

Name: \_\_\_\_\_

TA: \_\_\_\_\_

## **Physics 10263 Lab #1:** **Scale Models**

### **Introduction**

The Universe is a big place. But what does that statement really tell you? One of the goals of this course is to have each of you develop some sense for the size of the Universe and the objects in it (such as our own solar system). To do that requires more than just comparing numbers...it helps to actually design your own scale model of the solar system and demonstrate it to someone else.

You are already familiar with scale models. Perhaps you built models or played with toy cars or people when you were younger. Both of these are examples of scale models. In the case of model cars, they are usually 1/24th scale (or 1 inch = 2 feet). That means every dimension in the model is 24 times smaller than the real car. If the car is 12 feet long, the model car will be:

$$12 \text{ feet} * (1 \text{ inch}/2 \text{ feet}) = 6 \text{ inches long.}$$

The scale factor to convert from real units to model units would be 1 inch/2 feet.

If we asked you to make a scale model of TCU, you might choose to make 1000 feet equal to one step. Then the distance across the entire campus would be about ten steps and the model might fit inside SWR 360. The scale factor in this case would be 1 step/1000 feet. Thus, a real distance of 5000 feet would be equivalent to a model distance of:

$$5000 \text{ feet} * (1 \text{ step}/1000 \text{ feet}) = 5 \text{ steps.}$$

Our own campus map (at <http://maps.tcu.edu>) is an example of a scaled picture of TCU in which the scale factor is about 1 inch/1000 feet.

The solar system is very large compared with anything you have probably dealt with before (even though it is tiny compared to the size of our galaxy, the Milky Way, which is in turn very

tiny compared to the size of the visible Universe). So to fit the scale model within a realistic area, like this building, the TCU campus or the city of Fort Worth, we will require a tiny scale factor. Fortunately, when constructing a scale model of the solar system, we can treat it as a two-dimensional map like the map of TCU. That's because all the planets in the solar system lie roughly in the same plane, so we won't have to worry about climbing buildings or renting balloons to walk through our scale model.

**Example:** Suppose your scale factor is 1 meter /  $7.5 \times 10^7$  km...

$$\text{Step 1: } 1 \text{ parsec} * \frac{3.1 \times 10^{13} \text{ km}}{1 \text{ pc}} = 3.1 \times 10^{13} \text{ km}$$

Step 2:

$$3.1 \times 10^{13} \text{ km} * \frac{1 \text{ m}}{7.5 \times 10^7 \text{ km}} = 4.1 \times 10^5 \text{ m, so } 1 \text{ pc} = 413,000 \text{ m}$$

... so, on this scale, 1 parsec is about 400 km, which is about 260 miles, the distance from Fort Worth to Houston. So you can see that even with this tiny scale factor ("1 m /  $7.5 \times 10^7$  km" is the equivalent of "1 inch / 10 million miles"), the galaxy is an enormous place!

### **Part 1**

Let's begin by filling out the data table for objects and distances within our solar system. First, copy down the true values for each quantity from the reference sheet of Astronomical constants at the end of the lab. Now let's try two different scale factors and see which one is more appropriate.

**Scale Factor #1 : 1 meter / 32,000 km**

**Scale Factor #2 : 1 meter / 2,000,000 km**

The first scale factor shrinks down the Universe by a factor of 32 million, making the Earth about the size of a standard map globe like you can see in the classroom. Using this scale factor examples above and the values on the reference sheet to guide you, fill in the 3rd column (scaled value #1) on

your table (next page). Throughout this lab, all of your answers should have two significant figures.

The second scale factor shrinks down the Universe by a factor of 2 billion, making the Earth about the size of a green pea. Again, use this new scale factor to fill in the 4th column (scaled value #2) on your table.

Quantity	True Value (km)	Scaled Value #1 (m)	Scaled Value #2 (m)
Size of Sun			
Size of Earth			
Size of Jupiter			
Average Distance of Mercury			
Average Distance of Venus			
Average Distance of Earth			
Average Distance of Mars			
Average Distance of Jupiter			
Average Distance of Saturn			
Average Distance of Uranus			
Average Distance of Neptune			
Average Distance of Pluto			

**Part 2**

Now let's consider which scale factor is more appropriate. Our goal here is to create a scale model of the solar system that is relatively easy to grasp, so the objects in it must have scaled sizes that we can relate to (scaling the Sun down to a radius of, say, 1000 km or 0.0000001 m doesn't make any sense). Also, the model itself must be small enough that we can walk through and explore it. It is easier to walk a distance of 1 mile but much harder to walk 1,000 miles.

Answer the following questions about **scale model #1** below:

(2a) - Which is an example of an object (it doesn't have to be spherical, just roughly the same size) that has a size close to that of your scaled-down Sun. Remember, in this model, the Earth is about the size of a standard map globe.

- a) Basketball
- b) House
- c) City
- d) Continent

(2b) - Give an example of an object that has a size close to that of your scaled-down Jupiter.

- a) Basketball
- b) Van
- c) Fruit Fly
- d) Skyscraper

(2c) - Suppose you could walk with a speed of 3600 meters per hour (about 1 meter per second). Use  $d = vt$  to determine how much time it would take you to cover the following distances in **scale model #1** (in hours):

- Sun-Earth scaled distance #1  
Travel time = \_\_\_\_\_ hours
- Sun-Jupiter scaled distance #1  
Travel time = \_\_\_\_\_ hours
- Sun-Pluto scaled distance #1  
Travel time = \_\_\_\_\_ hours

(2d) - Based on your answers to question (2c), do you think you can easily walk through this scaled-down solar system and show it to someone else? Explain below

**Part 3**

Answer these questions about **scale model #2** below:

(3a) - Give an example of an object that has a size close to that of your scaled-down Sun. Remember, in this model, the Earth is about the size of a green pea.

- a) Basketball
- b) Fruit Fly
- c) House
- d) City

(3b) - Give an example of an object that has a size close to that of your scaled-down Jupiter.

- a) House
- b) Grape
- c) Fruit Fly
- d) Van

(3c) - Suppose you could walk with a speed of 60 meters per minute (about 1 meter per second). Use  $d = vt$  to determine how much time it would take for you to cover the following distances in your **scale model #2** (in minutes).

- Sun-Earth scaled distance #2  
Travel time = \_\_\_\_\_ minutes

- Sun-Jupiter scaled distance #2  
Travel time = \_\_\_\_\_ minutes

- Sun-Pluto scaled distance #2  
Travel time = \_\_\_\_\_ minutes

(3d) - Based on your answers to question (3c), do you think this scaled-down solar solar system would be easier or harder to show and explain to someone than scale model #1? Justify your answer.

**Part 4**

Ok, now let's have a look at the 2nd part of the table on the reference sheet, which focuses on objects and distances outside of our solar system. For each of our two scale models, fill out the table below. First, take the true value (in parsecs) from the data sheet, then convert it to kilometers as in the first part of the example in the Introduction. Write this value down in the 2nd column, then use your two scale factors (as in part 1) to find the scaled values in meters. Express your answers in scientific notation.

Quantity	True Value (pc)	True Value (km)	Scaled Value #1 (m)	Scaled Value #2 (m)
Distance to Nearest Star				
Distance to Center of Galaxy				
Distance to Andromeda Galaxy				

These are such large distances, so let's forget about walking and get in a car! On a long road trip, you can usually manage to drive about 800 km (500 miles) per day, or 800,000 meters per day (assuming you stop for gas, food and sleep). Since we decided above (I hope!) that scale model #2 was more appropriate, let's use those scaled distances. Figure out how long it would take to drive (in your scaled down model!)

- How many **days** to the nearest star? \_\_\_\_\_ days

- How many **years** to the center of the galaxy?

\_\_\_\_\_ years

(800,000 meters per day = 292,000,000 meters per year)

- How many **years** to the Andromeda galaxy

\_\_\_\_\_ years

### **Essay**

The essay portion was incorporated into the parts above as the answers to various questions, so there will be no formal essay at the end of this lab.

Wavelength (Nanometers)

700

600

500

400

Color



Red

Orange

Yellow

Green

Blue

Purple



Argon

Sodium

Helium

Hydrogen

Lithium

Mercury

Neon

Potassium

Note: There may be many fainter lines in these spectra that are not indicated on these diagrams but can be seen in the spectroscopes under ideal conditions.

Also, watch out for "line echoes" next to the bright lines. Some lines look like a bright/faint pair but are actually just a bright line with a faint echo due to the optics.



## Astronomical Constants

Object	Size (radius) in km	Average distance from Sun in km
Sun	$7.0 \times 10^5$	--
Mercury	2,400	$5.8 \times 10^7$
Venus	6,100	$1.1 \times 10^8$
Earth	6,400	$1.5 \times 10^8$
Mars	3,400	$2.3 \times 10^8$
Jupiter	71,000	$7.8 \times 10^8$
Saturn	60,000	$1.4 \times 10^9$
Uranus	26,000	$2.9 \times 10^9$
Neptune	25,000	$4.5 \times 10^9$
Pluto	1,200	$5.9 \times 10^9$

1 parsec (pc) =  $3.1 \times 10^{13}$  km

Distance to nearest star (alpha Centauri) = 1.3 pc

Distance to center of Milky Way Galaxy = 12,000 pc

Distance to Andromeda Galaxy = 750,000 pc

Distance to limit of observable Universe =  $3.5 \times 10^9$  pc

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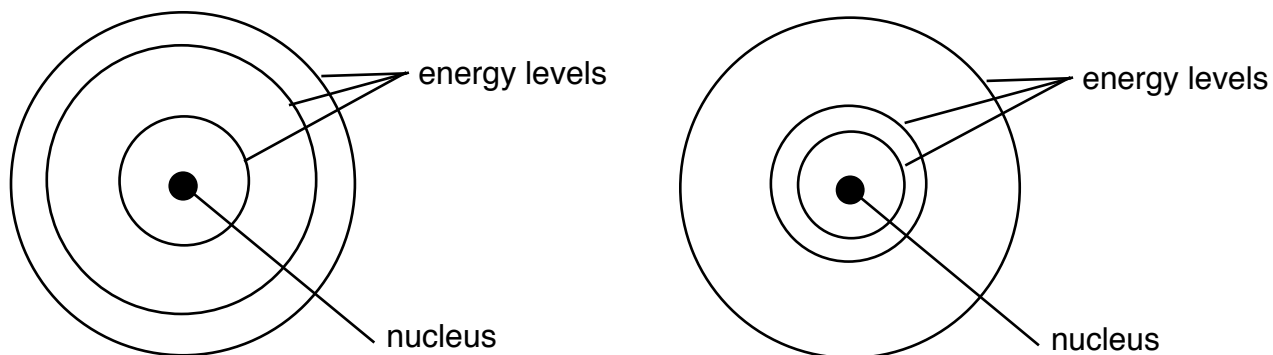
## Physics 10263 Lab #2: Spectroscopy

### Introduction

In this lab, we'll learn about how emission and absorption works, and we'll learn how to identify elements by observing their emission line "fingerprints".

First, let's talk about atoms and energy. Put very simply, an atom consists of a collection of protons and neutrons at the center called the nucleus. Somewhere in a sort of orbit around the nucleus you'll find electrons. An amazing fact about electrons in atoms is that they are only allowed to have specific values of energy. These precise values depend upon the nature of the nucleus, so the values of energy that an electron is "allowed" to have vary from element to element (i.e. the values for Hydrogen are different than the values for, say, Neon).

Another way of describing this is to say that electrons are only allowed to have certain "orbits" (or "energy levels") about the nucleus, and the precise orbital distances (hence, energies) vary from element to element. A simple model of an atom looks something like one of these two diagrams:



Note that each of these diagrams represents a different element. Electrons in the element on the left have a different set of "allowed energies" compared to electrons in the element on the right.

**Important Rule:** Electrons are only allowed to exist at certain energy levels within an atom. They aren't allowed to exist "between" levels. Thus, in the atom on the left, electrons might be allowed to have energies of 4, 8 and 11. In the atom on the right, they might be allowed to have energies of 3, 4 and 12.

Why is this important? Because atoms interact with light. By watching the interaction of atoms and light, we can determine the identity of the atom. This careful study of the light emitted and absorbed by atoms is called Spectroscopy. It involves splitting light up into its component wavelengths, or colors (the spectrum) and studying what is happening to the light at each wavelength.

