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Simulating strong gravity-lensing effect using python with 10 source and 20 lensing galaxies

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Abstract: This report explores using Python, a coding language, to create simulated images of a gravitational lens system, using the Hubble Space Telescope (HST) parameters. With Python's helpful tools, like NumPy for math operations and Astropy for astronomy tasks, we build algorithms that recreate the interactions within our chosen group of galaxies and take into account HST's unique imaging capabilities. Our method combines theory of gravitational lensing with practical coding strategies to make simulations show these complex light-bending interactions. The report walks through how the algorithms are developed with specific scientific simulation models like Sersic profile and point-spread function (PSF), showcasing the important role of computer simulations in deepening our understanding of space. In this report, I will introduce how we can use python code to create simulation images of a gravitational lens system. This system involves with 10 source galaxies ,20 lensing galaxies and with consideration of dark matter halo.

Keyword: Gravity Lensing, Simulation, Astronomy.

1. Introduction

Gravity lensing has always been a very popular field of study in astrophysics. It was first introduced by Albert Einstein. He proposed, according to general relativity, when the light from a distant source galaxy that is travelling to earth it may be bent by a massive lens galaxy that is closer to us and cause the image of the source galaxy to be magnified or distorted. This phenomenon was first approved with the observation of Twin QSO SBS 0957+561. Since then, various instrument had observed such cosmic anomaly include the famous HST (HST). Computer simulation is a very helpful way for us to understand gravity lensing and produce visual images for scientist to better understand it.

2. Simulation equations

To simulate lensing effect with computer, we first need to set the zero point. The zero point in a photometric system is defined as the magnitude of an object that produces 1 count per second on the detector hence it varies with the instrument we are observing with. It is used to calibrate a system to the standard magnitude system due to the flux detected from objects. Here in our case, the zero point for HST is set to be 25.95 magnitude $= -2.5 * \log(\text{flux}) + \text{zeropoint}$. Then, after setting the exposure time and maximum single exposure times, we can start creating surface brightness object for both source and lens galaxies.

To do that, we will need to introduce the Sersic profile [1]. Sersic profile is described by

$$I(R) = I_e \left[-k \left(\left(\frac{R}{R_{eff}} \right)^{\frac{1}{n}} - 1 \right) \right]. \tag{1}$$

I_e is the intensity at effective radius R_{eff}. The Sersic index n controls the degree of curvature of the radial light profile and is also increased with luminosity of the galaxy. The constant k is determined so that Reff is the half-light radius, q denotes the axis ratio.

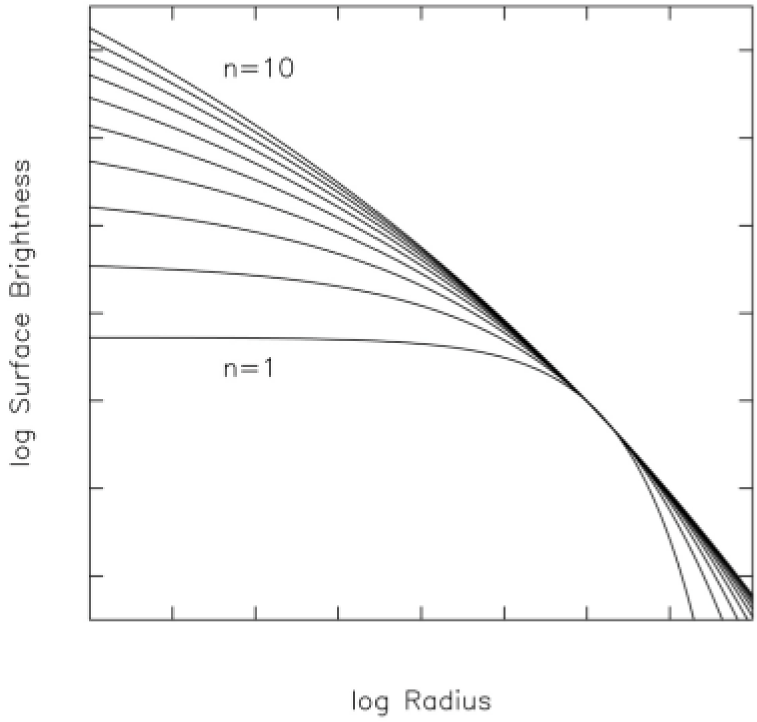


Figure 1. This graph shows Sersic profile with different n at log-log space.

