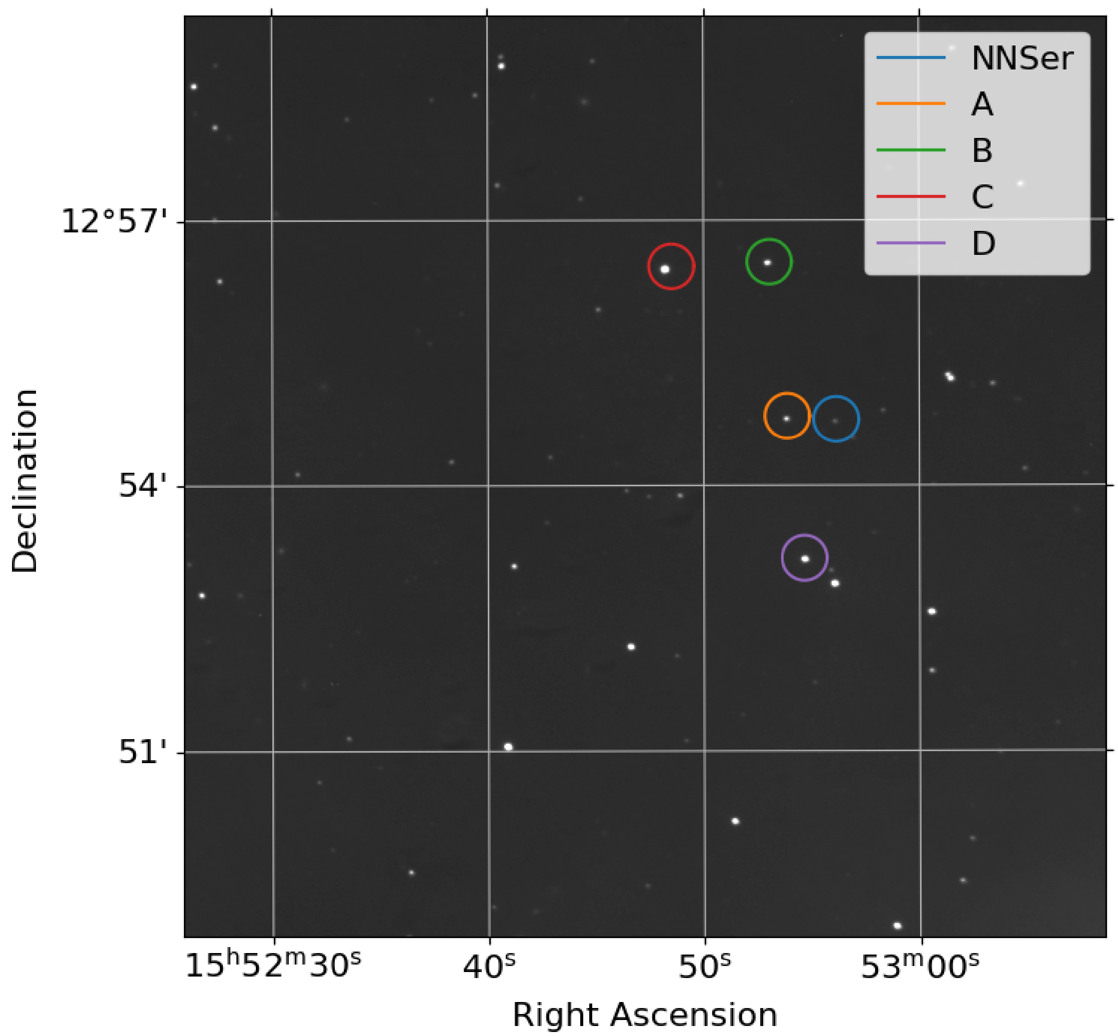
[26]:
```
def FindStarCoords(RA, DEC, offRA=0, offDEC=0):
    # Takes a reference star at RA and DEC (fmt: '15h52m56.131s') and an offset␣
 ↪RA and
    # DEC (arcseconds). Returns pixel coordinates of the offset star
    coords = SkyCoord(RA, DEC)

    offRA = Angle(offRA, u.arcsecond)
    offDEC = Angle(offDEC, u.arcsecond)

    starCoords = wcsToPixel(coords.ra.hour + offRA.hour, coords.dec.degree +␣
 ↪offDEC.degree, \
                            rootPath + r"/output/NNSer/nnserWCS.fits")[0]

    return starCoords
```

