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Fergusson College (Autonomous), Pune
Department of Physics

A Project Report on

Identifying lensed supernovae Ia from multi-band imaging data

As a part of BSc. (Physics) degree of Savitribai Phule Pune University

Submitted by
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CERTIFICATE

This is to certify that, Ms. Anushka Madhusudan Menon, Roll. no. 4315 of T.Y.B.Sc. Physics class of this department has satisfactorily completed the project entitled:
'Identifying lensed supernovae Ia from multi-band imaging data'
as part of completion of BSc. (Physics) degree of Savitribai Phule Pune University during the year 2019-2020.

Project Guide (Internal)

Project Guide (External)

Head, Department of Physics
Examiner Signature:

External Examiner

Internal Examiner

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Anushka M. Menon

List of Symbols

α	Angle of deflection
G	Gravitational constant
M	Mass of spherical object
c	Speed of light
ξ	Impact parameter
L	Luminosity of an object
$L_\odot$	Luminosity of Sun
h_{70}	Reduced Hubble's constant
R_0	Effective radius of galaxy
σ	Velocity dispersion of galaxy
M	Absolute magnitude
m	Apparent magnitude
D	Distance of galaxy from earth
F	Flux generated by galaxy
z	Redshift
θ_e	Position angle
σ_x,σ_y	Standard deviation in x, y

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1 Introduction

One of the consequence of Einsteins General Theory of Relativity is that light rays are deflected by gravity. The phenomena resulting from deflection of light in strong gravitational field is referred as Gravitational Lensing. Although lensing was predicted by Einstein in 1936, the first lensing caused by Quasars was observed in 1979. Lensing is a rare phenomena and it is difficult to differentiate lensed images from unlensed images. This formed the motivation for our project.

I started the project by understanding the theory behind lensing, on how lensing came to be predicted and later discovered, the types of lensing, the factors on which lensing depends and the research in the field. This was followed by getting well acquainted with python, analyzing software-glafic and various linux commands. As glafic is used extensively throughout our project, the manual of glafic had to be well-known so as to find and enter accurate parameters accordingly. We first fixed the type of galaxies causing the lensing and acting as host to the source and then assumed mass and light profiles for them respectively. We simulated the lensed images of supernova type Ia after studying the light curve, Philips relation, spectral energy distribution of the supernova type Ia. We did this task using a analyzing software glafic and with the help of programming using Python.

Through the course of the project report, we give an overview of the theory on lensing and various factors it depends on. It also highlights on the programming used and generated for obtaining the images and the insights acquired by studying these images. We conclude the report by discussing the results obtained and the future scope in the field of lensing.

2 Theoretical Background

2.1 Introduction to Gravitational Lensing

The possibility of starlight getting deflected in the presence of gravity was suspected much earlier by Isaac Newton (1704) and Pierre-Simon Laplace (1795). John Mitchellin 1784 and later Johann von Soldner in 1804, mentioned the possibility that light propagating in the field of a spherical mass M (like a star) would be deflected by an angle which he calculated by assuming light to be made of particles and following Newtonian Mechanics. Later on, Einstein published his General Theory of Relativity in the year 1915 giving the behaviour of light in gravitational field. He calculated the deflection of light by Sun using full field equations of General Relativity and discovered that the deflection angle is actually twice the previous results given by Soldner,the factor of two arising because of the curvature of the metric. The deflection angle is given by:

$$\alpha_N = \frac{4GM}{c^2\xi} \tag{1}$$

Einsteins final result was confirmed in 1919 when the apparent angular shift of stars close to the limb of the Sun was measured during a total solar eclipse by Arthur Eddington. This observation not only supported the Theory of Relativity but also gave the possibility of observing the phenomena of Graviational Lensing.

A gravitational lens is a distribution of matter between a distant light source and an observer that can cause light to bend from the source as the light travels towards the observer. The resulting phenomena is known as gravitational lensing.The propagation of light from the source can be broken into three zones. First zone is the propagation of light from source through unperturbed spacetime followed by deflection of light by a point near the lens in the second zone. Finally, in the third zone, light again travels through unperturbed spacetime. This is on assuming overall geometry of the universe is well described by the Friedmann-Lematre-Robertson-Walker metric and that the matter inhomogeneities which cause the lensing are no more than local perturbations.