Suppose an atom's electron is in an "excited state", which simply means its electron is at some energy level besides the lowest level. At any given time, the electron may spontaneously decide to jump down one or more levels. Note well that the electron cannot just move at random, it has to move from one energy level to another. For example, in the atom on the right, suppose the electron is in energy level 12. It can move down to either level 3 or level 4. By doing so, the electron must emit the amount of energy it loses.

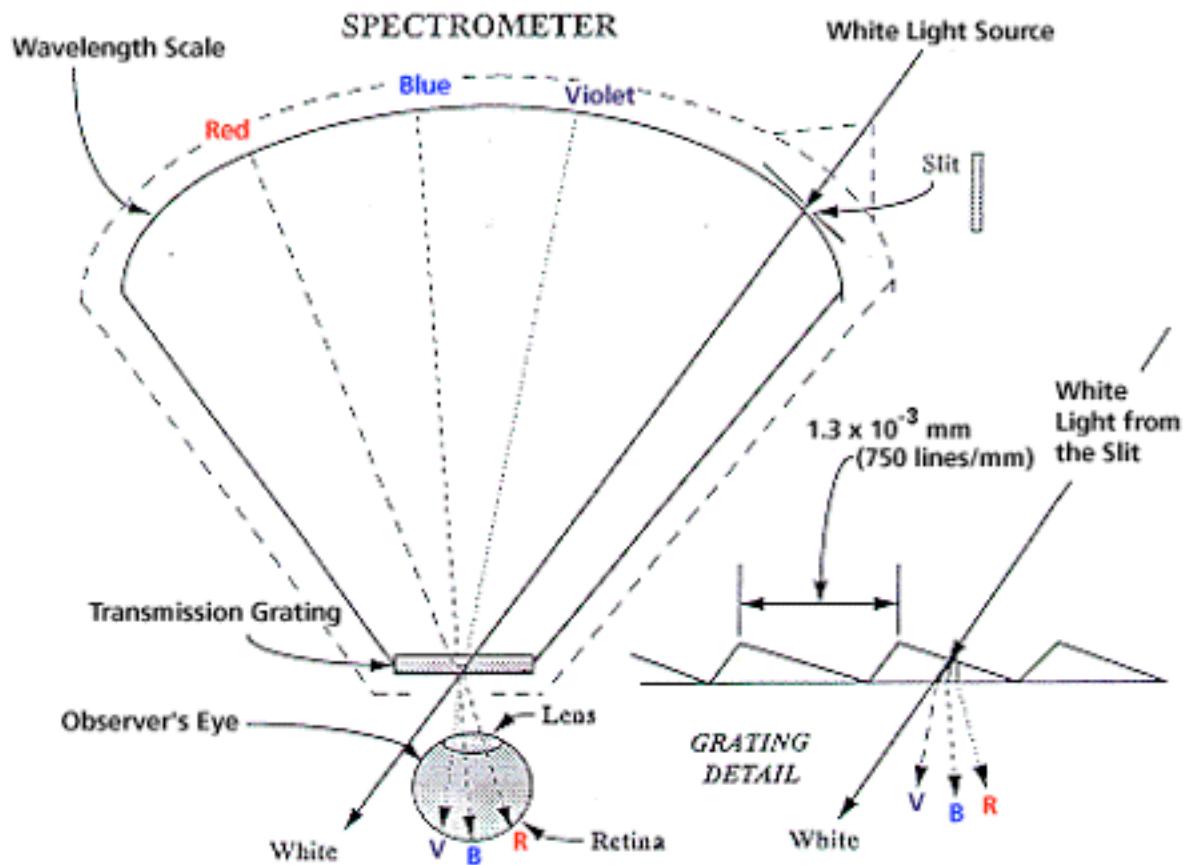
Thus, if an electron drops from level 12 to level 4, it must give off  $(12 - 4 =) 8$  energy in the form of light. If it drops from level 12 to level 3, it must give off 9 energy in the form of light. From the text and from lecture, we know that the energy of light is inversely proportional to its wavelength.

So, let's summarize how atoms emit light:

- 1) Electrons are excited to high energy levels (usually by heating up the atoms).
- 2) These electrons eventually drop down to lower energy levels, giving off light with an energy equal to the energy difference between the higher and the lower level.

- 3) Since every atom has a unique set of energy levels, the electrons in these atoms will give off light with a unique set of energies (corresponding to energy differences between the various levels).
- 4) Since energy is inversely proportional to wavelength, each atom will give off light with a certain "pattern" of energies or wavelengths.

So by breaking up light into its various wavelengths, we can identify the atom that is emitting the light, because each atom will have a unique pattern (a collection of such patterns or reference spectra are on the last page of this lab). To study the spectrum of light, we use instruments called Spectrometers. Here's a simple diagram of how your spectrometer works:



- 1) First, you point the little arrow (or slit) on the spectrometer in the direction of the light source.
- 2) Look through the eyepiece in the direction of the slit and move the spectrometer back and forth until you can see the light source through the slit. This takes practice!
- 3) Now look toward the little wavelength scale. You should see a series of spectral lines. By comparing the pattern you see on the wavelength scale with the known patterns of various elements (see last page for reference spectra), you can identify the element giving off the light.

This may not seem like such a big deal to you, but please remember that astronomers use spectrometers to study the compositions of stars that are sometimes billions of light years away. When you stop and think about it, it is pretty amazing that we can determine the composition of an object so far away without ever touching it or interacting with it. Without the science of spectroscopy, we wouldn't know much of anything about other planets, stars or galaxies.

### **Part 1**

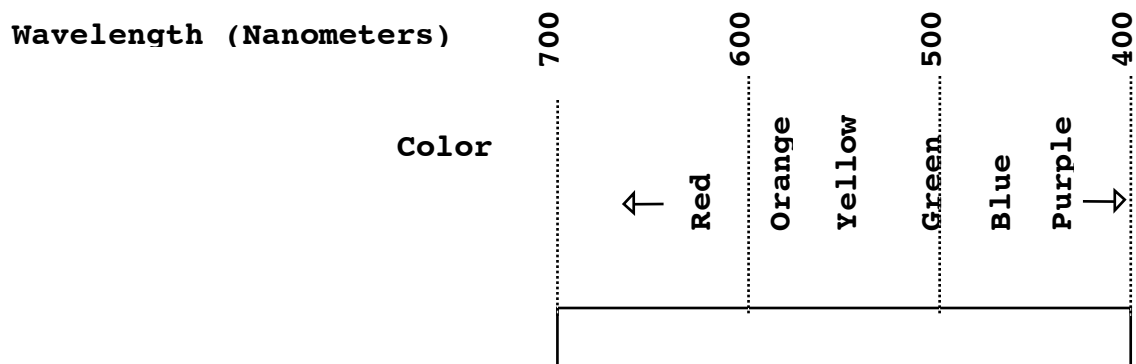
Below, you are asked to identify four different elements based upon their emission line spectra. Following the instructions above, use your spectrometer to sketch the spectra and identify the elements in four different gas tubes around the room (each tube will have a numeric label, you don't need to do them in order).

**Note:** Sometimes you will see additional lines in the spectrum of a given element. These lines are usually quite faint and should be ignored. They are often a result of atmospheric gases leaking into the tube over time.

### **The Wavelength Scale**

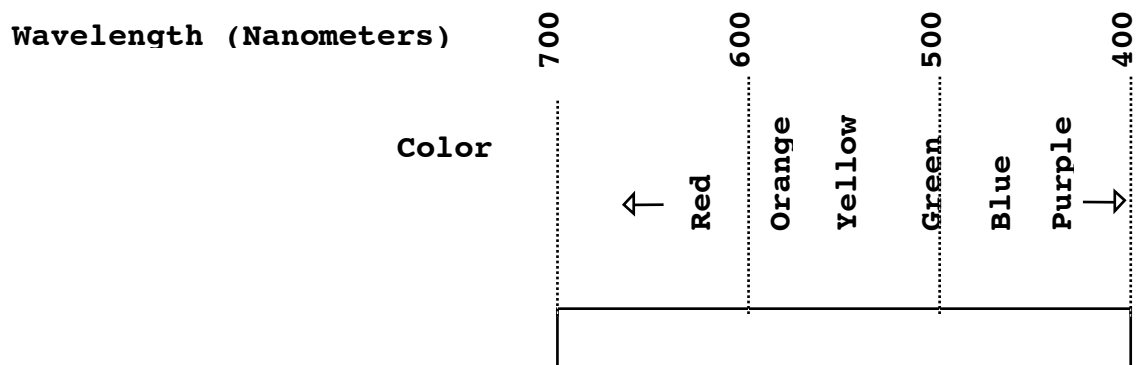
The wavelength scale in your spectrometer has two different scales on it, actually. The top one is an energy scale, and the bottom is the wavelength scale, in nanometers (1 nanometer = 0.000000001 meters). Visible light wavelengths range from about 400 to 700 nanometers. Notice that the wavelength scale increases toward the left while the energy scale increases toward the right. This reflects the fact that the energy of light is inversely proportional to its wavelength (in other words, as energy increases, wavelength decreases).

Sketch the spectrum for gas #1:



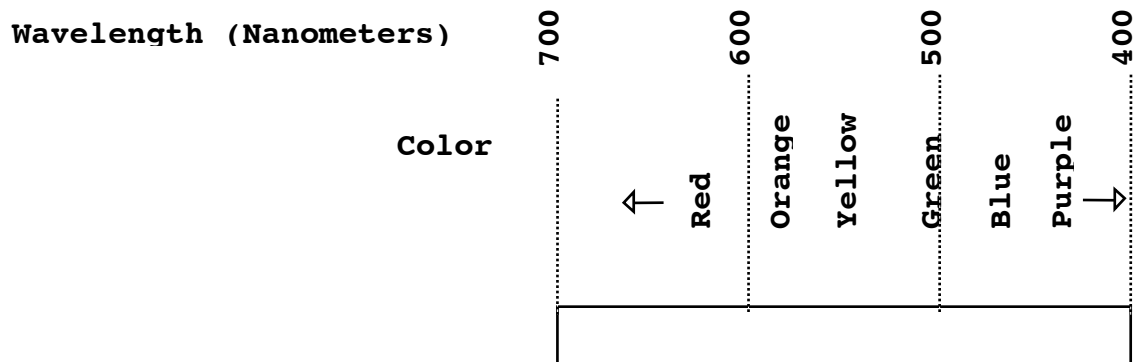
Identify gas #1: \_\_\_\_\_

Sketch the spectrum for gas #2:



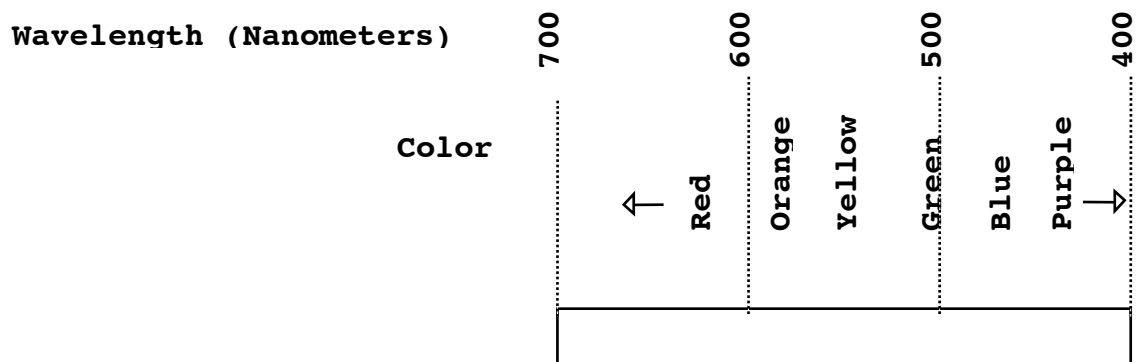
Identify gas #2: \_\_\_\_\_

Sketch the spectrum for gas #3:



Identify gas #3: \_\_\_\_\_

Sketch the spectrum for gas #4:



Identify gas #4: \_\_\_\_\_

### Part 2

One of your four spectra should have been identified as that for Hydrogen. The true values for the wavelengths of the three major lines in the hydrogen spectrum are:

- purple: 434.0 nm
- light blue: 486.1 nm
- red: 656.3 nm

Looking again through your spectrometer, carefully estimate the observed wavelengths of these three lines to the nearest nanometer (i.e. with 3 SF) using the wavelength scales in your spectrometer. Write down these values below, then calculate the percent error in each value.