[27]:

```
def plotCirc(x, y, r, label=None):
    t = np.linspace(0, 2*np.pi, 100)
    plt.plot(x + r*np.cos(t), y + r*np.sin(t), label=label)
```

[28]:

```
nnserIm17 = fits.open(rootPath + r"/output/NNSer/clear/NNSer_17.fits")[0].data
nnserIm17Head = fits.open(rootPath + r"/output/NNSer/clear/NNSer_17.fits")[0].
↪header

starNNSerCoords = FindStarCoords('15h52m56.131s', '+12d54m44.68s', "0sS", 0)
starACoords = FindStarCoords('15h52m56.131s', '+12d54m44.68s', -34.1, 2.2)
starBCoords = FindStarCoords('15h52m56.131s', '+12d54m44.68s', -46.4, 106.7)
starCCoords = FindStarCoords('15h52m56.131s', '+12d54m44.68s', -114.5, 103.7)
starDCoords = FindStarCoords('15h52m56.131s', '+12d54m44.68s', -22.2, -94.1)

wcs = wcsToPixel(15.8822, 12.9125, rootPath + r"/output/NNSer/nnserWCS.fits")[1]

radius = 50

plt.subplot(projection=wcs)
# NNSer
plotCirc(starNNSerCoords[0], starNNSerCoords[1], radius, label="NNSer")
# StarA
plotCirc(starACoords[0], starACoords[1], radius, label="A")
# StarB
plotCirc(starBCoords[0], starBCoords[1], radius, label="B")
# StarC
plotCirc(starCCoords[0], starCCoords[1], radius, label="C")
# StarD
plotCirc(starDCoords[0], starDCoords[1], radius, label="D")
plt.imshow(nnserIm17, cmap="Greys_r", vmax="10000")
plt.legend()
plt.xlabel("Right Ascension")
plt.ylabel("Declination")
plt.grid()
#plt.scatter(starD.position[0], starD.position[1])
```



5.1.2 Find Flux for each Star

[29]:
```
@dataclass
class Star:
    name:str
    position:list
    flux:float
    calibratedMagnitude:float

    def __init__(self, name, position, flux, calibratedMagnitude):
        self.name = name
        self.position = position
        self.flux = flux
        self.calibratedMagnitude = calibratedMagnitude
```

```python
def SearchStars(image, fwhm=8., threshold=4, showPlot=False):
    # Median absolute deviation
    medAbsDev = mad_std(image)
    daofind = DAOStarFinder(fwhm=fwhm, threshold=threshold*medAbsDev)
    sources = daofind(image)

    if (showPlot):
        plt.subplot(projection=wcs)
        plt.imshow(image, vmax=20000)
        plt.scatter(sources['xcentroid'], sources['ycentroid'], alpha=0.5,␣
↪color="orange")
        plt.grid()

    return sources

def FindStar(image, name, approxRA, approxDEC, tolerance = 50, showPlot=False):
    # Inputs approximate RA and DEC, and a tolerance range of pixels.
    # Function will search for every star in the image, and pick out from the␣
↪resulting table
    # the star which coresponds to the input parameters. (Using DAOStarFinder)
    # Returns A star class with the exact position and flux.
    # Calibrated magnitude will come from the r' band in Table 3 of the lab␣
↪manual.

    # Generate the table of stars found in image
    sources = SearchStars(image, showPlot=showPlot)

    # Find the approximate pixel coordinates from the approximate RA and DEC
    approxPos = FindStarCoords(approxRA, approxDEC)

    potentialStars = list()
    for el in sources:
        if (el["xcentroid"] - tolerance < approxPos[0] and el["xcentroid"] +␣
↪tolerance > approxPos[0] \
           and el["ycentroid"] - tolerance < approxPos[1] and el["ycentroid"] +␣
↪tolerance > approxPos[1]):

            potentialStars.append(el)

    if (len(potentialStars) > 1):
        print(f"Error: Cannot return star as there exist too many options␣
↪within tolerance: {len(potentialStars)}. Try reducing the tolerance range")
        return

    if (len(potentialStars) == 0):
        print("There are no stars within tolerance.")
```

```
        return

    if (len(potentialStars) == 1):
        foundStar = potentialStars[0]

        positions = np.transpose((sources['xcentroid'], sources['ycentroid']))

        # Set up aperture and annulus
        aperture = CircularAperture(positions, r=8.)
        annulusAperture = CircularAnnulus(positions, r_in=12., r_out=16.)

        # Make a list of apertures
        apertures = [aperture, annulusAperture]

        # Run aperture photometry
        photoTable = aperture_photometry(image, apertures)

        backgroundMean = photoTable['aperture_sum_1'] / annulusAperture.area
        backgroundSum = backgroundMean * aperture.area
        finalSum = photoTable['aperture_sum_0'] - backgroundSum

        newStar = Star(name, [foundStar["xcentroid"], foundStar["ycentroid"]],␣
↪finalSum, 0)
        return newStar
```