Chwolson (1924) and Einstein (1936) discussed the same problem of gravitational lensing of stars by stars.They considered a source to be perfectly aligned by a foreground object, concluding that the source should be imaged as a ring around the lens. Einstein concluded that the chance of observing lensing by stellar mass lens is quite less as angular image splitting caused by a stellar-mass lens is too small to be resolved by an optical telescope.

In 1937, Fritz Zwicky published two visinary papers considering "extragalactic nebulae" (nowdays called as galaxies) as lenses that can split images of back-

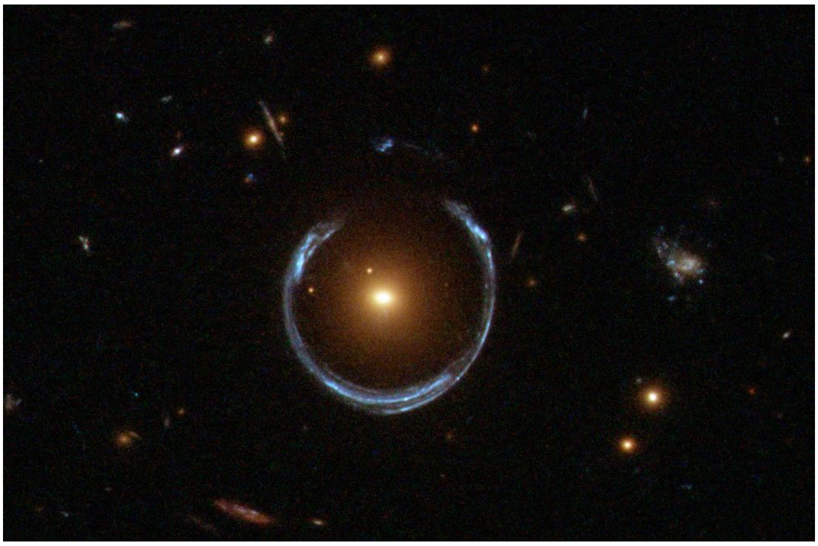

Figure 1: Einstein's ring formed from lensing by LRG 3-757

Source: ESA/Hubble and NASA

ground sources by large enough angle to be observed. He also predicted that not only lensing will provide an additional proof to the theory of General Relativity but also would be instrumental in magnifying distant galaxies and allow accurate determination of galaxy masses. He also estimated the probability that a distant source would be lensed to produce an multible images which would be 1 out of 400 distant sources. His work was revolutionary as all of his predictions came to be true.

2.2 Detection of Gravitational Lensing

Walsh, Carswell and Weymann in 1979 discovered a pair of Quasars QSO 0957+561A,B seperated by 6 arcseconds having identical colour, redshift and spectra, the first example of lensing.They also observed the presence of foreground galaxy between the two images. Quasars are distant, and so the probability that they are lensed by intervening galaxies is sufficiently large. Also, the magnification caused by Quasars are very large and the images are well seperated, hence can be detected easily. A year later, a triple quasar PG 1115+080 was discovered.

Sjur Refsdal in 1964, first proposed using time delayed images from a lensed supernova to study the expansion of the universe. Lensed supernova PS1-10afx was discovered by Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1) in 2010. In the year 2014, SN Refsdal the first detected multiply-lensed supernova, was visible within the field of the galaxy cluster MACS J1149+2223 using Hubble Space Telescope.

2.3 Gravitational Lensing by Galaxies

Arclets are images of background galaxies stretched by the lensing effect of a cluster or galaxy. In order to identify an arclet as such, the image distortion must be significant owing to the intrinsic ellipticity distribution of galaxies. The lensing of galaxy depends on foreground galaxy, background galaxy as well as source present in the background galaxy.

2.3.1 Foreground Galaxy

The galaxy which acts as a lensing, magnifying the background source is termed as foreground galaxy or lensing galaxy. Some of the random uncertainties in the lens statistics are being steadily reduced as new surveys better constrain the deflector and source populations, and more lenses are discovered. Elliptical galaxies are found to dominate the lensing probability.They are ideal candidates due to the following reasons:

1. Falco et al. (1999) found that ellipticals with redshifts of up to z=1 have minimal dust content
2. The surface brightness of ellipticals is flatter than an isothermal profile near the centre, which results in higher observed velocity dispersions for a given mass distribution than constant mass-to-light ratio models
3. Mass profile for ellipticals are taken to be singular isothermal where lensing cross section depends on fourth power of velocity dispersion.
4. Mao and Kochanek (1994) showed that the known quasar lenses were best explained if there was little or no evolution in the elliptical population to redshifts of order unity.
5. Elliptical galaxies obey de Vaucouleur's law (1948), a special case of sersic profile, giving sersic index to be n = 4.