The formula for %error is:

$$\%error = 100 * \frac{|\text{observed value} - \text{true value}|}{\text{true value}} \quad \leftarrow \text{positive number}$$

Remember, when calculating percent error, use the rules for significant figures.

For Hydrogen gas:

Estimated purple wavelength (nm): \_\_\_\_\_ %error = \_\_\_\_\_

Estimated light blue wavelength: \_\_\_\_\_ %error = \_\_\_\_\_

Estimated red wavelength: \_\_\_\_\_ %error = \_\_\_\_\_

### **Essay**

In your essay's first paragraph, summarize both the purpose of the experiment and state in a few sentences why different elements have unique patterns of spectral lines (also called "spectral fingerprints"). For the 2nd paragraph, point your spectrometer at a fluorescent light in the room and explain how you know the composition of the gas inside the light bulb (and identify the gas).



# Physics 10263 Lab #3:

## The Night Sky

### Introduction

In this lab, we'll learn how to use the Starry Night software to explore the sky, and at the same time, you'll get a preview of many of the topics that will be covered in lecture and lab this semester. Starry Night has a large number of features and options, and we will learn about some of the most useful ones for our purposes.

### Part 1

First, start up the program. When the program first starts up, you may be asked to update data or the software. Just hit "later" for these and ignore them. TCU is responsible for keeping the software updated, so we don't need to worry about it. You will need to tell it where you are viewing from, which should be Fort Worth. The tutorial we will work through can help you with this.

When you open the application, the left sidebar will likely be open to the SkyGuide. If it is not, type "Skyguide" into the search box in the upper right corner and follow the instructions that appear. We are going to walk through the Tutorial in this lab, so click on that link. It should open a pane on the left side of the application labeled "**Tutorial**".

Occasionally, to check your understanding, the Skyguide will ask a multiple choice question. Many (but not all) of the same questions appear on your worksheet for this lab, and you should answer them as you go along.

### In "2: The Toolbar - Cursor Tools"

How far away from Earth is Antares? \_\_\_\_\_ light years.

What is the approximate angular separation between the star Antares and the Moon? \_\_\_\_\_ degrees.

In "3: The Toolbar - Time and Date Controls"

On the date July 5, 2009, what is the approximate angular separation between the star Antares and the Moon? \_\_\_\_\_ degrees

In "4: The Toolbar - Time Flow Controls"

Write below the statement in question 5 that is INCORRECT.

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In "7: The Toolbar - Gaze"

Be sure to close to right-hand-side search pane so you can see correctly where the center of the view is when you are scrolling across the sky. The gaze display only shows the altitude and azimuth of your gaze while you are "grabbing the sky" and changing your viewing direction.

What compass direction corresponds to an Azimuth (Az) of 315 degrees? \_\_\_\_\_

In "8: The Toolbar - Zoom Controls"

What is the angular diameter of the Moon? \_\_\_\_\_

In "10: Finding Objects"

What is the best time for viewing Jupiter from Toronto, Canada on the night of July 4/5, 2009?

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**Part 2**

After you have finished the tutorial, proceed to the Student Exercises entitled "Unit E: Star Finding," which are buttons on the main sky guide pane. Answer the associated questions for these exercises on your worksheet for exercise E1, then move on to tutorial "Unit F: The Stars" and answer questions from exercises F1 - F8.

**Unit E: Star Finding**

In "E1 part 1: The Big Dipper"

What is the orientation of the Big Dipper asterism in winter?

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In "E1 part 2: Star Hopping"

Polaris is part of which constellation? \_\_\_\_\_

In "E1 part 3: Polaris and Latitude"

What happens to the position of Polaris in your sky as time advances over a period of a year?

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What is the relationship between the altitude of Polaris and the latitude of the observer?

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In "E1 part 4: The south star?"

What is the nearest star to the south celestial pole, shown in the main window? \_\_\_\_\_

In "E2 part 1: Apparent magnitude"

A magnitude 2 star is \_\_\_\_\_ times brighter than a magnitude 4 star.

Which of the listed stars in Orion is faintest? \_\_\_\_\_

In "E2 part 3: Comparing the brightness of objects"

The planet Venus is \_\_\_\_\_ brighter than the planet Mars on January 24, 2015.

In "E2 part 4: Absolute magnitude"

What is the absolute magnitude of the star Deneb? \_\_\_\_\_

**Unit F: The Stars**

In "F1 part 1: The Sun's atmosphere"

Approximately how long does it take for the Sun to complete one rotation? \_\_\_\_\_

In the simulation at the end of this tutorial, where on the Sun are you located?

\_\_\_\_\_

In "F1 part 2: The Sun's neighborhood"

About how far away are our neighboring stars?

\_\_\_\_\_

In "F2 part 1: Measuring stellar parallax"

What is the parallax of Alpha Centauri? \_\_\_\_\_

What is Alpha Centauri's distance from Earth? \_\_\_\_\_

In "F3 part 1: Proper motion"

Which of the listed stars shows the greatest amount of proper motion? \_\_\_\_\_

In "F3 part 2: Barnard's star"

What is the average annual proper motion of Barnard's star? \_\_\_\_\_

In "F3 part 4: Effects of proper motion - Gamma Caeli"

When will the star Gamma Caeli become located within the boundaries of the constellation Columba? \_\_\_\_\_

In "F4 part 1: Luminosity and apparent brightness"

How far away is Rigel when compared to Vega? \_\_\_\_\_

In "F4 part 2: Calculating luminosity"

The calculated value of Polaris' luminosity is \_\_\_\_\_ times brighter than the luminosity of the Sun.

In "F5 part 1: The light year"

How many of the visible stars in the tutorial view less than 10 light years away from the Sun? \_\_\_\_\_

In "F6 part 2: The Hertzsprung-Russell Diagram"

Which of the highlighted stars is a red giant? \_\_\_\_\_

Which of the stars is not a main sequence star? \_\_\_\_\_

Which best describes Antares? \_\_\_\_\_

Which labelled star is a class K star with an absolute magnitude of about 5? \_\_\_\_\_

In "F7 part 1: Life cycle of a star"

What is the expected main sequence lifetime of Wolf 359, a very dim star having 10% of the Sun's mass?

\_\_\_\_\_ years

In "F8 part 2: The event horizon"

What is the radius of the event horizon for the black hole Cygnus X-1? \_\_\_\_\_

**Essay**

There will be no essay for this week's lab!

# **Physics 10263 Lab #4:**

## **Citizen Science - Variable Star Zoo**

### **Introduction**

The concept of Citizen Science is that some Astronomical databases are so large and the data so complex that computer algorithms cannot accurately or reliably sort through all of the data to find the kinds of interesting things that Astronomers are looking for. So Astronomers are recruiting citizen scientists to pitch in and help analyze data in these projects.

In return, citizen scientists get to pour over incredible data sets and photos of the sky that no one has seen before, and they have a chance to be the first to make some pretty incredible discoveries (and get credit for doing so). Basically, as a citizen scientist, you get to do all of the stuff that makes science fun without any of the tedious part (writing grants, serving on committees, etc.).

In this lab, we will first learn a little background about variable stars, then we will be identifying different types of variable stars in our own Milky Way Galaxy. This work will help astronomers determine the luminosity, mass and age of these stars. With this information, astronomers can construct a more accurate three-dimensional map of the galaxy, learn more details about the process of stellar evolution, and reconstruct the history of star and cluster formation in the galaxy.

## **Introduction to Variable Stars**

Use a browser to navigate to <https://tinyurl.com/y7rnwxf>, and read through the introductory material, answering the questions below as you go.

**Q1.** Explain what is the Main Sequence on an H-R diagram, and also explain what all main sequence stars have in common (regarding their cores).

**Q2.** Explain what is a light curve for a star.



**Q3.** What two properties of a star's light curve determine which type of variable star it is?

**Q4.** Name two differences between the properties of Cepheid variable stars and RR Lyrae variable stars.

**Q5.** Name two differences between Long Period Variables (like Mira) and Semiregular Variables (like Antares).

Next, read through a more detailed discussion of Cepheid and RR Lyrae stars: [https://www.aavso.org/vsots\\_rrlyr](https://www.aavso.org/vsots_rrlyr)

**Q6.** Briefly describe one reason why the “binary hypothesis” for the variation in RR Lyrae stars was proven to be incorrect by Shapley.

In the section on the Instability Strip, we learn that RR Lyrae stars are sub giants, brighter than main sequence stars but dimmer than giant stars such as Cepheids.

**Q7.** What type of star is a ZZ Ceti variable?

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**Q8.** What type of star is a Delta Scuti variable?

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**Q9.** Explain what is the Leavitt Law.

**Q10.** Describe how Cepheids and RR Lyrae variables were used in order to establish the true size of the Milky Way galaxy.

Now, find out more about Delta Scuti stars by reading [https://www.aavso.org/vsots\\_delsct](https://www.aavso.org/vsots_delsct) and answer questions below.

**Q11.** Explain what is a radial pulsation for a star.

**Q12.** Describe two physical differences (besides amplitude of pulsation) between High-Amplitude Delta Scuti (HADS) stars and Low-Amplitude Delta Scuti (LADS) stars.

**Q13.** Explain what Astronomers hope to learn by carefully studying the the radial and non-radial oscillation modes of Delta Scuti stars and stars like our own Sun.

Now let's read some news related to the VVV survey we will be looking at in the Citizen Science project. Visit <https://tinyurl.com/ybshur4c> and answer below.

**Q14.** Two Cepheids from the survey are dubbed "The Twins." In what part of the Milky Way Galaxy are they located?

**Q15.** Explain why Astronomer Sukanya Chakrabarti predicted that a dwarf galaxy would be found on the far side of the Milky Way from our location, about 300,000 light years from our galaxy.

**Q16.** There is also a story here about five Cepheid variables found by Astronomer Michael Feast and collaborators. Describe where these were found and what it tells us about the structure of the Milky Way Galaxy.

Now let's proceed to the Variable Star Zoo website:

<https://www.zooniverse.org/projects/ilacerna/variable-star-zoo>

Make sure you create an account and log in (please note your username and password for later labs) before you get started so that you can get an accurate count of how much data you've looked at! Once you are logged in, read through the information in the "About" tab and the "FAQ" tab to help you better understand the project, then click on the "Classify" tab and work through the short tutorial.

Before you get started classifying variable stars, one last task! Click on the Field Guide tab on the right-hand side of your screen. Below, describe the main characteristics of the three main types of light curves for variable stars you will be classifying.

**Q17.** RR Lyrae or Cepheids:

**Q18.** Mira:

**Q19.** Binary:

Your group must classify at least 90 stars. Please split up the work so everyone gets to do the same amount. Once you have completed your contribution to the project, show your lab instructor your profile page (click your username on the top right, then select "Home"). The little ring around the circular icon can be hovered over to indicate how many data sets you have completed for any given project. Your lab instructor will initial below to verify your completion.

Lab Instructor Initials: \_\_\_\_\_





## Physics 10263 Lab #5: The Pleiades

### Introduction

In the constellation Taurus, a familiar sight in the evening sky during the spring, there is a small asterism known as "The Pleiades", which marks the location of a cluster of stars. In legend, the Pleiades are the seven sisters, daughters of Atlas, the titan who holds up the sky, and the Oceanid named Pleione. The sisters are Alcyone, Maia, Electra, Taygeta, Celaeno, Merope and Asterope. The great hunter known as Orion fell in love with them and chased them for seven years (and continues to "chase" them across the sky as they ride on the back of Taurus the bull).

Today there are only six stars in the Pleiades that are easily visible to the naked eye. There are many theories about what happened to the 7th one. Celaeno has often been called the "Lost Pleiad" because she was hit by lightning according to Greek mythology. In reality, the star we call Celaeno is just at the limit of human vision in terms of brightness. In today's lab, we'll take a closer look at this small cluster of stars with the help of some observational data collected by astronomers at Kitt Peak National Observatory.