[30]:
```
def ZeroPoint(flux, calibratedMagnitude, exposureTime):
    return calibratedMagnitude + 2.5 * np.log10(flux / exposureTime)

# Finding exact star position and flux
starA = FindStar(nnserIm17, "StarA", '15h52m56.131s', '+12d54m44.68s',␣
↪tolerance=30)
starB = FindStar(nnserIm17, "StarB", '15h52m55s', '+12d56m30s', tolerance=100)␣
↪# Tolerance higher here as we guess approximately the pos.
starC = FindStar(nnserIm17, "StarC", '15h52m48s', '+12d56m25s', tolerance=30)
starD = FindStar(nnserIm17, "StarD", '15h52m54s', '+12d53m30s', tolerance=50)

# Assigning Star r' band magnitudes
starA.calibratedMagnitude = 15.8
starB.calibratedMagnitude = 15.1
starC.calibratedMagnitude = 13.7
starD.calibratedMagnitude = 13.7

zeroPoints = list()
starsList = [starA, starB, starC, starD]
```

[31]:
```
def FindZeroPoints(image, imNum):
    for star in starsList:
```

```
        zeroPoints.append(ZeroPoint(star.flux, star.calibratedMagnitude,␣
↪float(objectFITS_NNSer[imNum][0].header["EXPTIME"])))

    avgZeroPoint = np.mean(zeroPoints)
    uZP = np.std(zeroPoints)

    return [avgZeroPoint, uZP]
```

[32]:
```
def ComputeUncertainties(counts, nStar, nSky, backgroundCounts, readoutNoise):

    sigNoiseRat = counts / np.sqrt(counts + nStar*(1 + nStar/nSky) *␣
↪(backgroundCounts + readoutNoise**2))

    return 2.5 * np.log10(1 + 1/sigNoiseRat)
```

[33]:
```
starNNSer = FindStar(nnserIm17, "NNSer", '15h52m56.131s', '+12d54m44.68s',␣
↪tolerance=30)

def GenerateLightCurve(star, originalFITS, path, searchTol = 10):
    mags = list()
    exposures = list()
    uncertainties = list()
    readoutNoises = list()

    for image in originalFITS:
        exposures.append(float(image[0].header["EXPTIME"]))
        readoutNoises.append(float(image[0].header["RDNOISE"]))

    files = glob(path)
    files.sort()
    fitsFiles = [fits.open(file) for file in files]

    t=0

    for file in fitsFiles:

        image = file[0].data

        ZPs = FindZeroPoints(image, t)
        ZP = ZPs[0]
        uZP = ZPs[1]
        sources = SearchStars(image)
        # Get the positions of sources in the field
        positions = np.transpose((sources['xcentroid'], sources['ycentroid']))

        # Set up aperture and annulus
        aperture = CircularAperture(positions, r=8.)
```

```
        annulusAperture = CircularAnnulus(positions, r_in=12., r_out=16.)

        # Make a list of apertures
        apertures = [aperture, annulusAperture]

        # Run aperture photometry
        photoTable = aperture_photometry(image, apertures)

        starInTable = False
        possibilities = list()
        for el in photoTable:
            if (el["xcenter"].value - searchTol < star.position[0] and␣
↪el["xcenter"].value + searchTol > star.position[0] \
               and el["ycenter"].value - searchTol < star.position[1] and␣
↪el["ycenter"].value + searchTol > star.position[1]):
                possibilities.append(el["id"])

        if (len(possibilities) > 1):
            print("Too many stars within tolerance")
            return
        if (len(possibilities) == 0):
            starInTable = False

        if (len(possibilities) == 1):
            starID = possibilities[0]
            starInTable = True

        # Limiting Magnitude
        lMag = 0
        lowestSum = -1
        lowestID = 0

        backgroundMean = photoTable['aperture_sum_1'] / annulusAperture.area
        backgroundSum = backgroundMean * aperture.area
        finalSum = photoTable['aperture_sum_0'] - backgroundSum

        for el in sources:
            if finalSum[el["id"] -1] < lowestSum or lowestSum == -1:
                lowestSum = finalSum[el["id"] -1]
                lowestID = el["id"]

        if (starInTable):
            mags.append(-2.5*np.log10(finalSum[starID-1] / exposures[t]) + ZP)
            uncertainties.
↪append(ComputeUncertainties(photoTable['aperture_sum_0'][starID-1],␣
↪backgroundSum[starID-1], \
```

```
↪sources[starID-1]["npix"], aperture.area, readoutNoises[t]))

        if (not starInTable):
            lMag = (-2.5*np.log10(finalSum[lowestID-1] / exposures[t]) + ZP)
            mags.append(lMag)
            uncertainties.
↪append(ComputeUncertainties(photoTable['aperture_sum_0'][lowestID-1],␣
↪backgroundSum[starID-1], \

↪sources[lowestID-1]["npix"], aperture.area, readoutNoises[t]))
        t+=1

    return [mags, uncertainties]

curveMags = GenerateLightCurve(starNNSer, objectFITS_NNSer, rootPath + r"/
↪output/NNSer/clear/*.fits")
```

