Lab #3 "Astronomical Photometry"

Lab report is due at 4pm on December 5 (Monday). Submission on Quercus.

Type Ia supernovae: seeding the elements and measuring the Universe ...... Prof. Moon

1. Overview and Goals

Photometry, which quantifies the intensity of light from astronomical objects recorded on the detector, is a fundamental tool in astronomy. One key aspect of photometry is standardization known as photometric calibration. In this lab, we will conduct photometric analysis of a supernova explosion. This will bring us an opportunity to learn how to measure signal intensisites, together with uncertainties, based on statistical principles and how to use standard stars in photometric calibration. In addition, we will explore a bit how to conduct a supernova light curve analysis.

Schedule: This is a five-week lab between October 31 and December 5. There will be no class on November 7 (the reading week) and also on December 5 (the final report due). Group-led discussions will happen on November 21 and 28. (More information on Group-led discussion will be given separately.)

2. Key Steps

1. Understand how photomety is done, including how to conduct basic photometric measurement on CCD images using aperture photometry and how to conduct differential photometry for standard calibration.
2. Develop and test your own Python photometric routine that you think works best on the given CCD images of the supernova. You can test your routine using reference stars to confirm it works acceptably first, and then apply it to the supernova on images where it appears bright enough for the test.
3. Once your photometric routine is established, apply it to the entire set of images. The supernova won't be detected on images obtained earlier dates, but it should be easily detectable on later days. Create the light curve of the supernova. (Also note that there will be some bad images which you should disregard.)
4. Conduct polynomial and power-law fittings to the supernova light curve to estimate some physical parameters of the supernova explosion..

3. Data

We will use a series of CCD images (433 images in total) obtained between 2015 September 20 and 2015 October 30. They are B-band images of 2251 × 2251 pixels. Each CCD pixel corresponds to 0.4 arcsec × 0.4 arcsec, resulting in a 15 arcmin × 15 arcminute angular size of the entire image. (Note that 1 arcminute is 60 arcseconds.) The data can be downloaded from the following link:

https://drive.google.com/drive/folders/1NraBhOIfOFIzlPZInldwEtJ2pmifWzoZ?usp=share_link where you can identify two files. The file "AST325-326-SN.egg" is a compressed and archived file that has 433 FITS files. (Software for extracting *.egg file is freely available.) The file "AST325-326-SN-filelist.txt" is a text file that contains the names of the 433 FITS files:

```
AST325-326-SN-20150920.9181.fits
AST325-326-SN-20150920.9361.fits
AST325-326-SN-20150920.9535.fits
AST325-326-SN-20150922.1458.fits
              ...
              ...
AST325-326-SN-20151030.0306.fits
AST325-326-SN-20151030.0479.fits
AST325-326-SN-20151030.0653.fits
AST325-326-SN-20151030.0806.fits
```

In the file name, the middle string **2015????.????** corresponds to the exact time when the data of the FITS file was obtained. For instance, 20150920.9181 means that it was taken on 2015 September 20.9181 (= September 20, 22.0344 hours.) All the images in the FITS files are centered at the coordinate (RA, DEC) = (00:57:03.19, -37:02:23.6) where a supernova explosion occurred sometime between September 23 and 27 in 2015. (The supernova is a Type Ia supernova and we will call it AST325-326-SN for convenience, hereafter.) See Figure 1 below.

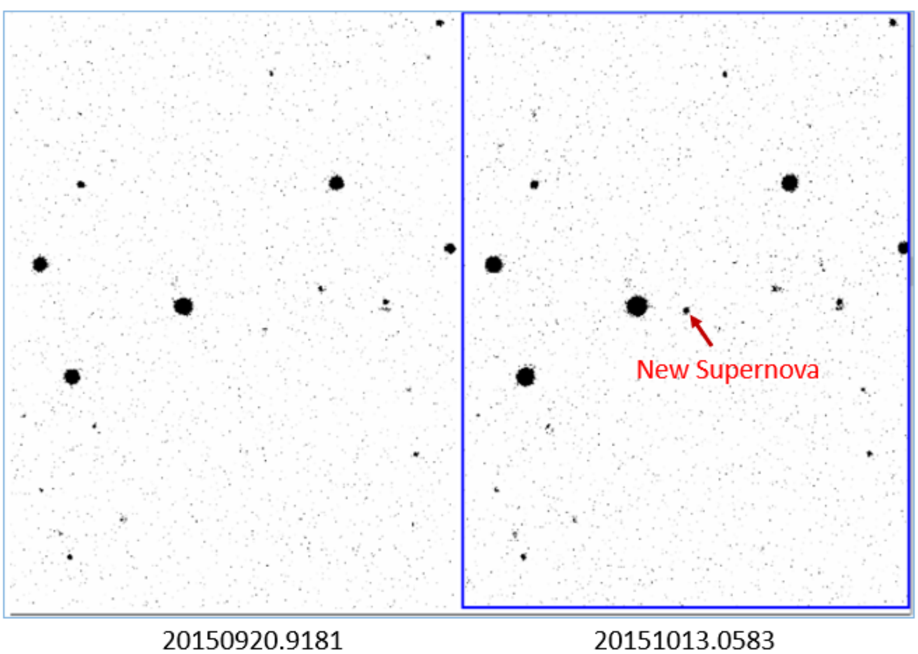

Figure 1(Left) DS9 view of the central part of the CCD image from 20150920.9181. (Right) Same as Left, but from 20151013.0583. We can identify the presence of a new source (= AST325-326-SN) at the center on the image obtained later.

