

CTA200H 2021 - Computing Project

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QUESTION 1 - Visualizing the Galaxy

In order to import and use the data contained in the `.fits` files, the Python module `astropy.io.fits` was used. The different components of the galaxy in the `galaxy_hydro.fits` - stellar, gas and dust mass and star formation rate - were imported and their images were plotted using `matplotlib.pyplot.imshow`, as seen in Figure 1. In order to more clearly view the structures of the galaxy, the logarithm of the data was calculated. Taking this logged data, the contour of the dust mass was plotted over the image of the stellar mass, and that of the gas mass plotted the image of the star formation rate; the contours were plotted using `matplotlib.pyplot.contour`. These plots can be found in Figure 2. The total sums of all the pixels in the image of each of these components was calculated and compared against what was expected in the `header` of the file; a summary of these calculations is in Table 1.

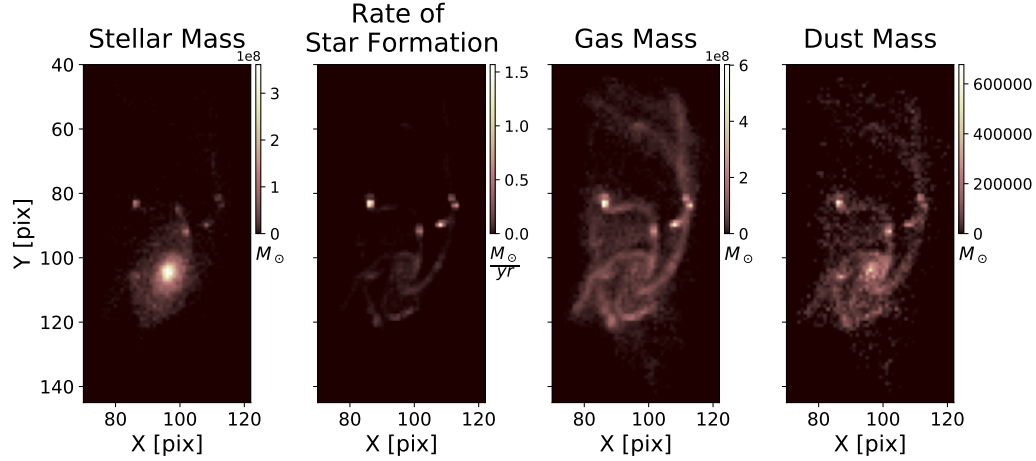
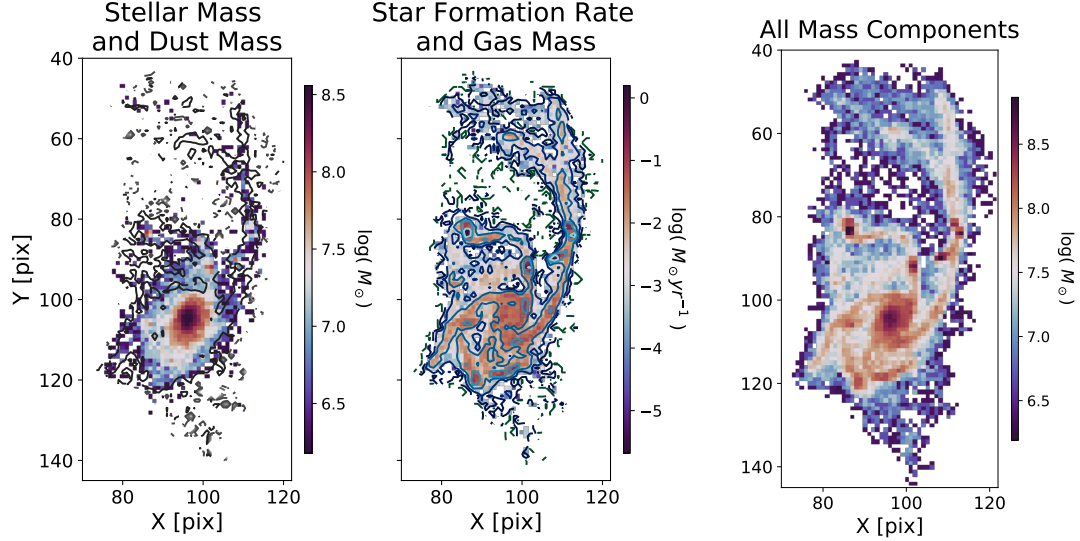


Fig. 1.—: Cropped images of galaxy components: Stellar mass; Star formation rate; Gas mass; Dust mass.