We therefore, consider an elliptical profile for the lensing galaxies. Moreover,the mass distribution of the galaxy can be given by the Faber-Jackson relation (1976). Initially, we find the luminosity of the galaxy using the relation between luminosity and effective radius:

$$\frac{L}{10^{10.2}h_{70}^{-1}L_{\odot}} = \left(\frac{R_0}{10^{0.52}h_{70}^{-1}kpc}\right)^{1.5} \tag{2}$$

Using Faber-Jackson relation we can calculate the velocity dispersion as:

$$\frac{L}{10^{10.2}h_{70}^{-1}L_{\odot}} = \left(\frac{\sigma}{10^{2.197}kms^{-1}}\right)^{4.0} \tag{3}$$

2.3.2 Background Galaxy

The background galaxies are lensed by the foreground galaxies producing distorted images of the galaxy in the form of arcs or rings depending on the alignment and mass distribution of the galaxies. The background and the foreground galaxy must be aligned so as to procure lensed images.

As we are considering the lensing of Supernovae we assume the host galaxy as a star forming galaxy. Star forming galaxies as the name suggests are galaxies with higher stellar population. Observations show that once galaxies settle down from an initial phase of exuberant star formation, most systems maintain roughly constant stellar production rates until they become dead red stellar fossils. Hence, these galaxies have a higher probability to host a supernova.

For the light profile of Star Forming Galaxy, the flux generated by the galaxy has to be calculated. This can be done by firstly calculating the apparent magnitude using the relation:

$$m = M + 5\log\left(\frac{D}{10pc}\right) \tag{4}$$

where, m is the apparent magnitude, M is the absolute magnitude and D is the distance of galaxy from earth in parsec. Using this we find flux by the relation:

$$m_1 - m_2 = -2.5\log\frac{F_1}{F_2} \tag{5}$$

where, F_1 and F_2 are the flux.

2.3.3 Lensed source

Supernova

The source that undergoes lensing is taken to be a supernova. A supernova is a powerful and luminous stellar explosion occuring during the last evolutionary stages of a massive star or white dwarf. Supernova is a transient astronomical event that the event. Transients are events whose duration may be from seconds to days, weeks, or even several years. Supernovas are classified into two types: type I and type II supernova.

1. Type I : These supernova have their light curves exhibit sharp maxima and then die away smoothly and gradually. They occur typically in elliptical galaxies. They hydrogen poor line spectra.

2. Type II : They have less sharp peaks and the curve dies away more sharply than type I. Type II have strong Hydrogen line spectra. These supernovae

are not observed to occur in elliptical galaxies, and are thought to occur in Population I type stars in the spiral arms of galaxies

Type Ia supernovae

Type I supernovae are subdivided on the basis of their spectra, with Type Ia showing a strong ionised silicon absorption line. Type Ia supernova happens when the mass passes the Chandrasekhar threshold of 1.44 solar masses, and therefore all start at essentially the same mass. Type Ia supernovae have become very important as the most reliable distance measurement at cosmological distance known to be standard candles. All type Ia supernovae reach nearly the same brightness at the peak of their outburst with an absolute magnitude of -19.3 ± 0.03.