The next quantity will be modeled is mass. By modeling mass, we can find figure out how the lens galaxy bends the light from source galaxy. To do that, we will be using a power-law model [2].

$$\Sigma(x, y) = \sum \mathrm{cr} \frac{(3 - \gamma')}{1 + q_m} \left(\frac{\sqrt{X^2 + {q_m}^{-2} Y^2}}{R_e} \right)^{1-\gamma'} \tag{2}$$

q_m is the axis ratio. $\gamma'$is the radial power-law slope, the {X, Y} principal axes are rotated by the lens position angle w.r. to the canonical x and y. R_e is the Einstein radius[3]. Critical density $\sum_{cr}$ is defined by

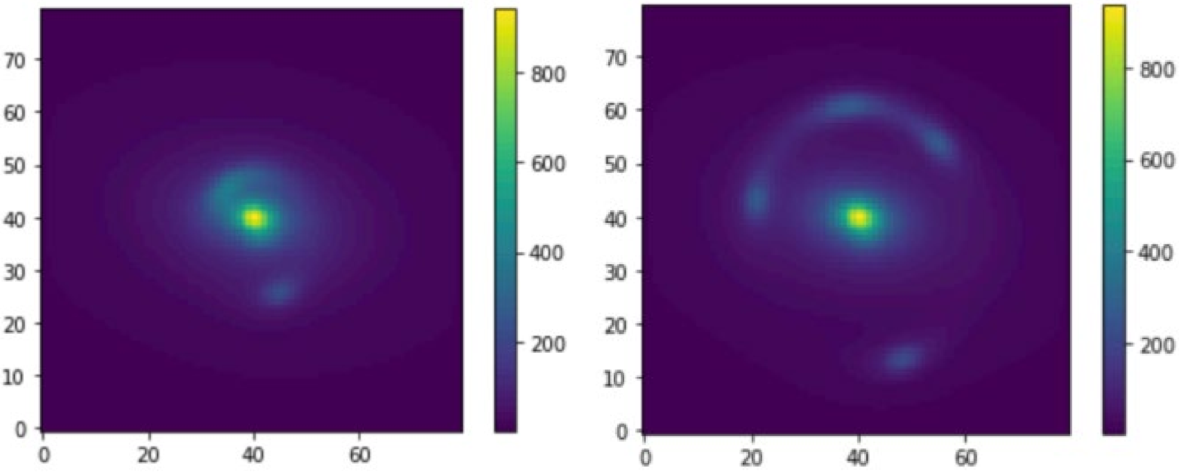
$$\sum \mathrm{cr} = \frac{c^2 D_s}{4\pi G D_d D_{ds}} \tag{3}$$

D_s is relative distance to the source. D_d is relative distance to the deflector. D_{ds} is the distance between deflector and source. Also, the Einstein radius is chosen such that in the spherical limit, it encloses a mean surface density equal to $\sum_{cr}$.

Power-law models of elliptical galaxies have often been used with success over the years to model gravitational lenses. Fast methods to compute 2D deflections from elliptical power-law profiles, as a special case of the formalism for homoeoidal profiles. In our code, power-law mass model includes 6 parameters:

Lensmass1 = MassModels.powerLaw('lens',{'x':600.00,'y':600.00,'b':9.8,'q':0.61,'q':-9.6,'eta': 1.0})

Here x and y are the central position of mass distribution, q is the axis radio, pa is the position angle, eta is the power-law mass slope, and b is the Einstein radius.