From lecture, you are probably familiar with the equation that relates the apparent luminosity and absolute luminosity of a star. This relationship is known as the inverse square law:

$$L_{\text{app}} = \frac{100}{r^2} L_{\text{abs}} - X$$

where "r" is the distance to the star (in parsecs) and "X" is the reduction factor that accounts for the extinction and reddening of starlight due to the intervening interstellar medium. If there is no material between us and the distant star, "X" = 0, and we are left with the simple form of the inverse square law.

In plain English, we say: "The more intervening material between us and the star, the fainter and redder the star appears

to be.” The value of “X” reflects changes in the apparent luminosity and the perceived absolute luminosity (estimated by looking at the apparent color and thus temperature of the star).

Because of a longstanding tradition, astronomers rarely express the inverse square law this way in practice. Instead of expressing the brightness of a star as a luminosity, astronomers use the magnitude system. Magnitudes are defined as follows:

$$m = \text{apparent magnitude} = -2.5 \log L_{\text{app}}$$

$$M = \text{absolute magnitude} = -2.5 \log L_{\text{abs}}$$

Notice the negative sign in the definition...this means that the larger the luminosity of an object, the smaller the magnitude. So the magnitude system actually goes in reverse. A star with a magnitude of 1 is actually much more luminous than a star with a magnitude of 15!

Using these definitions of apparent magnitude and absolute magnitude, we can substitute them into the inverse square law and rewrite the equation in terms of magnitudes. If you're pretty good at algebra, you can do this yourself, but we'll save you the work and just tell you what the resulting equation looks like:

$$r \text{ (pc)} = 10^{\left( \frac{m - M + 5 - x}{5} \right)}$$

$r(\text{pc})$  = distance to the star (in parsecs)  
m = apparent magnitude of the star  
M = absolute magnitude of the star  
x = correction term for extinction

So, if you can determine m, M and x, you can just plug them into this equation and solve for the distance to the star. As an example, suppose  $m = 6$ ,  $M = 1$  and  $x = 0$ .  $r(\text{pc})$  is then equal to 10 to the  $[(6 - 1 + 5 - 0)/5]$  power, or 10 to the 2nd power, which is 100. So r would be 100 parsecs.

Most stars in our galactic neighborhood have distances from 10-1000 parsecs. You may recall the scale models lab we did at the beginning of the semester to give you an appreciation for such large distances. To drive at 60 mph average speed to the nearest star to our Sun, Alpha Centauri (about 1.3 pc away), would require about 45 million years.

### **Procedure**

In order to find the distance to the Pleiades, we need to find the correction term for extinction, the apparent magnitude and the absolute magnitude. Let's take these in order:

### **Extinction**

We will assume for the sake of simplicity that the extinction term (which both reduces the apparent luminosity and causes the color of a star to appear redder than it actually is) is zero, but we will explore later how this (faulty) assumption affects our calculations.

### **Step 1**

Find the **shortcut icon** for Starry Night on the left side of the desktop. Double-click on this to launch Starry Night. Now do the following step-by-step:

- 1) Set the time to 8pm tonight.
- 2) In the search box on the upper right, type "options" and the options menu should pop up below it.
- 3) From this menu, look under the Constellations tab, and select the options "Labels" and "Stick Figures".
- 4) Use the +/- keys on the lower left of the screen to zoom in until the constellation fills the window. If you like, you can toggle "Classical Illustrations" on and off in the options window under "Constellations" so you can see the half-submerged form of Taurus.

We will now use Starry Night to assist us here with data collection.

Find M45. Here is a step-by-step:

- 1) Type M45 in the search box.
- 2) Double-click on the M45 entry that appears just below the search box. You will find it in the constellation Taurus.
- 3) Hide the left and right sidebars using the buttons just to the left of the search box.
- 4) Use the +/- keys on the lower left of your screen to zoom in until the photo of the Pleiades fills the screen.
- 5) We want to turn off the photograph of the nebulosity in M45 and just focus on the stars, so re-open the options sidebar, look under the "Deep Space" tab and de-select "Messier Objects".
- 6) Now close the options sidebar.

Most of the stars on your display now are members of the open cluster known as the Pleiades Cluster. Many of the faintest stars have names like "TYC1800-1579-1". Avoid these stars during the exercise since they don't have sufficient color and brightness information to be useful. Instead, select one of the brighter stars. Some of these have names, but all of them have SAO numbers or HIP numbers (catalog numbers from the Smithsonian Astrophysical Observatory or the Hipparcos Guide Star Catalog).

For 15 of these stars, do the following step-by-step:

- 1) Select the star.
- 2) Click on the blue "i" button next to the star to show an info window for the star.
- 3) Within the info window, select "Other Data."
- 4) In the table on the next page, fill in
  - a) the name of the star,
  - b) the apparent magnitude of the star, and
  - c) the B-V color for the starin the appropriate columns. If the star does not have all three items of information then select a different star. The brighter stars are more likely to have all of this information.

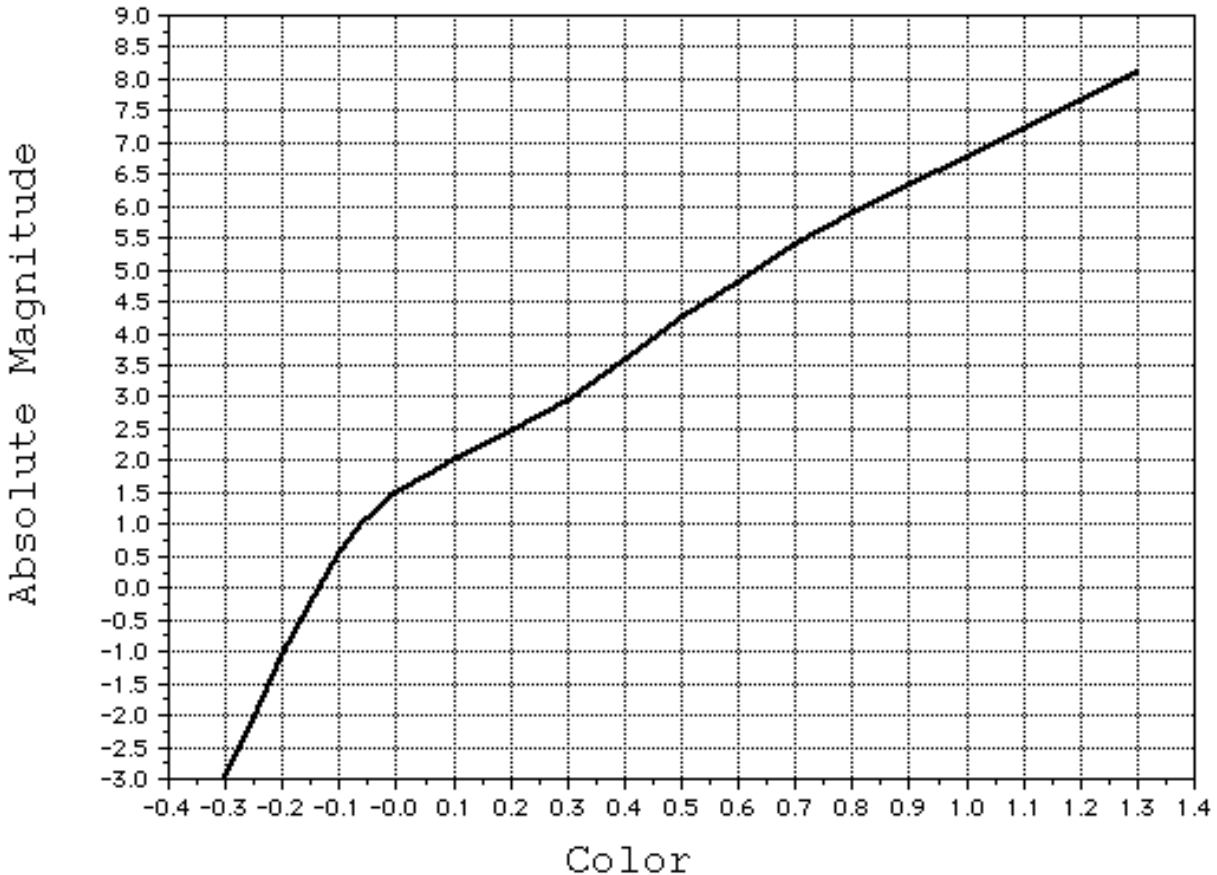


Very blue stars tend to have temperatures much hotter than the Sun, for example, and very red stars tend to have temperatures much cooler than the Sun.

Astronomers have also studied stars like those found in the Pleiades, and from this collection of "standard stars", they have determined how the size varies with star color (bluer, hotter stars tend to be somewhat larger than stars like the Sun). This information about the sizes and temperatures of standard stars leads us to the graph on the next page, showing the relationship between color and absolute magnitude for standard stars (the so-called "Main Sequence" stars) like the stars in the Pleiades. Note that "color" in this exercise is expressed as a difference in magnitudes (blue absolute magnitude - yellow absolute magnitude), so the lower the color number, the bluer the star appears to be on the sky. It is no surprise then that the bluer (more negative) the color, the brighter (more negative) the absolute magnitude of that star.

Using the graph in Figure 1 on the next page and the color information from your worksheet table, estimate the absolute magnitude for each of the 15 stars in your sample and put this information in the appropriate column in your table. For example, a star with a color of -0.20 has an absolute magnitude of -1.0. As another example, a star with a color of +0.95 has an absolute magnitude of 6.5. Verify these two examples yourself on the graph to make sure you understand how to fill in your table.

# Figure 1 Colors and Absolute Magnitudes for Standard Stars



### Step 3

Now that we have estimates of the extinction (which we are assuming to be zero), the apparent magnitude and the absolute magnitude (from our table) for each of the stars in our sample, we can average these quantities in order to estimate the distance to the Pleiades.

In column 5 on your table, calculate "m-M", the apparent magnitude (column 3) - the absolute magnitude (column 4). Do this calculation for each star in your sample.

In the space below, write down the average of your 15 "m-M" values. Write your average with 3 significant figures.

Average m-M value from table: \_\_\_\_\_

**Step 4**

The value "m-M" is often referred to as the "distance modulus" because it appears in the distance equation back in the Introduction. Use your average distance modulus value in the distance equation in the Introduction and determine the distance in parsecs to the Pleiades cluster. Don't forget that, for simplicity, we have assumed the correction term for extinction (X) is zero. Write down your distance value on the next page with two significant figures.

Estimated distance to the Pleiades cluster: \_\_\_\_\_ pc

Given that the true distance to the Pleiades cluster is approximately 126 parsecs, calculate the percent error in your answer.

The formula for %error is:

$$\%error = 100 * \frac{|\text{observed value} - \text{true value}|}{\text{true value}} \quad \leftarrow \text{positive number}$$

Remember, when calculating percent error, use the rules for significant figures.