Light curve

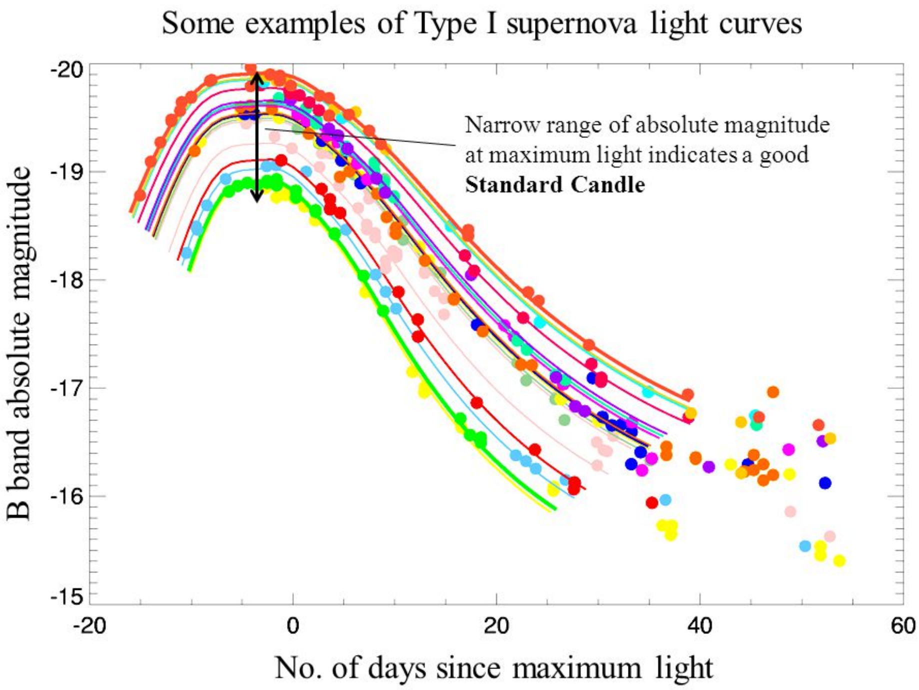

Figure 2: Light curve of supernova type I

Source: J.Garcia-Bellido, "Modern Cosmology"

Light curve is a graph of intensity of celestial object as afunction of time. The light curve for supernova shows the variation of magnitude over the time period for which the supernova explodes.

Philips relation

Phillips relationship is the relationship between the peak luminosity of a Type Ia supernova and the speed of luminosity evolution after maximum light. Bert Woodard Rust and Yury Pavlovich Pskovskii in the 1970s, found that the faster the supernova faded from maximum light, the fainter its peak magnitude was.

Spectral Energy Distribution (SED)

A spectral energy distribution (SED) is a plot of energy versus frequency or wavelength of light. At high redshift,the effect of the expanding Universe will decrease the SN rate of a factor (1 + z) due to time dilution, but the same effect will stretch the light curve of a SN by the same factor. In general, for each given redshift there is a preferred colour in which the magnitude variation due to the SNIa event is larger. This can be studied using the Spectral Energy Distribution.

2.4 Lensing of Supernova

In 2010, a peculiar supernova PS1-10afx, was discovered by the Panoramic Survey Telescope and Rapid Response System 1 (Pan-STARRS1). It was suspected that PS1-10afx belonged to a rare class of Superluminous Supernova (SLSN). But it distinguished itself from SLSN as it was much redder and evolved much faster than SLSN.

An alternate theory was that PS1-10afx is a Type Ia supernova with a normal luminosity, but its apparent brightness had been magnified by a gravitational lens. For this hypothesis to be confirmed there must be observation indicating the existence of foreground galaxy causing the lensing and the host galaxy of the supernova. Also, the fact that foreground galaxy would act as an candidate for lensing had be found. This shed a light on the need for follow-up observations of lensed SN Ia candidates while they are on rise or near maximum light. An efficient vetting process must be employed to eliminate the non-lensed supernovae that out number lensed SNIa by a few thousand to one. This was done by using flux-limited survey for given selection bias.

2.5 Large Synoptic Survey Telescope (LSST)

Large Synoptic Survey Telescope is a ground based telescope currently under construction in Chile which will survey the entire visible southern sky every few days for a decade. Gravitational lensing is the best tool for finding and studying dark matter. Finding enough gravitational lenses to constrain the properties of dark matter structures requires a powerful telescope with a huge field of view. The