Galaxy Component	Value	Log Value
Stellar Mass	$1.986 \times 10^{10} M_{\odot}$	$10.298 \log(M_{\odot})$
Gas Mass	$6.547 \times 10^{10} M_{\odot}$	$10.816 \log(M_{\odot})$
Dust Mass	$5.844 \times 10^7 M_{\odot}$	$7.767 \log(M_{\odot})$
Star Formation Rate	$24.401 \frac{M_{\odot}}{yr}$	—

Table 1:: The total mass of each component of the galaxy and the total star formation rate.

Next, the `galaxy_allwav.fits` file was imported; this file contained data of this galaxy as observed at 20 varying wavelengths. Of these wavelengths, 5 of were selected and their images were plotted in Figure 3. These 5 wavelengths were specifically chosen to be in the ultraviolet ($0.16 \mu\text{m}$), blue ($0.435 \mu\text{m}$), red ($0.606 \mu\text{m}$), infrared ($1.6 \mu\text{m}$), and far infrared ($1300 \mu\text{m}$) ranges.



(a) Left - The dust mass contour (black line) plotted over the cropped image of the stellar mass. Right - The gas mass contour (grey line) plotted over the cropped image of star formation rate.

(b) The sum of all mass components.

Fig. 2.—: Different components of the galaxy over-plotted to view the structures.

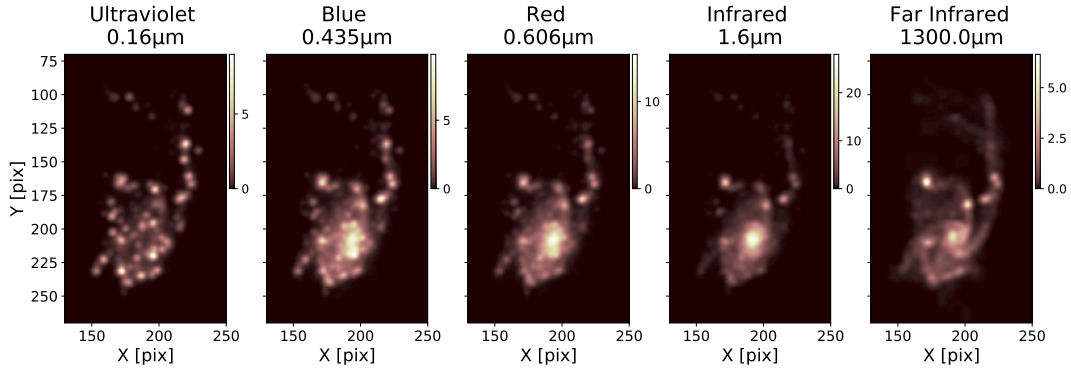


Fig. 3.—: Cropped images of the galaxy at the selected wavelengths: Ultraviolet (0.16 μm); Blue (0.435 μm); Red (0.606 μm); Infrared (1.6 μm); Far Infrared (1300 μm).

For all the 20 files, the pixel values were summed and recorded as the total flux of the galaxy at that wavelength in arbitrary units ¹. The total flux for the 5 selected wavelengths can be found in Table 2 and all of the total flux values were plotted as a function of wavelength in Figure 4.

¹Note that the units on the flux were likely in nano-Jansky (nJy) but converting this to SI units was inconsistent with the expected units of flux. Thus, the units on the flux were deemed arbitrary and further analysis on this value and the nJy units would be the next steps to understanding and applying these fluxes.

Wavelength	Total Flux [a.u.]
UV: 0.16 μm	4610.024
Blue: 0.425 μm	8654.571
Red: 0.606 μm	10876.035
IR: 1.6 μm	12957.026
Far IR: 1300 μm	3896.321

Table 2:: The total flux of the galaxy as observed at varying wavelengths.