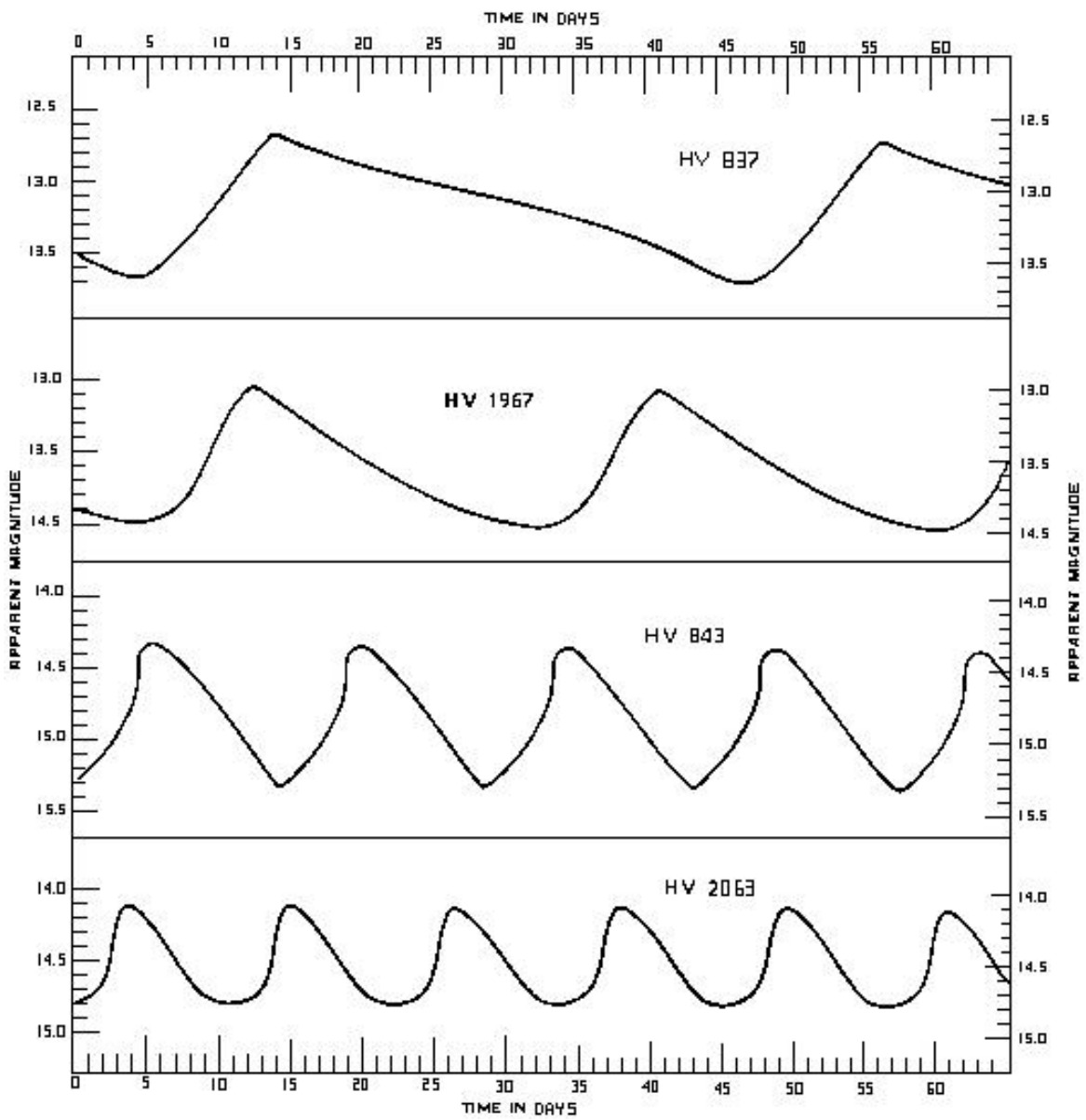
Percent error in distance estimate: \_\_\_\_\_ %







TIME IN DAYS





## Physics 10263 Lab #6: Cepheid Variables

### Introduction

In a previous lab, we used the inverse square law to determine the distance to the Pleiades cluster. The inverse square law is one of the most common distance indicators used in astronomy. As a reminder, it can be written as follows:

$$L_{\text{app}} = \frac{100}{r^2} L_{\text{abs}} - X$$

This is the "linear form" of the inverse square law. Assuming you can measure the apparent luminosity of an object, the "X" correction term for interstellar extinction and redding, you need to find some way to measure the absolute luminosity. If you are successful in these three tasks, you can solve the equation above for the distance (r).

Another form of the inverse square law is often used by astronomers. It uses the logarithmic form of the luminosity (apparent and absolute magnitudes):

$$m = \text{apparent magnitude} = -2.5 \log L_{\text{app}}$$

$$M = \text{absolute magnitude} = -2.5 \log L_{\text{abs}}$$

Substituting these terms into the inverse square law and solving for r, we get:

$$r \text{ (pc)} = 10^{\left( \frac{m - M + 5 - x}{5} \right)}$$

r(pc) = distance to the star (in parsecs)  
m = apparent magnitude of the star  
M = absolute magnitude of the star  
x = correction term for extinction

When finding the distance to the Pleiades cluster, we used the color (B-V) information for individual stars in the cluster. That information translated into an estimate of the absolute luminosity. Combined with the measured apparent luminosity and an estimate of "X", we were able to find the distance to that cluster.

Finding the distance to other galaxies, however, can be a bit more difficult. Whereas the Pleiades cluster is about 120 parsecs away, the Small Magellanic Cloud (a small satellite galaxy orbiting our own Milky Way) is about 53,000 parsecs away, making observations of individual stars much more difficult. Thus, we cannot use the Pleiades method with the Small Magellanic Cloud since the only individual stars we can successfully pick out are the rare, very bright ones.

Fortunately, some of these very bright stars belong to a class of stars called **Cepheid Variables**. Cepheid Variables are typically anywhere from 100 to 10,000 times more luminous than our own Sun, and their brightnesses vary with periods from 1 to 100 days. The prototype of this group is the fourth brightest star in the constellation Cepheus, Delta Cephei, the properties of which were discovered in 1784 by John Goodricke, an English amateur astronomer. After more such stars were discovered, theorists surmised that the brightness variations were caused by pulsations in the stars (growing larger and smaller periodically).

In 1912, Harvard astronomer Henrietta Leavitt discovered a correlation between the absolute luminosity and the period of Cepheid Variable stars. The longer the period of the star, the higher its absolute luminosity (this proportionality is known as the Leavitt Law). This proved enormously beneficial to astronomers, since the variation period in a light curve of a star is much easier to determine than the spectral type (the light curve period is also a much more accurate indicator of absolute luminosity, as it turns out).

In this lab, we will study four Cepheid Variable stars located in the Small Magellanic Cloud (SMC). Even if these stars are spread out all over the SMC, we can assume they are all at the same distance. Assuming the distance to the SMC is 53,000 parsecs, the worst case would be that one would be at, say, 52,000 parsecs and another would be at 54,000 parsecs. In other words, our experimental error in determining the distance to the SMC (probably around 10% - 20% of the distance) will likely be larger than the size of the cloud itself (probably only 1% - 2% of the distance).

### **Procedure**

Before we can use the Cepheid Period-Luminosity (P-L) Relation to determine the distance to the SMC, we need to calibrate it. In other words, we need to determine the actual relationship between period and absolute luminosity by using a sample of local stars (whose absolute luminosities we can determine independently). Once we have this information, we'll find the periods of stars in the SMC, use the P-L relation to guess the absolute luminosity, and thus find the distance.

Fortunately for us, two astronomers (Walter Baade and Robert Kraft) have already attempted to calibrate the Leavitt Law for us. Their work is summarized in the table the follows, but note that each Astronomer has come up with a different solution!

<b>log P</b>	<b>M (Baade)</b>	<b>M (Kraft)</b>
0.80	-3.7	-3.4
1.00	-4.4	-3.8
1.20	-5.1	-4.8
1.40	-5.9	-5.7
1.60	-6.6	-6.2
1.80	-7.3	-7.0

(1) On your worksheet graph, plot the six points from the table log P vs M (Baade). Note that the scale for Absolute Magnitude (M) is on the lower half of the graph. To save space, part of the y-axis has been cut out. After you have plotted the six points, use a ruler and draw the best fit straight line that passes as close as possible (but not necessarily through) all six points. Label this line "M(Baade)".

(2) On the same graph, plot the six points from the table log P vs M (Kraft). Again, use the lower half of the graph since you're plotting absolute magnitudes. After you have plotted the six points, use a ruler and draw the best fit straight line that passes as close as possible (but not necessarily through) all six points. Label this line "M(Kraft)".

We have now plotted the calibrated P-L relation (two versions) for all Cepheid Variables. Next we will plot the period and apparent magnitude information for Cepheids in the SMC. This information, combined with the information in the calibrated graph, will provide us with an estimate of the distance to the SMC.

(3) On the data sheet that accompanies these notes are light curves of four Cepheid Variables based on photographic observations by astronomer Halton C. Arp. Estimate to a precision of 0.1 magnitudes the average value of the apparent magnitude of the minima of each light curve (note the magnitude scales on the right and left are identical and the increase **downward**). Enter this data in column 1 of the table on your worksheet.

(4) For each star, determine the time between any two minima (for greater accuracy, measure across more than one minima and divide by the number of periods you've covered) to a precision of 1 day. Enter this data in column 2 of the table on your worksheet.

(5) Take the logarithm of each of your four period values in column 2. Write these values in column 3 of your table with three significant figures.

(6) Now, on the upper part of the graph on your worksheet, plot the data from column 3 (log P) vs the data from column 1 (apparent magnitude). As in parts (1) and (2), after you've plotted your four points, draw the best fit straight line that passes as close as possible (but not necessarily through) all four points. Label this line "m".

You should now have three roughly parallel lines on your worksheet graph, one at the top and two at the bottom.

(7) For each of the four points on your top (apparent magnitude) graph, use a ruler to draw a vertical line straight down from that point all the way to the bottom of the graph. These four lines will intersect your other two absolute magnitude graphs.

Using these lines as guides, read off the value (to a precision of 0.1 magnitudes) of the M(Baade) line where the M(Baade) graph intercepts your four vertical lines. Enter this data into column 4 of your table. For each of the four stars you measured, you now have a value of apparent and absolute magnitude!

(8) Again using the lines as guides, read off the value (to a precision of 0.1 magnitudes) of the M(Kraft) line where the



M(Kraft) graph intercepts your four vertical lines. Enter this data into column 5 of your table. Now we have two absolute magnitude estimates for each of the four stars. We'll determine which astronomer did a better job calibrating the data!

(9) In column 6 of your table, calculate " $m - M(\text{Baade})$ ". In other words, subtract column 4 from column 1. Your answer should have a precision of 0.1 mag.

(10) In column 7 of your table, calculate " $m - M(\text{Kraft})$ ". In other words, subtract column 5 from column 1. Your answer should have a precision of 0.1 mag.

# Lab #11 Worksheet

**Name:**

**Home TA:**

(1) - (2) See back of this page for graph.

(3) - (10)

	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7
Star	Apparent Magnitude (m)	Period (days)	Log P	M (Baade)	M (Kraft)	m - M(Baade)	m - M(Kraft)
HV 837							
HV 1967							
HV 843							
HV 2063							

(11)

Average value of "m - M(Baade)" = \_\_\_\_\_

Average value of "m - M(Kraft)" = \_\_\_\_\_

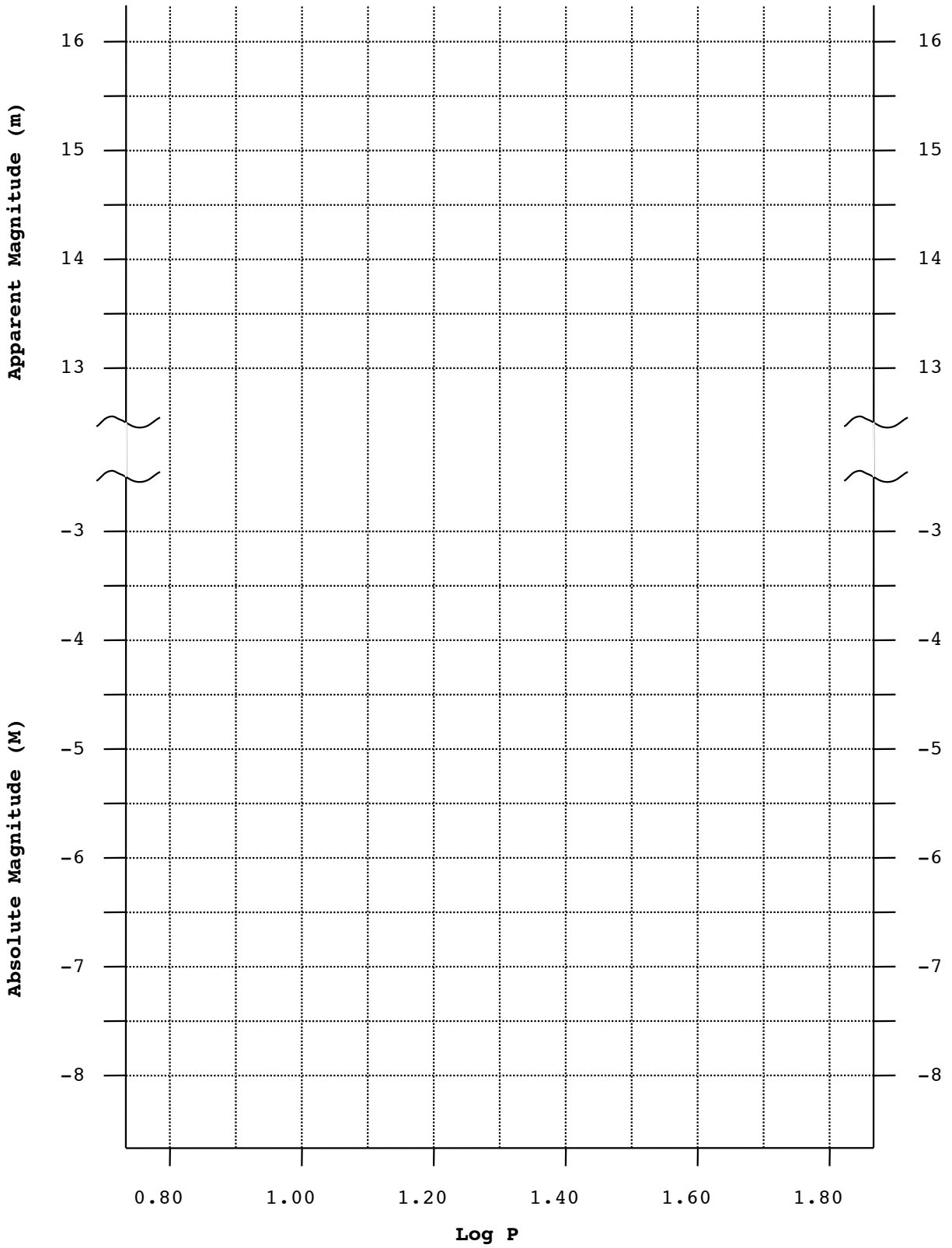
(12)