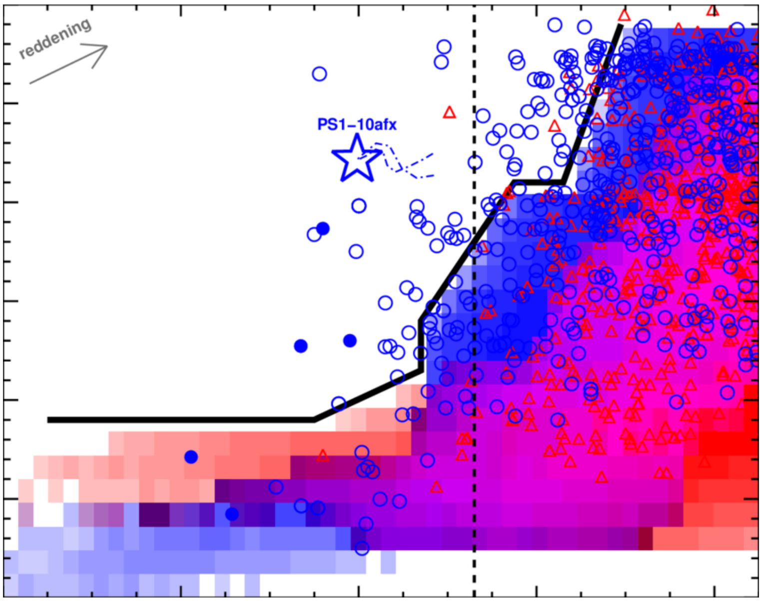

Figure 3: Color-magnitude diagram showing how lensed SNIa can be distinguished from unlensed events

Source: R. Quimby et al., "Detection of Gravitational Lensing Magnifying a type Ia Supernova"

LSST will find thousands more gravitational lenses of all sizes and configurations, and what these lenses show about themselves as well as the objects they magnify will expand our understanding of the universe.

The LSST camera contains a carousel that holds five on-board filters. The optimized wavelength range for the LSST camera is 3201050 nm (near ultraviolet to near infrared). This range is divided into six spectral bands labeled u-g-r-i-z-y, each associated with one of the filters.

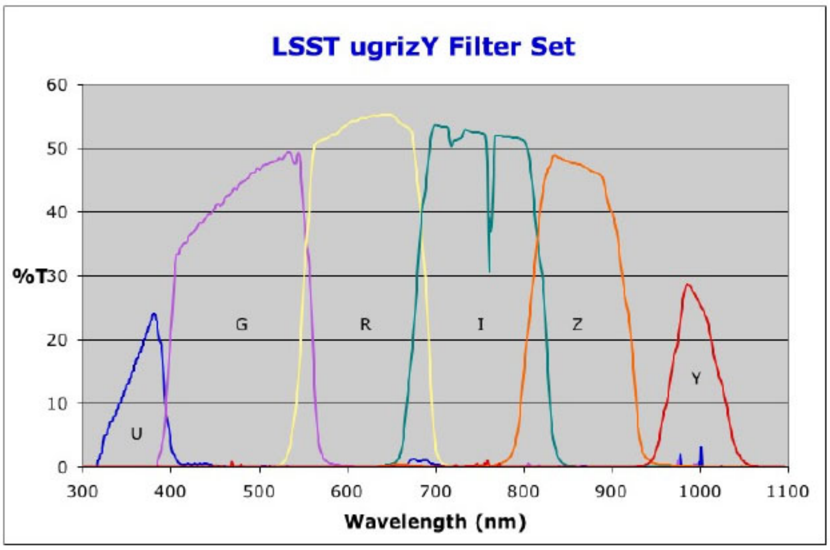

Figure 4: LSST wavelength range of filters ugrizY

Source: LSST

3 Work Carried

The objective of this project is to generate images of lensed supernova type Ia taking various lensing parameters into account. This was done using the software Glafic.

3.1 Glafic

Glafic is a software for studying strong gravitational lensing developed by Masamune Oguri (2010). Its main function include to calculate lensed images for both point and extended sources, and to model observed strong lensing of sources at various redshifts. The code can handle various brightness profiles for extended sources.

3.1.1 Primary Parameters

These parameters are specified before the input file. Some of the primary parameters are as follow:

1. Standard cosmological parameters such as $\Omega_M, \Omega_{DE}, \omega_0, h$.
2. The lens redshift, z_1. Here, the lens is at a redshift of z = 0.3.
3. The parameters xmin, ymin, xmax, ymax specifying the rectangular region of the lens plane in which lens equation is solved (in units of arcsecond).

3.1.2 Model Reference

Lens

The lens model has to be specified at the begining of the input file. As we have taken the foreground galaxy as elliptical galaxy we assume the mass profile to be Singular Isothermal Ellipsoidal (SIE).Singular Isothermal Ellipsoidal (SIE) profile is a three-dimensional radial profile used more frequently to model lensing galaxies. More generally, isothermal ellipsoids with finite core radii are useful in modeling galaxy-scale lenses.