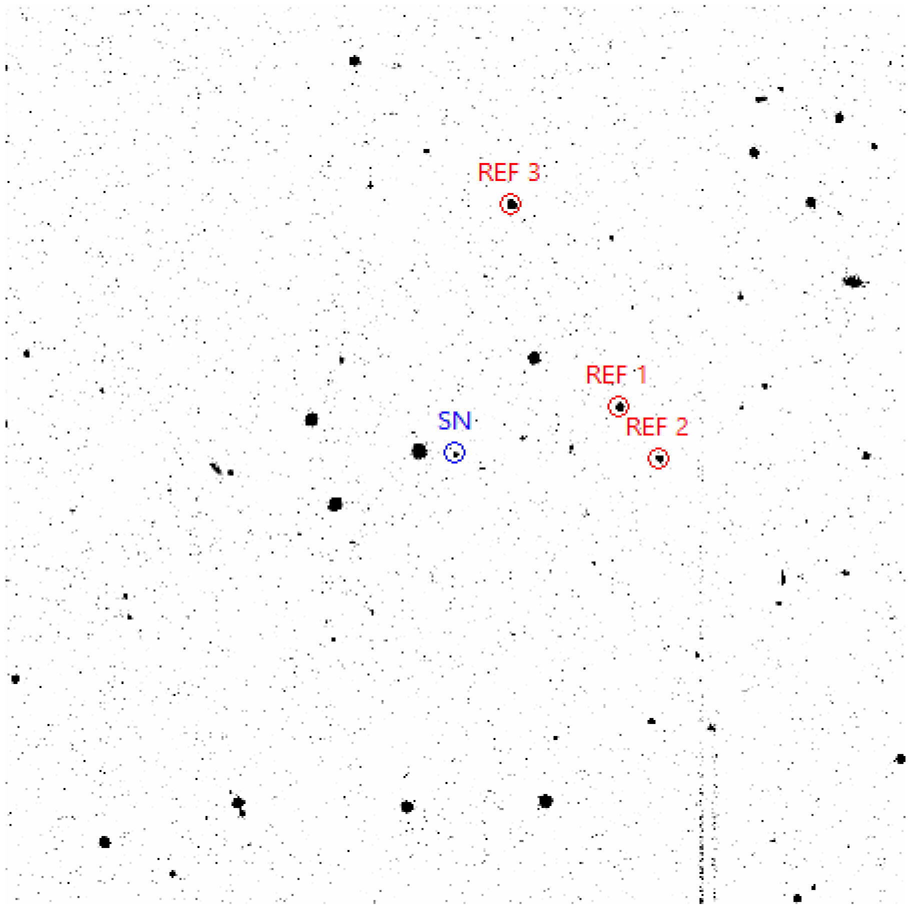

*Figure 2 Image from 20151013.0583 centered on AST325-326-SN (marked as SN), showing the locations of three standard reference stars (**REF 1, 2, 3**) whose magnitudes are known.*

Near the location of AST325-326-SN, there are three standard reference stars with known magnitudes (Figure 2). Their coordinates and B-band magnitudes given in Table 1.

Table 1. Photometric standard reference stars near AST325-326-SN.

Reference Stars	(RA, DEC)	B-band Magnitudes
REF 1	(00:56:49.70, -37:01:38.31)	16.32 ± 0.07
REF 2	(00:56:46.43, -37:02:29.50)	17.16 ± 0.08
REF 3	(00:56:58.27, -36:58:16.60)	15.61 ± 0.02

Notes on the distrubted data and FITS files:

(1) Not all the FITS files contain acceptable quality images. Images can go wrong for various reasons (such as malfunctioning of instruments, poor sky conditions, some other artifacts). You should discard obviously bad images.

(2) Basic reduction process (such as biad/dark subtraction and flat-fielding) has been already applied to the FITS file images.

(3) Don't try to examine all the 433 individual images individually using DS9 since it will take too long. Just examine a few test cases first and those images that you think bad.

4. Photometric Analysis and Calibration

The core part of this lab is to conduct measurements of the intensity of AST325-326-SN on CCD images and compare them with those of nearby reference stars. In order to conduct this effectively, you should follow the following procedure.

(1) Develop a Python routine that measures the intensity of a point source (such as AST325-326-SN) on the CCD images based on aperture photometry. This should return the signal intensity as well as uncertainties. (See lecture slides on aperture photometry and differential photometry.)