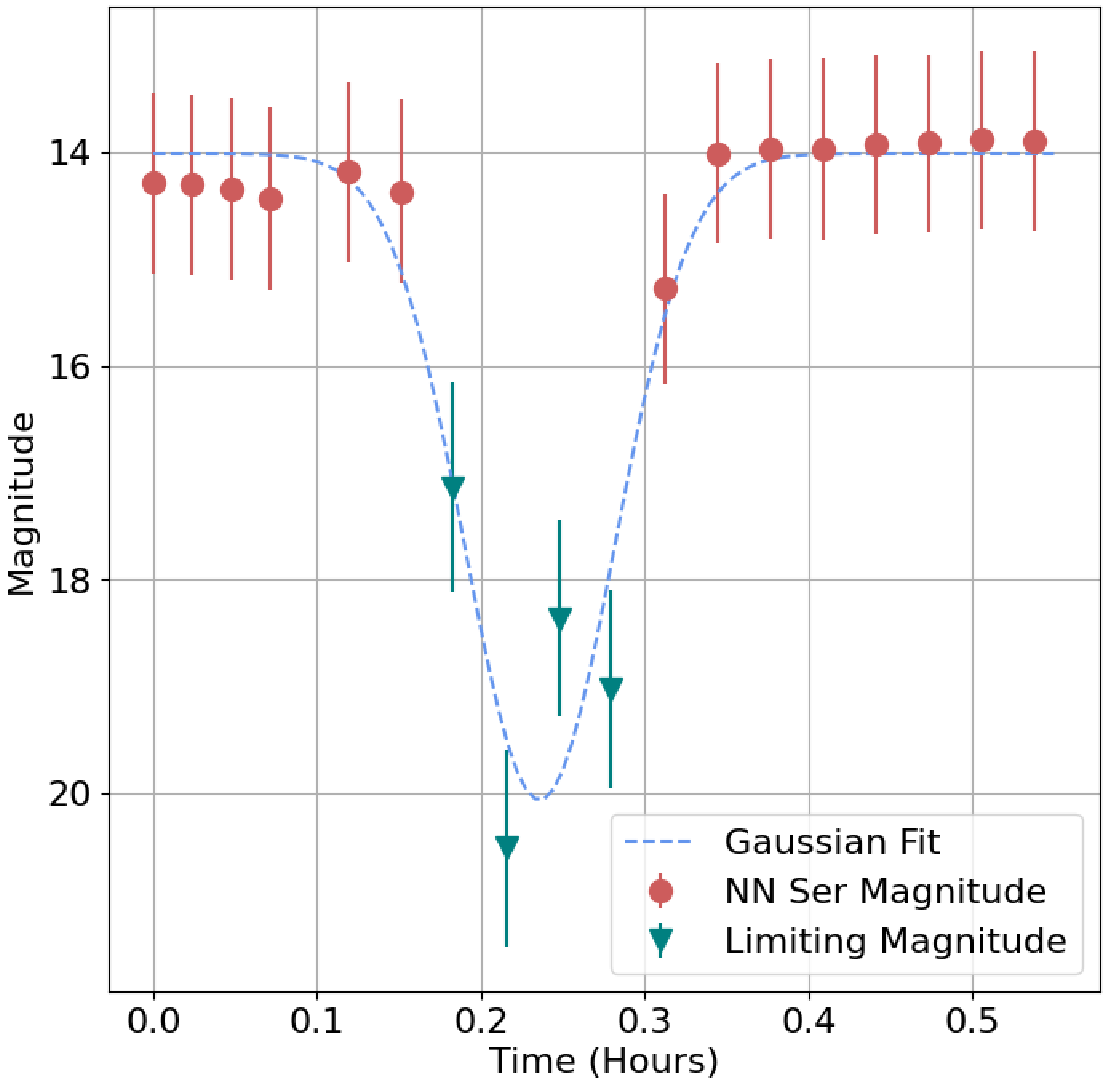
[34]:
```
from datetime import datetime as datetime

def GetTimePositions(fitsList, offset):

    timePositions = list()

    for image in fitsList:
        totalHours = 0.0
        time = image[0].header["ST"]

        date = datetime.strptime(time, "%H:%M:%S")

        totalHours += date.hour
        totalHours += date.minute / 60
        totalHours += date.second / 3600

        timePositions.append(totalHours - offset)
    return timePositions
```