(a) (b)

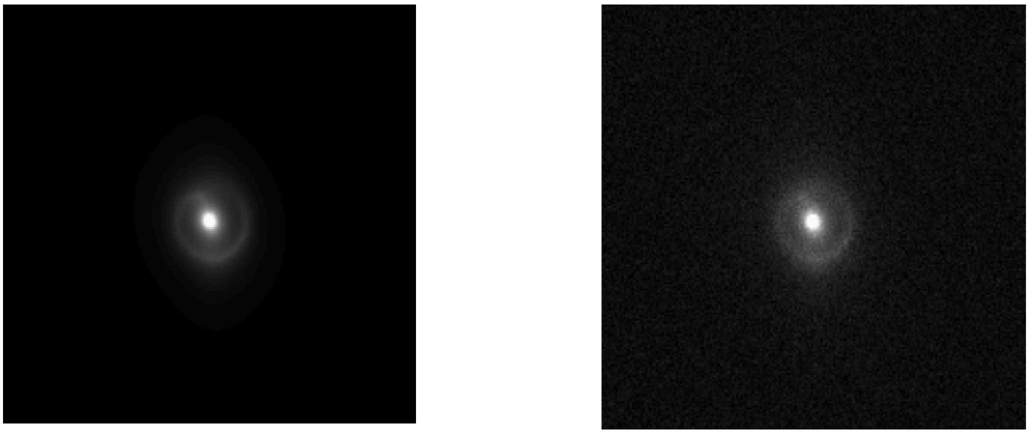
Figure 2. Two lensing system with the same parameters except for Einstein radius. (a) has 10.8 pixel and (b) has 22.8 pixel.

Now, after modeling the brightness and mass of the galaxy, we will need a point spread function (PSF) [4] to describe the response of the image system to a point source, which is the galaxies we are modelling. Each instrument of observation has its own PSF so our result is highly instrument dependent. After settle up the PSF, we can use PSF to convolve source and lens galaxies and form the image. Then, we can use our mass model to get the deflection angles that created by the lensing effect. Not only the galaxy itself, the mass model should also include the dark matter haloes that locate around the modeling galaxies since the gravitation effect of dark matter is very important [5].

The last thing in our modeling process is adding noise to the image. There are three types of noises, read out noise (N_read), background noise (B) and counts noise (C). Read out noise is caused by camera's electronics. It is the noise of the on-chip amplifier which converts the charge (i.e., the electrons) into a change in analogue voltage. As each pixel value is being read, a few extra electrons are lost or gained randomly, cause the readout value to vary a little from the actual value. The read-out noise only depends on the intrinsic property of the instrument and no others. The causes of background noise are sky background and/or detector dark current. Some of the source of sky background noise are Earthshine (ES), Zodiacal light (ZL), Geocoronal emission (GC). Counts noise is the signal from clean lens system in electrons per second per pixel. As usual, the variance of noise per pixel is given by

$$VARpix = \sqrt{\mathrm{Ct} + \mathrm{Bt} + \mathrm{NreadR2}} \qquad (4)$$

C is the signal from clean lens system in electrons per second per pixel; t is the integration time in seconds; C*t means the noise source from counts statistic noise. B is the sum of the sky background and detector dark current in electrons per second per pixel; B*t is the noise source from background noise. Nread is the number of detector readouts; R is the standard deviation of the read noise in electrons. NreadR^2 is the noise source from readout noise.



(a) (b)

Figure 3. Same lensing system. (a) Without noise. (b) With noise

3. Data set

Table 1. Source galaxy data.