Table 1: SIE profile

P	p[1]	p[2]	p[3]	p[4]	p[5]	p[6]	p[7]
SIE	σ	x	y	e	θ_e	r_{core}	-

According to the above table, we find the parameters for lensing galaxy for the SIE profile.

1. The velocity dispersion (σ) is calculated using equation (2) and (3) by substituting the mean value of effective radius of elliptical galaxies.
2. x and y position of galaxy is taken at the origin.
3. Ellipticity (e) and position angle (θ_e) are specified in arcseconds.
4. The core radius tends to zero, hence this parameter is taken as zero.

Further, the light profile of lens galaxy is taken as sersic profile.

Table 2: Sersic profile

P	p[1]	p[2]	p[3]	p[4]	p[5]	p[6]	p[7]	p[8]
Sersic	z	flux	x	y	e	θ_e	r_{eff}	n

The parameters p[1], p[3]-p[6] have same values as specified in SIE profile. The other parameters of sersic profile are:

1. The flux of the elliptical galaxy is calculated using equation (4) and (5) knowing the fact that elliptical galaxy has a magnitude of 21 in I band.
2. The mean effective radius of elliptical galaxy is taken and converted into arcseconds.
3. According to de Vaucouleur's law, the sersic index of elliptical galaxy is given as n = 4.

Extend Source

Sources have to be specifed at the begining of the input file. We take the Star forming galaxy as our source. The light profile assumed for SFG is Sersic profile as given in Table 2. According to the table:

1. The redshift of the Star forming galaxy is taken at z = 1.
2. We alter the x, y position of SFG according to the type of lensing we want.
3. Ellipticity (e) and position angle (θ_e) of the SFG are specified in arcseconds.
4. Mean value of effective radius in arcseconds of SFG is calculate using a survey of galaxies.
5. The mean sersic index of SFG is calculate using a survey of galaxies given as, n = 1.3.

Point Source

The type Ia supernova is our point source located in the star forming galaxy. The light profile of SN Ia consits of redshift, x, y position and flux of galaxy.

1. The redshift of supernova is taken same as that of the Star forming galaxy that is z = 1.

2. The x, y position of supernova has to mentioned according to the position of SFG. There is a higher chance of finding the supernova in the exterior partof host galaxy.

3. The flux of supernova changes with time, hence we find the flux by studying the light curve of SN Ia. Also, due to redshift of galaxies, the flux of galaxy changes. Hence, the flux is studied in 3 different colour bands: g (400nm-552nm), r (552nm-691nm), i (691nm-818nm).

3.1.3 Point Spread Function (PSF)

The point spread function is the response of the imaging system to a point object. It is the impulse respone of a focused optical system. The primary source of error in lensing measurement is due to the convolution of the PSF with the lensed image.The tendency of a camera's point spread function to distort the shape of a galaxy and the tendency of atmospheric seeing to distort images must be understood and carefully accounted for.

For this, we consider the point spread function as a 2-dimensional Gaussian function and evaluate the mean deviation σ. As it is 2-dimensional Gaussian function, for $\theta = 0$ we calculate σ_x and σ_y for a particular full-width half maximum (FWHM) of 0.8 arcseconds.This is done by the relation:

$$F.W.H.M. = 2\sqrt{2\ln\sigma} = 2.35482\sigma \tag{6}$$

4 Results

4.1 Flux of Supernova Ia

As mentioned earlier, the flux of supernova varies with time and hence, we need to generate the light curve of SN Ia for days before and after the explosion. This light curve taken in g, r, i bands taking into account the change in flux with redshift is obtained.