Figure 4 demonstrates the relationship between flux and the wavelength at which the light is emitted. At lower wavelengths, below 10 μm , a slight peak was noticed at approximately 1 μm which corresponds roughly to the beginning of the infrared wavelength range, which can be seen in the left plot in Figure 4. After this, there was a very large peak in the mid to far infrared wavelength range, peaking roughly at 100 μm . Note that the galaxy is at redshift $z = 2$, indicating that the light emitted from it was stretched to larger wavelengths by a factor of 3, as from found from the Doppler shift for wavelengths, equation 1:

$$\frac{\lambda_f}{\lambda_i} = 1 + z. \quad (1)$$

Thus, the peak at roughly 100 μm was in the lower to mid infrared range when it was emitted, and the slight peak in the near infrared range was initially emitted as ultraviolet light. Different components of galaxy emit light at different wavelengths and can account for these peaks. Younger stars emit light at shorter wavelengths since they are hotter and dust obscures light at short wavelengths only to re-emit it in infrared. This is very consistent with what was found in Figure 4 since there was a peak in the infrared. The smaller peak emitted in the ultraviolet could have been due to younger stars or star formation whose light was not obscured by the dust.

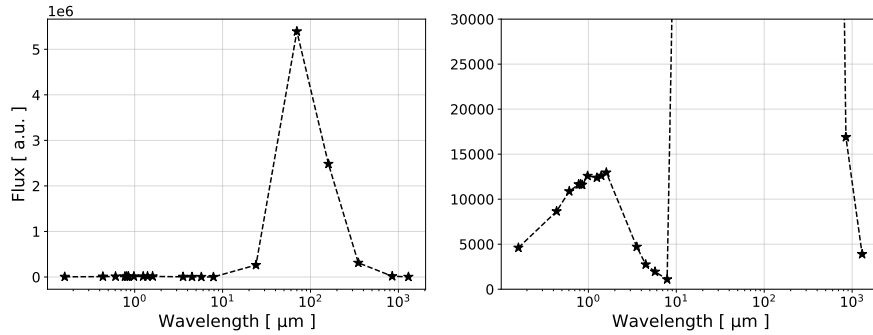


Fig. 4.—: Flux, in arbitrary units, plotted as a function of observed wavelength of the galaxy in μm . The plot on the right is the same as the one on the left with a limited y-axis in order to see how flux behaves at lower wavelengths.

QUESTION 2 - Galaxy Size

To calculate the half-mass size of the galaxy, the module `photutils.aperture.aperture_photometry` was used to find the radius of a circular aperture which contains half the mass of the galaxy. The stellar, gas and dust masses from the `galaxy_hydro.fits` file were summed to form a total mass data array and the sum of all pixel values was calculated to find the total mass. Next, `photutils.aperture.aperture_photometry`

was iterated at incrementally increasing radii until the mass contained within the radius was half the total mass. The radius at which this occurred was the half-mass size of the galaxy in pixels and was found to be $r_{\text{half-mass}} = 27.214$ pixels. To convert this value to a physical size, the following steps were done: the `PIXELSCALE` and `Z` were read in from the `header` of the `galaxy_allwav.fits` file as the conversion from pixels to arcseconds and redshift, respectively,

$$\text{pix_scale} = 0.03 \times \frac{384}{194} \approx 0.0594 \frac{\text{arcsec}}{\text{pixel}}, \quad z = 2$$

Multiplying the `pix_scale` by the size in pixels converts the size to an angular value in arcseconds. Next, the cosmological parameters of the universe were assumed to be:

$$\Omega_{\text{M}0} = 0.2865, \Omega_{\Lambda 0} = 0.7135, H_0 = 69.32 \frac{\text{km}}{\text{Mpc s}}, \quad (2)$$

Using all the aforementioned constants, the following equations were employed to convert size in pixels to size a physical size:

$$R = (1 + z)^{-1}, \dot{R} = H_0 \sqrt{\frac{\Omega_{\text{M}0}}{R} + \Omega_{\Lambda 0} R^2} \quad (3)$$

$$D_A(R) = R D_c(R), \text{ where } D_c(R) = c \int_R^1 \frac{1}{R \dot{R}} dR \quad (4)$$

$$\ell = D_A(R) \times \theta, \text{ where } \theta = \text{pix_scale} \left[\frac{\text{arcsec}}{\text{pix}} \right] \times r_{\text{half-mass}} [\text{pix}] \quad (5)$$

After applying these calculations on the half-mass size of the galaxy in pixels, the half mass size in kilo-parsecs (kpc) was $r_{\text{half-mass}} = 27.214 \text{ pixels} = 6.983 \text{ kpc}$, as seen in Table 3.