Source number	magnitude	Sersic model
1	24.5	{‘x’:1530.0,’y’:1570.0,’re’:4.6,’q’:0.92,’pa’:54.0,’n’:1.3}
2	24.2	{‘x’:730.0,’y’:890.0,’re’:8.3,’q’:0.52,’pa’:4.0,’n’:2.0}
3	25.0	{‘x’:1880.0,’y’:939.0,’re’:5.5,’q’:0.71,’pa’:-54.0,’n’:2.3}
4	25.1	{‘x’:2280.0,’y’:1090.0,’re’:5.1,’q’:0.88,’pa’:120.0,’n’:3.1}
5	24.7	{‘x’:1430.0,’y’:1610.0,’re’:6.1,’q’:0.77,’pa’:64.0,’n’:2.8}
6	22.7	{‘x’:2180.0,’y’:2169.0,’re’:4.9,’q’:0.83,’pa’:-99.0,’n’:3.3}
7	23.9	{‘x’:1442.0,’y’:1488.0,’re’:8.6,’q’:0.76,’pa’:-10.0,’n’:3.4}
8	23.5	{‘x’:2290.0,’y’:789.0,’re’:5.2,’q’:0.66,’pa’:154.0,’n’:2.7}
9	24.4	{‘x’:630.0,’y’:2489.0,’re’:4.4,’q’:0.65,’pa’:39.0,’n’:1.5}
10	24.8	{‘x’:1670.0,’y’:2059.0,’re’:5.8,’q’:0.73,’pa’:-100.0,’n’:1.9}

Table 2. Lense galaxy data.

Lense number	magnitude	Sersic model
1	20.69	{‘x’:600.0,’y’:600.0,’re’:15.2,’q’:0.61,’pa’:-9.6,’n’:4.0}
2	18.8	{‘x’:1500.0,’y’:1500.0,’re’:50.2,’q’:0.91,’pa’:200.6,’n’:4.0}
3	22.3	{‘x’:1350.0,’y’:750.0,’re’:30.2,’q’:0.51,’pa’:32.6,’n’:3.0}
4	21.5	{‘x’:2250.0,’y’:1800.0,’re’:18.2,’q’:0.91,’pa’:-80.6,’n’:2.5}
5	21.9	{‘x’:900.0,’y’:2100.0,’re’:25.2,’q’:0.81,’pa’:180.6,’n’:3.3}
6	20.7	{‘x’:1050.0,’y’:450.0,’re’:27.2,’q’:0.41,’pa’:-10.6,’n’:2.9}
7	20.4	{‘x’:450.0,’y’:2250.0,’re’:20.2,’q’:0.81,’pa’:-200.6,’n’:1.9}
8	19.7	{‘x’:2550.0,’y’:900.0,’re’:20.2,’q’:0.38,’pa’:20.6,’n’:2.8}
9	21.5	{‘x’:1950.0,’y’:1950.0,’re’:20.2,’q’:0.31,’pa’:-110.6,’n’:2.9}

Table 2. (continued).

10	22.0	{‘x’:1800.0,’y’:1050.0,’re’:19.2,’q’:0.45,’pa’:70.6,’n’:2.9}
11	23.3	{‘x’:2000.0,’y’:1750.0,’re’:22.2,’q’:0.65,’pa’:50.6,’n’:2.0}
12	24.1	{‘x’:2800.0,’y’:2750.0,’re’:18.2,’q’:0.35,’pa’:180.6,’n’:1.9}
13	22.7	{‘x’:500.0,’y’:1250.0,’re’:20.8,’q’:0.51,’pa’:110.2,’n’:2.5}
14	23.4	{‘x’:1000.0,’y’:1350.0,’re’:24.2,’q’:0.63,’pa’:-44.6,’n’:2.8}
15	22.6	{‘x’:1270.0,’y’:1750.0,’re’:26.2,’q’:0.66,’pa’:10.6,’n’:3.3}
16	23.5	{‘x’:1860.0,’y’:1310.0,’re’:35.2,’q’:0.38,’pa’:-10.6,’n’:3.6}
17	19.4	{‘x’:1400.0,’y’:1670.0,’re’:40.2,’q’:0.85,’pa’:100.6,’n’:3.9}
18	19.6	{‘x’:1620.0,’y’:1590.0,’re’:43.2,’q’:0.80,’pa’:280.6,’n’:4.6}
19	20.1	{‘x’:1850.0,’y’:1910.0,’re’:40.5,’q’:0.88,’pa’:88.6,’n’:4.2}
20	19.5	{‘x’:2189.0,’y’:2166.0,’re’:38.3,’q’:0.77,’pa’:-44.6,’n’:4.1}

Table 3. Noise data.