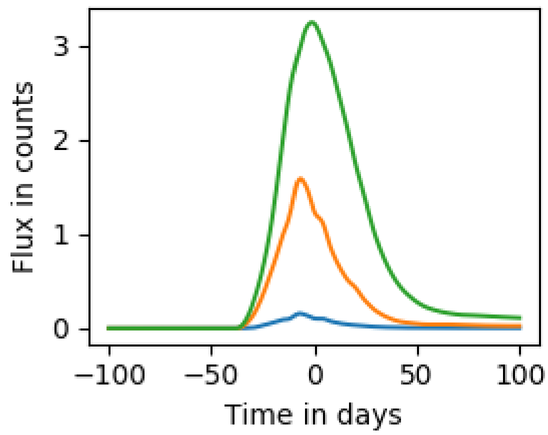

Figure 5: Light curve of SN Ia in g, r, i bands

4.2 Point Spread Function

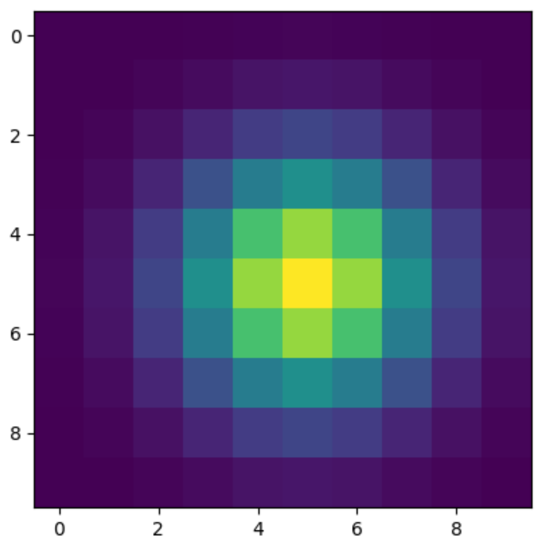

Figure 6: Gaussian PSF for FWHM = 0.8 arcsec

The Gaussian Point Spread Function for FWHM = 0.8 arcsec is generated and then convolved with the lensed images.

4.3 Lensed Images

Our aim was to generate lensed images of SN Ia taking varying flux into account. The following results were obtained:

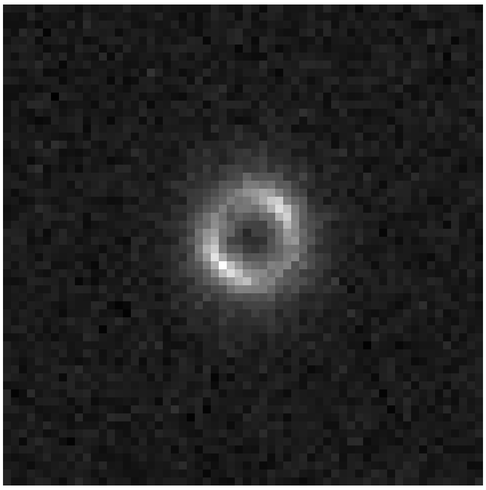

Figure 7: Lensed image of SNIa in g band

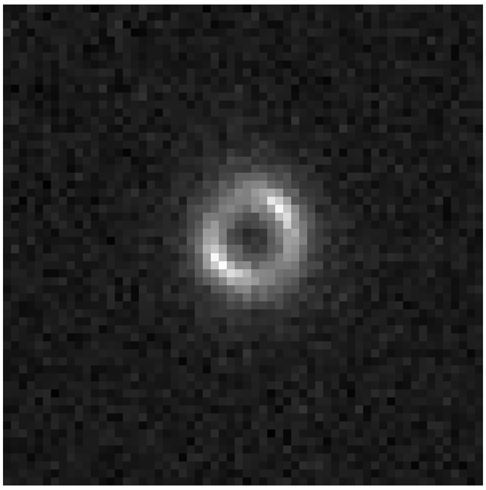

Figure 8: Lensed image of SNIa in r band

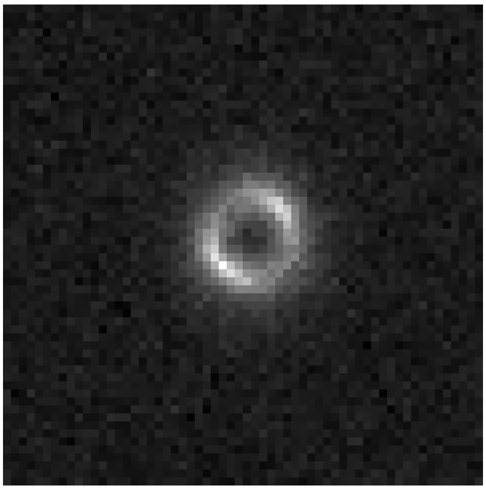

Figure 9: Lensed image of SNIa in i band

5 Summary

By taking various lensing parameter into account, we generated realistic images of lensed supernova Ia in g, r, i bands. The parameters were so chosen that it had higher probabilty to occur in nature.