Distance to the SMC (Baade's calibration): \_\_\_\_\_ pc

% error in Baade's calibration: \_\_\_\_\_ %

Distance to the SMC (Kraft's calibration): \_\_\_\_\_ pc

% error in Kraft's calibration: \_\_\_\_\_ %



No essay for this week's lab.



## **Physics 10263 Lab #7:** **Citizen Science - Supernova Hunting**

### **Introduction**

This lab is the another "Citizen Science" lab we will do together this semester as part of the [zooniverse.org](http://zooniverse.org) project family. This time, we will be searching for objects in the sky that vary, the brightest of which include variable stars (some of which we studied in previous labs), active galactic nuclei and supernova explosions.

Supernova explosions are extremely important for establishing the distance scale in the Universe. Knowing how far away supernovae are helps us figure out what our Universe was like in the past and how it is likely to change in the future. In order to measure such distances accurately, we need to know all we can about these rare and powerful explosions, so we will spend a bit of time learning about supernovae before diving in to the supernova hunting project.

Start by reading the relevant section of your textbook. Use a browser and search for "OpenStax Astronomy," then find Chapter 23.2 and answer the following questions based on that section (we will just be reading the first half of the section). Alternatively, a direct link to the chapter section is <https://bit.ly/2RsLAt7> .

**Q1.** Why is it that only stars with initial masses greater than about 10 times the mass of the Sun undergo the type of explosion described in this section (a Type II supernovae)?

**Q2.** Explain why iron fusion in the core triggers a supernova explosion.

**Q3.** Describe what provides the energy for the explosion once the core of the star has collapsed.

—

Next, we will move on to [Chapter 23.3](#), which discusses observations of supernovae. Just click on the right arrow “Next” button at the bottom of Chapter 23.2 to get there.

**Q4.** Explain what is the mechanism that causes the ring that appears in images of Supernova 1987A.

**Q5.** Roughly 40 days after the initial supernova 1987A explosion, the expanding cloud of superheated gas was still getting brighter, but not because of the energy of the explosion itself. What was the source of this energy? Explain.

Our final textbook section we will read to learn about supernovae involve Type Ia supernovae, which are extremely important in establishing the cosmological distance scale. Please proceed to Chapter 23.5 of your textbook, "The Evolution of Binary Star Systems," to learn about these supernovae and answer the associated questions below.

**Q6.** Briefly describe the process that causes a nova explosion, a much fainter version of the Type Ia supernovae we will study later.

**Q7.** Briefly describe the process that results in a Type Ia supernova.

Note that all white dwarfs that undergo this type of explosion have a very similar mass, so these explosions have the potential to make great standard candles. A standard candle is a source of light with a very predictable and well-understand absolute luminosity (or magnitude). If we know the absolute luminosity of an object and can measure its apparently luminosity, determining the distance is a simple matter of solving the inverse square law (recall we did this with Cepheid Variables and stars in the Pleiades cluster).

**Q8.** The distinguishing spectral characteristic that allows us to determine whether a supernovae is a Type Ia or type II is that type Ia's should have very little or no evidence of Hydrogen atoms in their spectra. Explain why this difference exists between the two types of supernovae.



In our Citizen Science project today, we will be analyzing data from the Zwicky Transient Facility, a project designed to detect events like supernovae explosions very quickly after they first start getting bright. Getting information about a supernova explosion during the very early stages of its brightening is critical to understanding in detail the nature of these explosions and, in turn, accurately predicting their brightness so that we calculate an accurate distance.

Astronomers are trying to understand whether a Type Ia supernova occurs when either (a) two white dwarfs merge together or (b) when a white dwarf receives too much mass from a companion (which is in an earlier part of its evolution, still with a Hydrogen envelope like our Sun). For brief animations of these two types of explosions, see <https://go.nasa.gov/2NFtL92> and scroll down to the relevant video clips.

For an example of how the science of supernovae can be impacted by quick observations of the early stages of an explosion, please read <https://bit.ly/2NGAoYR>, and answer the questions below about the article.

**Q9.** Astronomers believe that detecting Hydrogen in the spectrum of an exploding type Ia supernova would favor the “mass transfer from companion” model over the “white dwarf merger” model. Explain why.

**Q10.** In this particular article, the light curve of the explosion led Astronomers to believe this is in fact a “white dwarf merger.” What, then, is their explanation for the presence of Hydrogen in the spectrum?

The significance of these studies is that each supernova that can be detected early and studied closely tells us more about how to determine the true brightness of these explosions and therefore the true distance to the galaxies that contain them.

So now we will do a little bit of hunting for supernovae (and other kinds of things that vary in the sky) using the Zwicky Transient Facility (ZTF). Go to <https://bit.ly/2TBxx7a> in order to access this Citizen Science project. You will have to log in to the Zooniverse project in order to keep accurate stats on how much data you have examined. Just use the same log in you used for our previous project, the Variable Star Zoo.

Click “Learn More” and watch the first video to learn about this project, then answer the following:

**Q11.** Describe the two types of real varying objects (as opposed to bogus objects) that we will be detecting with the ZTF.

Next, under the "Classify" tab, click on the Tutorial link to learn how the classification process works and then click on the "Field Guide" and read through the examples of different kinds of things we will see. Then answer the following:

**Q12.** What kind of object typically has a lot of points plotted on its light curve?

**Q13.** If a light curve for an objects is longer than about 200 days, there will often be a large gap in the data. What is the cause of this?

**Q14.** What are two indicators in the image and the light curve that suggest an image you are looking at is a newly discovered supernova?

**Q15.** How do "orphan transients" differ from supernova detections?

Now you are ready to get started classifying images and finding supernovae and other light sources in the sky that vary. Your group should classify at least 90 images. Please split up the work so everyone gets to do the same amount. Once you have completed your contribution to the project, show your lab instructor your profile page (click your username on the top right, then select "Home"). The little ring around the circular icon can be hovered over to indicate how many data sets you have completed for any given project. The number below the ring is the total number of data sets for all projects combined. Your lab instructor will initial below to verify your completion.

Lab Instructor Initials: \_\_\_\_\_

## **Physics 10263 Lab #8:** **Citizen Science - Galaxies**

### **Introduction**

In this lab, we'll extend the capabilities of Starry Night and take advantage of the Internet to learn about coordinate systems and our home galaxy, the Milky Way. Then we will do another Citizen Science project by analyzing some interesting observations that have been collected for other galaxies.

Because we live in a galactic disk, our view of the night sky is profoundly affected. For example, the billions of distant, unresolved stars in the disk of our galaxy stretch around us in a ghostly band that rings the sky. We call this the Milky Way. The dust from the disk that surrounds us substantially limits our ability to look for objects outside of our own galaxy, particularly in the direction of the surrounding disk.

Because of this, Astronomers thought that our galaxy was the only large object in the Universe until the first half of the 20th century. Other galaxies were too faint or too obscured by clouds of gas and dust for us to examine closely to determine their distances. Even after other galaxies were discovered outside of our own, we still had trouble seeing objects outside our own galaxy in the direction of the disk. Less than 20 years ago, a huge, faint companion spiral galaxy to our own, Malin 2, was discovered. It hadn't been seen previously due to the fact that it is blocked by the gas and dust in our galaxy and the fact that Malin 2 has a very low surface brightness.

The structure of the Milky Way also affects our observations of objects within the galaxy. For example, even though we know that stars are more or less uniformly distributed around the Milky Way ring, there are places where the star counts vary by factors of hundreds or even thousands. This is due to gas and dust obscuring our line of sight so that only the brightest and/or nearest stars are visible. Without taking this into account, our theories about the structure and dynamics of the Milky Way would be woefully incomplete.

The gas and dust itself has many interesting properties worth exploring. Photometry and spectroscopy of these clouds of gas and dust at varying wavelengths reveals properties such as mass,

size, temperature, composition and motion. Often, the thickest clouds along our line of sight harbor forming stars that can only be seen with very long wavelength observations, using radio wavelengths that are less prone to scattering by dust and gas.

Because the sky looks so different near the ring of the Milky Way, we often use a Galactic coordinate system to find our way around the sky. Much like the Earth's equator marks 0 degrees latitude on the Earth while the Earth's north and south poles mark +90 and -90 degrees latitude, we consider the Milky Way in the night sky to mark the galactic equator. So the galactic equator makes a great circle spanning the entire sky, parallel to the faint band of the Milky Way itself.

Objects observed at low galactic latitude (near the galactic equator) tend to be obscured or otherwise affected by the presence of gas and dust along one's line of sight. Conversely, objects near high galactic latitude (near either the North or South galactic poles) are often easily seen, even if they are at enormous distances (like distant galaxy clusters).

We are going start this lab by using Starry Night to get familiar with a few basics about our galaxy. Launch Starry Night, and set the time to 8pm tonight.

Follow this step-by-step:

- 1) Type "options" into the search box on the upper right to launch the options sidebar.
- 2) Under the Solar System tab, turn on the labels tab for planets.
- 3) Turn off Asteroids, Comets, Satellites and Space Missions under the Solar System tab.
- 4) Under the Constellations tab, turn on the Labels, Boundaries and Stick Figures tabs.

Now, on the following page, your first question to address:

**Q1.** For each of the eight major planets, which ones are above the horizon at this time, and in what constellation is each planet found?

<u>Planet</u>	<u>Constellation</u>
---------------	----------------------

Next, let's take a look at a couple of useful coordinate systems Astronomers use to find their way around the night sky. In the options sidebar, look under "Guides" and "Celestial Guides", then turn on "Grid" and "Poles". This produces a faint grid on the sky that is the Earth-based celestial coordinate system. Use the zoom feature (+/- keys on lower left) to zoom all the way out so you can see the celestial sphere.

Now scroll around so that the North Celestial Pole is centered on your screen and zoom in until you only see one or two stars in your field of view.

**Q2.** What is the name of the brightest star with a proper name (not a catalog number) near the North Celestial Pole?

---

Further down the options sidebar, under "Local View", turn off "Local Horizon". Now zoom in on the South Celestial Pole, but not too far (maybe until your screen is about 70° x 45° or so)!

**Q3.** Find the star closest to the South Celestial Pole with a proper name (not a catalog number), write down its name and the name of the constellation in which it is found.