Next, a very similar process was followed for the half-light size of the galaxy as observed at an optical wavelength of $\lambda = 0.425 \mu\text{m}$. The pixel values were all summed and the radius which contained half the total flux was found by iterating `photutils.aperture.aperture_photometry`. This radius, found to be $r_{\text{half-light}} = 30.880$ pixels, was then converted to kpc using the cosmological parameters in 2 and equations 3, 4, 5. The pixel scale and the redshift used for this data set were:

$$\text{pix_scale} = 0.03 \frac{\text{arcsec}}{\text{pixel}}, \quad z = 2.$$

The resulting half-light size of the galaxy was $r_{\text{half-light}} = 30.880 \text{ pixels} = 7.924 \text{ kpc}$. The ratio of the half-mass size to half-light size was calculated to be $\frac{r_{\text{half-mass}}}{r_{\text{half-light}}} = 0.8813$, which was consistent with what was expected of the ratio of a galaxy with this mass and this redshift.³ This indicates that at the optical wavelength chosen, the half-light size is slightly larger than the half-mass size of the galaxy; the two circular apertures were plotted over the image of the galaxy at the optical wavelength in Figure 5a. Despite the consistency in the ratio of half-mass to half-light sizes, the actual values of the two appear larger than what was expected - which was approximately 2 kpc or less.⁴ Ultimately, this variation between expected and calculated values was likely caused when locating the region at which to perform the aperture photometry

²Note that `pix_scale` = 0.03 was the scale for the images from the `galaxy_allwav.fits` file. In order to use this to convert pixels to arcseconds in the `galaxy_hydro.fits` file, it was multiplied by the ratio of the pixels between the two files. This ratio was calculated to be $\frac{384}{194} \approx 1.9794$.

³<https://arxiv.org/pdf/1904.10992.pdf> : *Half-mass Radii for 7000 Galaxies at $1.0 \leq z \leq 2.5$: Most of the Evolution in the Mass-Size Relation Is Due to Color Gradients*. Suess, Katherine A.; Kriek, Mariska; Price, Sedona H.; Barro, Guillermo. (2019).

⁴See footnote 3.

iteration. When automating this task, this location was noticed to be on the arm of the galaxy rather than in proximity to the galactic centre on several data sets. Thus, the location was manually selected and was possibly the cause of the discrepancy in the values.⁵

Wavelength	Total Flux [a.u.]	$r_{\text{half-light}}$ [pix]	$r_{\text{half-light}}$ [kpc]	$\frac{r_{\text{half-mass}}}{r_{\text{half-light}}}$
UV: 0.16 μm	4610.024	37.055	9.508	0.7344
Optical/Blue: 0.425 μm	8654.571	30.880	7.924	0.8813
Red: 0.606 μm	10876.035	29.286	7.515	0.9292
IR: 1.6 μm	12957.026	27.095	6.952	1.0044
Far IR: 1300 μm	3896.321	32.274	8.281	0.8432
–	Total Mass [M_{\odot}]	$r_{\text{half-mass}}$ [pix]	$r_{\text{half-mass}}$ [kpc]	–
–	8.538×10^{10}	27.214	6.983	–

Table 3:: The half-light size of the galaxy as observed at varying wavelengths.

This process was then repeated for the data at all 20 wavelengths and a summary of these values for the 5 previously selected wavelength data sets is in Table 3. The ratios of $\frac{r_{\text{half-mass}}}{r_{\text{half-light}}}$ were again consistent with the expected values at this mass and redshift. The half-light size was plotted against wavelength, Figure 5b.