(2) Test the developed aperture photometry routine in order to confirm it works reasonably. You can use the reference stars in Table 1 for the test. Are their intensities that you measure with your Python routine consistent with their magnitude differences? (For this, you should understand astronomical magnitude system – see lecture slides.)

(3) Once you confirm that you have reliable aperture photometry routine, you can run the routine to the entire set of 433 images. You should do it using a loop, rather than handling each image individually. (Note that you have a text file that contains the name of the entire FITS files.) On the early images where AST325-326-SN has not appeared yet, your routine should return a very low signal (or something equivalent) that gives no confidence of detection. You also should check images individually with DS9 if you get a strange result since there can be a few images with bad quality that need to be discarded.

(4) Construct the light curve of AST325-326-SN. Figure 3 shows an example of Type Ia supernova light curve constructed by several well-studied supernovae. The light curve of AST325-326-SN will be similar to this, but with increased noise. AST325-326-SN has the coverage of earlier part than the example. Note that Type Ia supernovae reach the peak brightness in about 15–20 days from the explosion.

(5) Conduct estimation of the following parameters:

   A. The epoch of the first detection. What is the earliest epoch when you detect AST325-326-SN with S/N-ratio greater than 3? How does it change if you lower your criterion to S/N-ratio greater than 2? Explain your results and provide an image of the first detection.

   B. Conduct polynomial fitting to the AST325-326-SN light curve to determine the epoch of its peak brightness. What is the magnitude difference between the fitted peak brightness and that of your first detection? How many times is AST325-326-SN brighter at the peak brightness than the first detection?

   C. Conduct power-law fitting to the early part of the light curve to estimate its epoch of first light. How long did it take for AST325-326-SN to reach the peak brightness from the first light? (This parameter is known as a supernova rise time.) You can use the following power-law equation for the early light curve (when the brightness of the supernova is lower than 40% of the peak brightness):

$$\text{Supernova brightness } (t) \propto C\,(t - t_1)^2$$

   where t is time C is a fitting coefficient t_1 is the epoch of the first light. Note that the the fitting needs to be done with supernova brightness, not with magnitudes (which are logarithmic scale representation of the brightness).

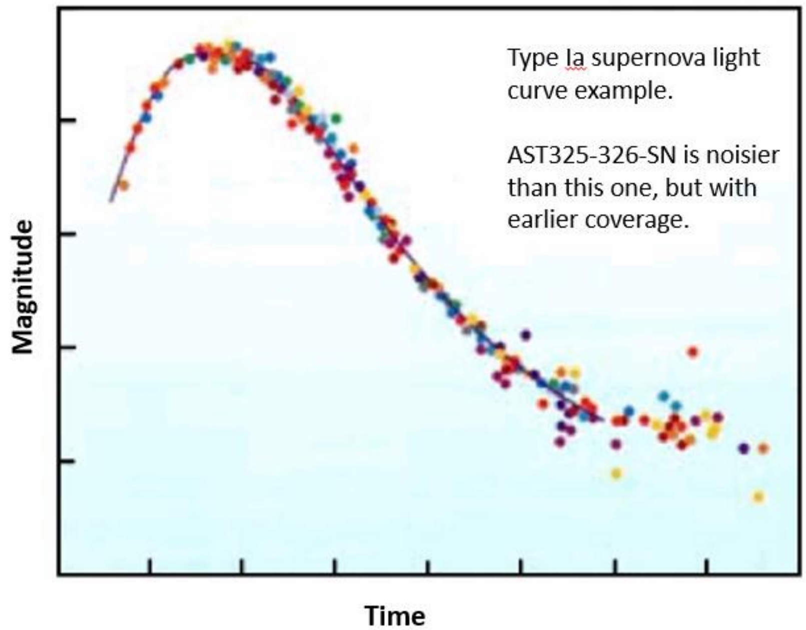

Figure 3 Example of Type Ia supernova light curve constructed by several well-studied Type Ia supernovae.

5. Uncertainty Measurements, Plots and Final Report

In the report, you should explain how you conduct your analysis following the instructions on how to write a lab report on the class web page. Your report **should include (but not limited to)** the following results and plots.

(1) Test results and plots showing the acceptable performance of your aperture photometry routine when applied to the reference stars in Table 1. (Also, don't forget to attach your code to the report.)
(2) First detection image of AST325-326-SN as well as description of observational/analysis parameters (e.g., epoch, magnitude, etc) and statistical significance of the detection;
(3) Your light curve plot (x-axis: time, y-axis: magnitude) of AST325-326-SN with error bars representing the magnitude uncertainties. (Assume that the CCD Gain is 4 – see lecture slides). Overlay your fitted polynomial on the light curve plot and provide the results of the fitting required in §4(5)B above.
(4) Plot for the power-law fitting of the early light curve and the estimation of the epoch of first light as well as the rise time as described in §4(5)C above.

In principle, all estimated parameters (e.g., magnitudes, epochs, etc) need to be given with their uncertainties. Apply tye proper uncertainty measurement and error propagation processes explained in the lecture slides.