---

The equatorial coordinate system's gridlines are based on the latitude and longitude grid of the Earth's coordinate system. Our galaxy, however, does not naturally align itself in Earth's coordinate system. In fact, our solar system is tipped about 60 degrees with respect to the plane of the Milky Way galaxy's disk. Follow this step-by-step:

- 1) Under "Guides", look for the tab "Celestial Guides", and turn off the "Poles" and "Grid" tabs.
- 2) Under "Guides", look for the tab "Galactic Guides", and turn on the "Poles" and "Grid" tabs.
- 3) Under the "Stars" tab, double-click on "Milky Way" to open a window. Turn the brightness of the Milky Way all the way to maximum so you can see better this faint band of light that encircles us. Notice that the Galactic Equator in our grid lines up with the Milky Way's ring of light in the sky.
- 4) Under the "Constellations" tab, turn on the "Labels" and "Boundaries" tabs.

**Q4.** In what constellation is the North Galactic Pole found?

- 
- 5) Now go back and turn off the tabs under "Constellations" and re-center your view so that the Milky Way galaxy and the galactic equator spans across the center of your view.
  - 6) Under "Solar System", turn off "Planets-Moons"
  - 7) Under the main "Stars" tab, turn off the sub-header "Stars" tab (sorry, we know this is confusing).
  - 8) Under the main "Stars" tab, turn on the sub-header "Star Clusters" and turn off "Globular Clusters" and "Labels".

What you are now seeing is the collecting of open clusters in the galaxy. Open clusters are typically a younger population of stars that formed recently, and so they are typically found where there is the greatest concentration of gas and dust clumps, which is in the plane of the Milky Way Galaxy.



You should also notice two concentrations of open clusters that are well outside the disk of the Milky Way. Those are satellite galaxies of the Milky Way that are nearby.

9) To find their names, look under the main "Deep Space" tab, under the "Bright NGC Objects" tab, and turn on the "Labels" tab.

**Q5.** What are the names of these two satellite galaxies?

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10) Now, under "Deep Space", turn off the "Bright NGC Objects" tab.

11) Under "Stars"/"Star Clusters", turn off "Open Clusters" and turn on "Globular Clusters"

12) Under "Constellations", turn on "Labels" and "Boundaries"

Now we are looking at a much older population of stars, the globular clusters in our galaxy. Since these are older, they are not necessarily found where we find a lot of gas and dust, so they don't have a flat distribution like the open clusters did.

In fact, they are concentrated in a particular direction on the sky.

**Q6.** In what two constellations do we find the majority of the globular clusters?

\_\_\_\_\_ and \_\_\_\_\_

That concentration marks the direction of the center of our Milky Way galaxy.

Finally, let's look outside the galaxy and learn about the "Zone of Avoidance".

13) Under "Constellations", turn off "Labels" and "Boundaries".

- 14) Under "Deep Space", turn off "Bright NGC Objects"
- 15) Under "Deep Space", turn on the "NGC-IC Database" tab, and under this tab, turn off everything except "Galaxy".
- 16) Click the words "NGC-IC Database" (not the toggle switch). There is a slider in the window that appears for "Number of objects". Move the right hand slider all the way to the right to "More".

Now, Starry Night is showing us several hundred galaxies that are visible to us from the Earth (through telescopes). Notice that with few exceptions, these galaxies are all outside of the band of light we know as the Milky Way. This has historically been called the "Zone of Avoidance," as if galaxies somehow physically avoid that part of the sky.

We have learned, however, that the distribution of galaxies actually fills the entire sky uniformly. It's just that we can't see very many galaxies near the galactic equator because of the gas and dust in the Milky Way galaxy.

## **Part 2**

For helpful background information about what astronomers are hoping to learn by studying bubbles, star forming regions, clusters and other structures in the Milky Way, please read through the February 2010 Scientific American article, "Cloudy with a Chance of Stars."

In order to access this article, just use your browser and go to <http://personal.tcu.edu/dingram/cloudy.pdf> .

Read through the and answer the questions below, which are arranged in the same order that they are covered within the article.

**Q7.** From the article, "Cloudy with a Chance of Stars," what four questions about star formation does the author seek to answer with his research?

1.

2.

3.

4.

**Q8.** When collapsing interstellar clouds reach a density of about 1000 atoms per cubic centimeter, we call them molecular clouds. Why can molecules survive in these clouds and not in other parts of interstellar space?

**Q9.** Describe two leading ideas that may explain what upsets the balance of pressure and gravity in order to initiate the formation of a star from an interstellar cloud.

1.

2.

**Q10.** Explain the evidence from the W5 region (described in the photograph on page 39) that radiation pressure from massive stars has triggered the collapse of surrounding dust clouds and subsequent star formation at the rim of the bubble.

**Q11.** Describe the competitive accretion model for the formation of star clusters.

**Q12.** Describe the evidence in the Christmas Tree cluster that seems to support competitive accretion as a major influence, at least for some stars.

**Q13.** Explain how recent theoretical simulations solve the problem of super-massive star formation, allowing stars to form with masses larger than 20 solar masses despite the enormous radiation they emit (which “should” disperse surrounding gas and dust, limiting further growth).

### **Part 3**

We will now move on to the “Citizen Science” part of the lab, In this lab, we will be exploring the structure and interesting features of nearby galaxies. By learning about clumps in these nearby galaxies, we can get a better understanding for similar features in our own galaxy (which are very hard to see from inside the galaxy itself) as well as how galaxies like our own have changed over time.

Close Starry Night. Using a web browser, navigate to <https://bit.ly/2RC31XZ> and from there, sign in to the Zooniverse website if you haven't already (you should have one by now from the Variable Star Zoo or the Zwicky Transient Facility projects). You may need to create an account. This will enable the site to keep a record of your work so that we know how many data sets you have completed.

Now select “About” and read through the short introduction, then answer the questions starting on the next page.

From the "About" section under the first tab ("Research"),

**Q14.** Describe two ways astronomers think clumps within galaxies may form.

**Q15.** Describe what two different models say about what will happen to galaxy clumps as time goes on.

Next, click on the "FAQ" tab. Read the answers to these questions and answer:

**Q16.** Explain why humans are needed to analyze these galaxy images instead of just leaving it all to automated software.

For the next part of the lab, open up the "Classify" tab and click through the brief tutorial. Then, on the right hand side of your browser window, click on the "Field Guide" tab and look at the various examples of what you will be seeing. This will help make your classification tasks proceed much more quickly!

Now proceed to classify 60 images. If you have some uncertainty after looking at a few images, go through the tutorial carefully again. Also, click the "Need some help with this task?" button for some examples of things commonly marked. Many frames (maybe half) have nothing obvious to mark, and that's fine. Just inspect the image for a few seconds to be sure, then move on to the next.

Once you have completed your contribution to the project, show your lab instructor your profile page (click your username on the top right, then select "Home"). The text below the image will tell you the total number of classifications/data sets you have completed on ALL zooniverse websites, but we are only interested today in what you've completed on the Milky Way Project.

The little ring around the circular icon can be hovered over to indicate how many data sets you have completed for any given project, indicated by the different colors of the ring if you have done more than one project.

Lab instructor initials to validate completion: \_\_\_\_\_



# **Physics 10263 Lab #9:**

## **Citizen Science - The Galaxy Zoo**

### **Introduction**

Astronomy over the last two decades has been dominated by large sky survey projects. The Sloan Digital Sky Survey was one of the first attempts to create a precise digitized map of the sky. Large telescopes with sensitive megapixel digital cameras were held in place while strips of the sky drifted past. Many strips were combined to make a large sky map, and then the process was repeated with different filters.

Since then, many more precise and more sensitive surveys have been conducted, resulting in an enormous database of millions of galaxy images culled from the large survey maps. Classifying the properties of many of these galaxies is a task that requires judgement and creativity, and in many cases, this is not something computers can do better than humans.

The Galaxy Zoo project is very simple. It shows you a tiny square patch of the giant sky map with a galaxy in the center of the image. It then asks you a series of questions about that image, and all you need to do is examine the image closely and answer the questions as accurately as you are able.

A good analogy is that you are acting like a census-taker. The idea behind a census is that you ask a large number of people about their "properties" (like age, weight, height, ethnicity, marital status, income, living arrangements, etc). Sociologists can then use this information to see if there are any surprising relationships that reveal deeper truths about the human condition or at least are worth further exploration.

Here, you are recording galaxy properties, like size, shape, mass distribution, color, relationship status (e.g. mergers with other galaxies), etc. Astronomers will then use this collected data to search for deeper truths about galaxies, such as how and when they formed, how they change over time, where different types of galaxies are found, what kinds of stars do each type of galaxy have, etc.

The Zooniverse project does not expect you to be perfect. There are going to be some questions about galaxies for which

you are not sure of the answers, and you may find yourself making a few educated guesses about whether there is a merger going on, whether you are seeing a disk or a bar, and you may guess wrong. That's okay! Zooniverse is going to be showing the same objects to dozens or hundreds of other people as well, hoping to use crowdsourcing to achieve some kind of consensus on the correct answers to these questions. So you don't have to be perfect, but your best effort is appreciated.

Keep in mind that there will be some objects you are the first human to lay eyes on since new data is entering the project all the time from various sources. Keep a sharp eye out, therefore, for anything unusual, and you may be credited with assisting in the discovery of a new, interesting object never before studied by any human!

### **Part 1**

Once you have logged in to [galaxyzoo.org](http://galaxyzoo.org), click the "About" tab to read some background on galaxy morphology and what we hope to learn from it. You will learn why you are being asked to classify properties of galaxies, then you will need to answer the associated questions below.

**Q1**. Explain how the presence of black holes in galaxy centers can cripple star formation in the galaxy.

**Q2.** Why are galaxy mergers not likely in the centers of galaxy clusters, where galaxies are packed closely together?

**Q3.** Why are galaxy mergers not likely in the outer edges of clusters or in between clusters of galaxies?

Now proceed to the following online exercise about galaxy classification and the Sloan Digital Sky Survey:

<https://bit.ly/2ReQ2wJ>

We are not going to perform the exercise itself, but I would like you to read through it (click the "Next" box at the bottom of each page to proceed through the explanations) to familiarize yourself with how galaxies are classified. Answer the associated questions below.

**Q4.** On the page "Classifying Galaxies": Who developed the first galaxy classification system, still in use today?

**Q5.** On the page "Spiral Galaxies": Describe the difference between type a, b and c spirals.

**Q6.** On the page "Spiral Galaxies": Describe the main differences between the disk and the bulge of a spiral galaxy in terms of their color, activity, and composition.

**Q7.** From the page "Elliptical Galaxies": Explain the difference between an E0 galaxy and an E7 galaxy.

**Q8.** From the page "Lenticular Galaxies": Explain what a lenticular galaxy is and how it appears.

**Q9.** From the page "Irregular Galaxies": How common are irregular galaxies? And what is a starburst galaxy?

**Q10.** From the page "The Hubble Tuning Fork": Sketch and label the Hubble Tuning Fork diagram in the space below.

**Q11.** From the same page, explain which types of galaxies are "early" and which type are "late" type galaxies are and why Hubble designated them as such.

**Q12.** From the page "Galaxy Collisions": What often happens to the brightness of a galaxy after it interacts with another galaxy and why?

**Part 2**

Time to return to Galaxy Zoo. Click on "Classify" and click through the Tutorial, then read through the tabs in the "Field Guide" (available on the right side of the browser window), then start classifying! Once you (or the combined members of your group) have classified 60 galaxies, show your lab instructor your stats (on the zooniverse profile page) to verify that you have completed this part of the lab. Your lab instructor will initial your lab below.

You can determine how many galaxies you have classified by visiting your profile.

Lab Instructor Initials: \_\_\_\_\_





# Physics 10263 Lab #10:

## Measuring the Hubble Constant

### Introduction

In the 1920's, Edwin Hubble discovered a relationship that is now known as Hubble's Law. It states that the recession velocity of a galaxy is proportional to its distance from us. The equation used to express this is:

$$v = H*d, \text{ where}$$

$V$  = recession velocity of the galaxy (in km/sec)

$H$  = Hubble constant (in km/sec/Mpc)

$d$  = distance to galaxy (in Mpc, or millions of parsecs)

This equation tells us that a galaxy moving away from us twice as fast as another galaxy will be twice as far away.