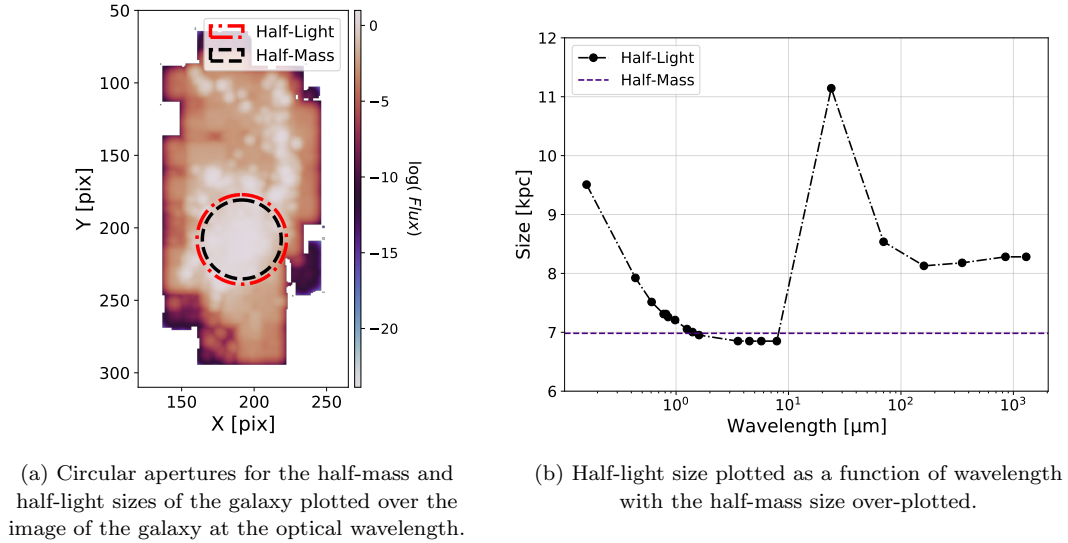


Fig. 5.—: Half-Light and Half-Mass sizes of the galaxy.

However, this method for measuring the size of the galaxy does not work for images of real galaxies on the sky, only simulations. The `galaxy_onsky_F160W.fits` file was imported and analyzed for this. The sum of all the pixels is where the problem arises, simply due to the real image having noise in the background rather than pixels of value 0 everywhere except the galaxy itself. Though not an efficient method, the noise can be manually filtered out such that only the galaxy remains as pixels with value. This was done for

⁵Multiple methods were employed for this calculation and yielded many varying results. The method that was selected - manually choosing the location at which aperture photometry was performed - yielded the most consistent results between all the wavelengths.

the `galaxy_onsky_F160W.fits` file and the flux density of the pixels before and after filtering was plotted, Figure 6. Using this filtering and the aforementioned method using aperture photometry, the half-light size of the galaxy was found to be $r_{\text{half-light}} = 7.362$ kpc. This is consistent with the previous results for the simulations, however the method to obtain this required extensive manual computation and a more efficient method would be better suited to measure the size of this galaxy.

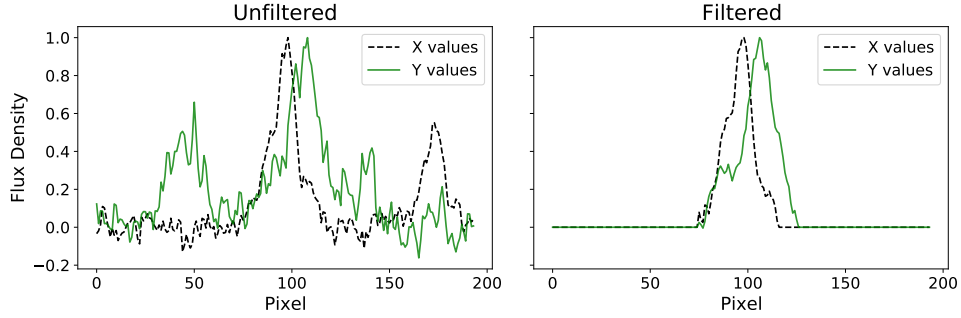


Fig. 6.—: Pixel flux density of the `galaxy_onsky_F160W.fits` galaxy image before (left) and after filtering the noise (right).