[35]:
```
mags = curveMags[0]
magsUncertainty = curveMags[1]
print(f"Points with uncertainty of around: {magsUncertainty[0]:0.3f}")

tOffset = GetTimePositions(objectFITS_NNSer, 0)[0]
timePositions = GetTimePositions(objectFITS_NNSer, tOffset)

def gaussian(x, mu, std, scale, height):
    ans = list()
    for el in x:
```

```
        ans.append(scale * np.exp(-(el-mu)**2/(2*std**2)) + height)
    return ans

pars, cov = curve_fit(gaussian, timePositions, mags, [0.25, 0.05, 5, 14])

fig, ax = plt.subplots()

pointColor = "indianred"
arrowColor = "teal"
plt.errorbar(timePositions[0:6], mags[0:6], yerr = magsUncertainty[0:6],␣
 ↪fmt="o", \
             color=pointColor, markersize=10, label="NN Ser Magnitude")
plt.errorbar(timePositions[10:], mags[10:], yerr = magsUncertainty[10:],␣
 ↪fmt="o", \
             color=pointColor, markersize=10)
plt.errorbar(timePositions[6:10], mags[6:10], yerr = magsUncertainty[6:10],␣
 ↪fmt="v", \
             color=arrowColor, markersize=10, label="Limiting Magnitude")

t = np.linspace(0, 0.55, 100)
plt.plot(t, gaussian(t, pars[0], pars[1], pars[2], pars[3]), "--",␣
 ↪label="Gaussian Fit", color="cornflowerblue")

plt.xlabel("Time (Hours)")
plt.ylabel("Magnitude")
plt.gca().invert_yaxis()
plt.grid()
plt.legend()
```

```
Points with uncertainty of around: 0.846
```

[35]: <matplotlib.legend.Legend at 0x7f968a553430>



[36]:
```
# Duration of the eclipse is assumed to be within 2 standard deviations from
↪the mean of the fitted gaussian.
# i.e. 4 times the standard deviaiton

def duration(std):
    return 4*std

print(f"Duration of the eclipse: {60 * duration(pars[1]):0.3f} minutes")
print(f"Uncertainty on the duration: {60 * duration(pars[1] + 0.005) - 60 *
↪duration(pars[1]):0.1f} minutes")
```

```
Duration of the eclipse: 11.000 minutes
Uncertainty on the duration: 1.2 minutes
```

[37]:
```
#### What parameters can be found, What info would be useful to better
↪constrain the system.

def Ratio(depth):
    smallOverBig = np.sqrt(depth) # where depth is the percentage depth in the
↪light curve
    return smallOverBig

print(f"Ratio of radii: {Ratio((mags[7] - mags[11])/14)}")
print(f"Uncertainty of ratio: {Ratio((magsUncertainty[7])/14)}")
```

```
Ratio of radii: 0.6819119574074364
Uncertainty of ratio: 0.2559602025732462
```