An important problem in lensing is differentiating lensed images from un-lensed images. As in the case of lensing of Supernova, lensed and un-lensed images can be differentiated by comparing the flux of the image in different bands. The lensed image of supernova would appear more redder than the nearby population of un-lensed supernova. Thus, the images we produced can act as references for future observations and produce ease in detection of lensed images. We have generated these images by taking factors similar to the Large Synoptic Survey Telescope (LSST). This telescope will find thousands more gravitational lenses of all sizes and configurations and further our understanding of the universe.

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7 Codes

1. Glafic

```
# example input file (for ver. 1.2.9)
# generated by glafic -d

# setting primary parameters
omega 0.260000
lambda 0.740000
weos -1.000000
hubble 0.720000
zl 0.300000
prefix out
xmin -6.000000
ymin -6.000000
xmax 6.000000
ymax 6.000000
pix_ext 0.200000
pix_poi 3.000000
maxlev 6

# define lenses and sources
startup 1 3

#mass profile of lens galaxy
lens sie 229.18 0.0 0.0 0.2 45.0 0.0 0.0

#light profile of lens galaxy
extend sersic 0.300001 275.0 0.0 0.0 0.2 45.0 2.1 4.0 #Reff=10kpc

#host galaxy
extend sersic 1.0 392.5 0.2 0.2 0.2 10.0 0.878 1.3 #Reff=7000pc

#SNe
```

extend point 1.0 573494.74727318 0.89 0.89 0.0 0.0 0.0 0.0
end_startup

execute commands
start_command

writeimage 0.0 10.0
readpsf out_psf.fits
quit

2. Flux for galaxy

```
#Flux from absolute magnitude

import math

def absmag_to_appmag(M,D):
app_mag = M+5*math.log(D/10,10) # m is apparent magnitude
return app_mag
def appmag_to_flux(app_mag):
flux = 10**((app_mag-25)/2.5) # zp mag = 25
return flux

D = float(input("The effective radius in parsec : "))
M = float(input("The absolute magnitude is : "))
a = absmag_to_appmag(M,D)
b = appmag_to_flux(a)
print(a)
print(b)
```

3. Velocity dispersion of Galaxy

#Velocity Dispersion

def luminosity(h,R):
$lum = ((10 * *10.2 * h * * - 2) * (R/10 * *0.52 * h * * - 1) * *1.5)$
return lum
def vel_dispersion(L,h):
$sigma = (((L/10 * *10.2 * h * * - 2) * *0.25) * 10 * *2.197)$
return sigma

R = float(input("Enter the effective radius in kpc: "))
h = float(0.72/0.7) # h=h70 is reduced Hubbles constant
lum = luminosity(h,R) # In terms of solar luminosity
sigma = vel_dispersion(lum,h) # In kilometer/sec
$print("Lumin1e10Lsun : ", lum/1.e10)$
$print("Velocitydispersioninkm/s : ", sigma)$

4. Flux of supernova Ia in g, r, i bands

```
import sncosmo
import matplotlib.pyplot as plt
import numpy as np

model = sncosmo.Model('hsiao')
model.set(z=1.0, t0=1.)
```

$model.set_source_peakabsmag(-19,' besselli',' ab')$

```
timeax=np.linspace(-100,100,300)
abg=model.bandflux(['sdssg'], timeax, zp=25, zpsys='ab')
abr=model.bandflux(['sdssr'], timeax, zp=25, zpsys='ab')
abi=model.bandflux(['sdssi'], timeax, zp=25, zpsys='ab')

ax=plt.subplot(2,2,1)
ax.plot(timeax,abg)
ax.plot(timeax,abr)
ax.plot(timeax,abi)
plt.xlabel('Time in days')
plt.ylabel('Flux in counts')
plt.show()
```

5. Point Spread Function

#PSF 1 pixel = 0.2 arcsec
#FWHM = 0.8 arcsec = 4 pixel, $sigma_x = sigma_y = 1.698643633$

import numpy as np
import matplotlib.pyplot as plt
from astropy.modeling import models

$y, x = np.mgrid[-5:6, -5:6]$
$g = models.Gaussian2D(amplitude = 1.0, x_{mean} = 0, y_{mean} = 0, x_{stddev} = 1.698643633, y_{stddev} = 1.698643633, theta = None)$
plt.figure(figsize=(2.5,2.5))
plt.imshow(g(x,y), origin='lower')
plt.show()