QUESTION 3 - Using statmorph

The Python module `statmorph` was installed and imported. The tutorial⁶ was run and the morphological parameters of the example galaxy `galaxy_onsky_F160W.fits` were measured, Table 4. The gain and the number of standard deviations per pixel above the background value for which to consider a pixel as possibly being part of a signal were both changed from the tutorial values to accommodate for this example galaxy: $\text{gain} = 100.0$ and $n_\sigma = 1.1$, respectively. The final plot output from the tutorial for the example galaxy can be found in Figure 7.

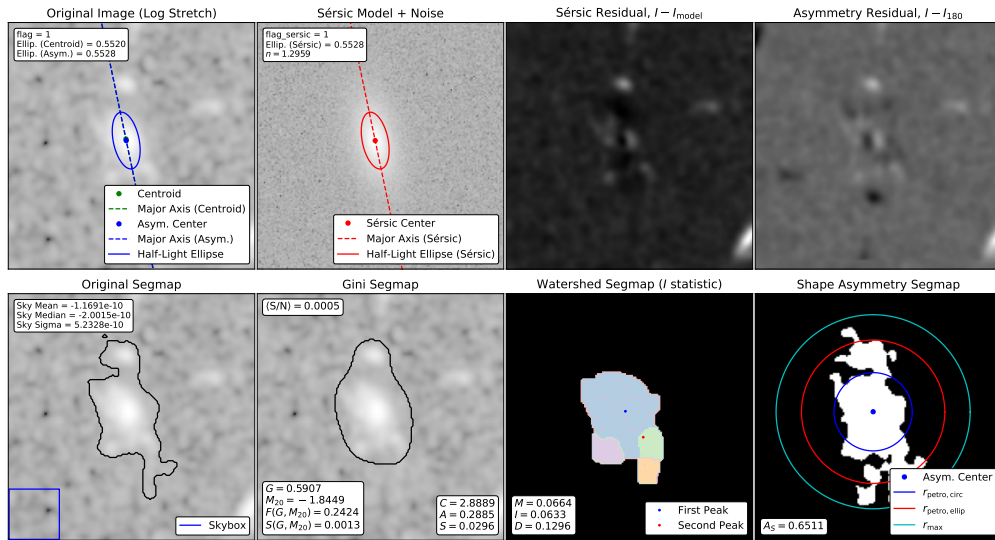


Fig. 7.—: `statmorph` summary image.

⁶<https://statmorph.readthedocs.io/en/latest/notebooks/tutorial.html> : Rodriguez-Gomez, V.; et al. (2019)

Parameter	Value
Time	0.454042 s
xc_centroid	96.07801134603386
yc_centroid	106.68958740021499
ellipticity_centroid	0.5519703098752687
elongation_centroid	2.231994937035535
orientation_centroid	-1.3639754348274544
xc_asymmetry	96.223338879882
yc_asymmetry	105.69277091100385
ellipticity_asymmetry	0.5527798962058413
elongation_asymmetry	2.236035436502355
orientation_asymmetry	-1.364261316762682
rpetro_circ	24.135623219047734
rpetro_ellip	44.21015440825346
rhalf_circ	12.292743156853122
rhalf_ellip	17.803864742346722
r20	5.358802246026299
r80	20.269707202270837
Gini	0.5906853165188031
M20	-1.8449260814572326
F(G, M20)	0.24242609121793723
S(G, M20)	0.0013337380310596836
sn_per_pixel	0.0004933233
C	2.888898722956452
A	0.2884936132231093
S	0.029582708725406928
sersic_amplitude	4.965930669634471e-09
sersic_rhalf	17.803864742346722
sersic_n	1.2958749929724942
sersic_xc	96.223338879882
sersic_yc	105.69277091100385
sersic_ellip	0.5527798962058413
sersic_theta	1.777331336827111
sky_mean	-1.1690968e-10
sky_median	-2.001517e-10
sky_sigma	5.2327714e-10
flag	1
flag_sersic	1

Table 4:: Morphological parameters from **statmorph**, taken directly from the printed output parameters as done in the tutorial.