Readout noise	4.2 counts per pixel
Background noise	0.11 counts per pixel

halo parameters:
HaloMass: {‘x’:1500.0,’y’:1500.0,’b’:1000.0,’q’:1.0,’pa’:0.0,’eta’:1.0}
PSF:
HST F814W PSF

4. Result

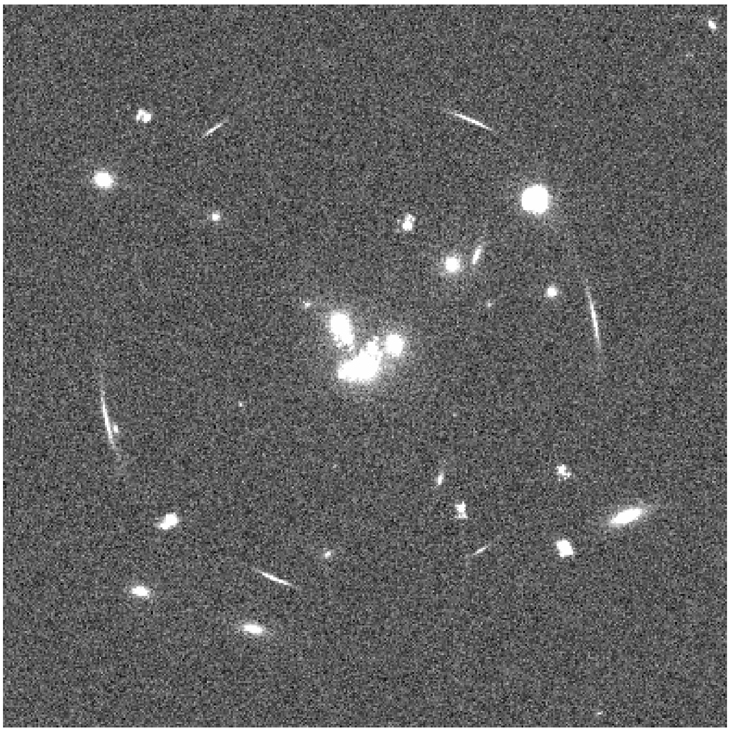


Figure 4. Full simulation of 10 source and 20 lensing galaxies.

Here we can see that the galaxy cluster in the middle of the picture and several other galaxies spread in the other location. Also, we can see a very distinctive gravitational lensing effect is shown in the simulation. The galaxy cluster in the middle; the lensing galaxies; bends the light of the source galaxies in the back. And those light from the source galaxies are formed into this ring-like structure due to the strong gravitational field of the lensing galaxy cluster.

5. Conclusion

In this paper, we have demonstrated how we can use python code through integrating different rigorous scientific model to create a complex gravitational lensing system. In this paper, we have showed a gravitational system contain 10 source galaxies and 20 lensing galaxies with consideration of the dark matter halo.

Despite the fruitful outcomes, challenges like accounting for all variables that might impact gravitational lensing, and ensuring the simulations are precise and authentic representations of the actual cosmic phenomena, persist. The complexity and variability of celestial configurations necessitate a comprehensive and meticulously detailed approach to simulations.

Moreover, there exist inherent limitations in the simulation models. Real-world interactions within and between galaxies, inclusion of dark matter, and other unseen variables in the universe offer a myriad of possibilities that can't always be accurately represented or predicted through simulations. Additionally, certain approximations and assumptions made during the study might not encapsulate the full scope of actual cosmic events.

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