The velocity is relatively easy for us to measure using the Doppler effect. An object in motion will have its radiation (i.e. light) shifted in wavelength according to the following formula:

$$v * \lambda_{\text{rest}} = c * (\lambda - \lambda_{\text{rest}}), \text{ where}$$

$\lambda$  = observed wavelength (in Angstroms, or  $10^{-10}$  m).

$\lambda_{\text{rest}}$  = rest wavelength

$V$  = speed of the object (in km/sec)

$C$  = the speed of light ( $3.0 \times 10^5$  km/sec)

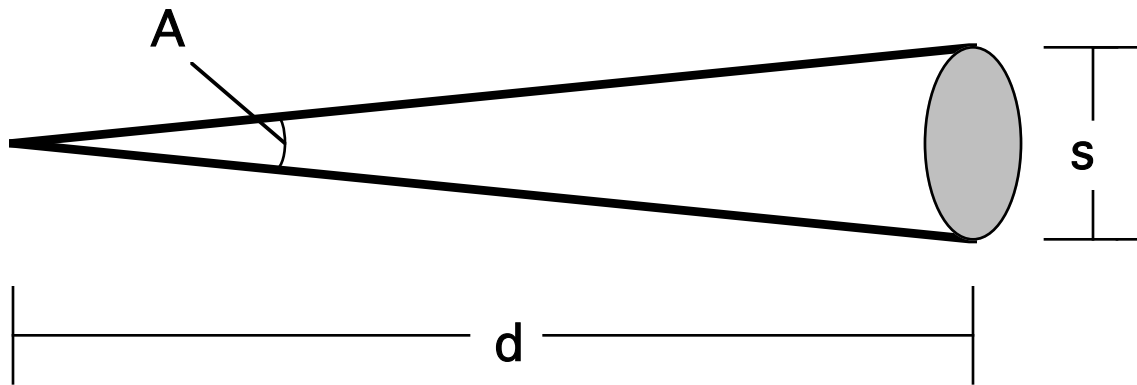
So, we can determine the velocity of a galaxy from its spectrum. We simply measure the wavelength shift (the difference between observed and intrinsic wavelength) of a known spectral absorption line and solve for  $v$ .

**Example:** Suppose a certain absorption line has a true wavelength of 5000 Angstroms. When analyzing the spectrum of a particular galaxy, we observe the absorption line at a wavelength of 5050 Angstroms. We then conclude that the galaxy is moving away from us with a velocity of:

$$v = \left[ \frac{(5050-5000)}{5000} \right] * 300,000 = 3000 \text{ km/sec}$$

In order to estimate the distances to galaxies, we're going to use a distance determination technique known as the "standard ruler". In this technique, we assume that all galaxies have the same intrinsic linear size (just like all rulers are 12" long). In other words, if one says that the Milky Way is 120,000 light years (about 37,000 parsecs, or 37 kiloparsecs) across, then we would assume that every galaxy in the sky also measures 120,000 light years across.

We can now use a method similar to parallax to determine the distances to the galaxies in our data set.



In the diagram above, we are assuming that we know  $s$  (the standard ruler size of 37 kiloparsecs, or kpc), and we wish to measure  $A$  in order to find  $d$ . To determine the distance,  $d$ , to a galaxy with a known linear size ( $s$ ) and known angular size, we simply use the small-angle formula:

$$d = S / A, \text{ where}$$

$d$  = distance to the galaxy (in Mpc)

$S$  = linear size of the galaxy (in kpc)

$A$  = angular size of the galaxy (in milliradians)

You can measure the angular size of the galaxy,  $A$ , in milliradians, provided you know the proper scaling factor. In this case, the scale factor for converting a measurement in millimeters into an angular size in milliradians is 0.037 mrad/mm.

Example: Suppose we measure the photographic size of the galaxy to be 14 mm. To convert this measurement into an angular size, simply multiply by the scale factor:

$$A = 14 \text{ mm} * 0.037 \text{ mrad}/1 \text{ mm} = 0.52 \text{ mrad}$$

For this lab, we are going to assume that the standard linear size for a galaxy is **22 kpc** (or about 70,000 light years, which is small compared to the Milky Way, but we know that the Milky Way is unusually large compared to most galaxies).

### Step 1

There are 19 different galaxy data sheets in your lab manual after the text of this lab. Each data sheet has the name of the galaxy, a photograph of the galaxy and a partial spectrum of the galaxy, showing the intrinsic and observed wavelengths of two different absorption lines (the Calcium "H" and "K" lines). **For 12 different galaxies**, fill in the data table (which is a few pages ahead of this text) as follows:

- (1) - Fill in the galaxy catalog number
- (2) - Measure the size of the galaxy on paper in millimeters with two significant figures. If the galaxy is not circular in shape, measure the longest axis.
- (3) - Use the scale factor (0.037 mrad/mm) as above to convert the measured size to an angular size.
- (4) - Assuming the linear size of the galaxy is 22 kpc, use the standard ruler equation above ( $d = s/A$ ) to calculate the distance to the galaxy in Mpc. Write down this distance with two SF.
- (5) - Measure the location of the center of the Ca-K absorption line (the left of the pair) to the nearest Angstrom.
- (6) - Subtract the true value (3933 Angstroms) of the Ca-K wavelength from the measured value of the Ca-K wavelength (should get a positive number). This is the "Ca-K shift".

- (7) - Measure the location of the center of the Ca-H absorption line (the right of the pair) to the nearest Angstrom.
- (8) - Subtract the true value (3969 Angstroms) of the Ca-H wavelength from the measured value of the Ca-H wavelength (should get a positive number). This is the "Ca-H shift".
- (9) - Average your values from column (6) and column (8) to get the average measured redshift.
- (10) - Using the wavelength of the Ca-K line as your "rest" wavelength (3933 Angstroms), use the equation on page 1 to calculate the velocity of this galaxy. Write down this velocity with two SF.

One of the galaxies (NGC 3147) has already had its properties calculated for you. Double-check the entries in the table yourself so that you know how to fill out the rest of the table for other galaxies with confidence! In making your measurements, you were bound to come across some uncertainties. For example, suppose that you conclude the photographic size of a particular galaxy is 10 mm, but your neighbor decides to measure further out into the faint fringes and measures an angular size of 20 mm.

**Q1.** Will your estimated distance to that galaxy be larger or smaller? Explain your answer below.

### **Step 2**

On the graph paper provided, plot your values for distance (Mpc) and velocity (km/sec). Draw a straight line that passes through the origin and best fits the general slope of the points on the graph. Use a ruler to ensure the line is straight. Before committing to drawing your line, move your ruler around to gauge for yourself what is the best fit to these data points.

Measure the slope of your line, (rise / run) or (change in  $v$  / change in  $d$ ). This is the Hubble constant,  $H$ .

**Q2.** What is the slope of your line? \_\_\_\_\_ km/sec/Mpc

### **Step 3**

It turns out that the Hubble constant is a measure of the age of the Universe. To determine roughly what the age of the Universe is from your Hubble constant, perform the following calculation. We'll discuss this calculation much more during lecture.

Age (in billions of years) =  $700/H$ . (use two SF)

**Q3.** Estimated age of Universe: \_\_\_\_\_ billion years old.

### **Step 4**

Suppose you systematically underestimated the photographic sizes of the galaxies, as discussed in question #2.

**Q4a.** Would your slope be larger or smaller than the "true" slope? Explain!

**Q4b.** Will your age for the Universe be smaller or larger than the "true" age of the Universe? Explain!

**Step 5**

Suppose we are wrong about the typical linear size of a galaxy. Instead of 22 kpc, it is really more like 30 kpc (closer to the size of the Milky Way). We decide to recalculate everything using this new value.

**Q5.** Will our estimated age for the Universe be larger or smaller? Explain!

### **Step 6**

Suppose new observations were reported tomorrow in which astronomers are arguing for the existence of a star with a very low mass and an observed age of 100 billion years.

**Q6.** Would this necessarily conflict with your results? Explain!

### **Essay**

No essay for this lab. Answers to steps 1-6 are sufficient analysis and interpretation.

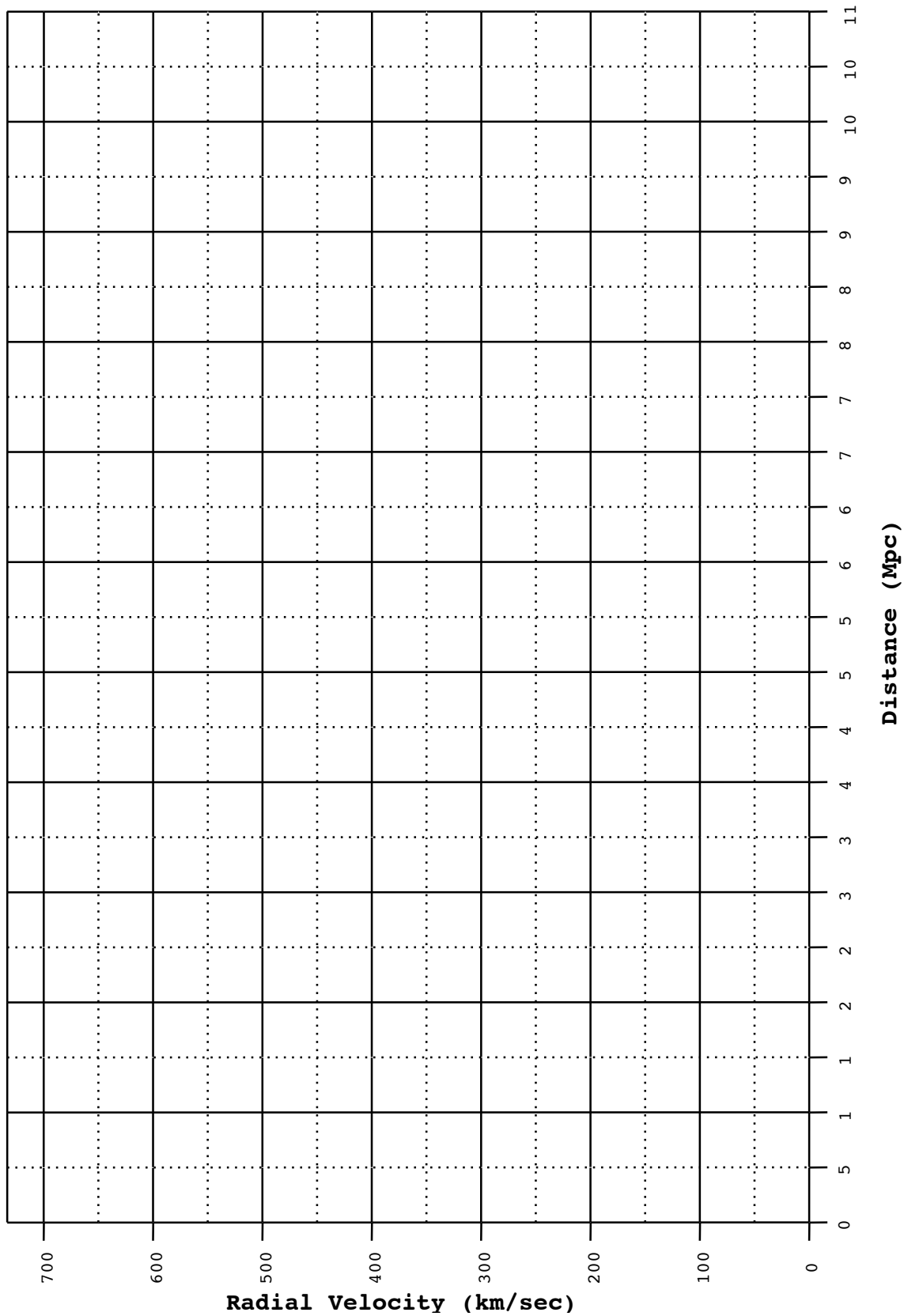
### **Credits**

The galaxy spectra for this lab were obtained from Robert C. Kennicutt, Jr. of the University of Arizona. They are published in the Astrophysical Journal Supplement Series, volume 79, pp. 255-284, 1992. The digital images of the galaxies have been extracted from the Palomar Digital Sky Survey, which can also be found on the World Wide Web at [http://stdatu.stsci.edu/cgi-bin/dss\\_form](http://stdatu.stsci.edu/cgi-bin/dss_form). We gratefully acknowledge the various copyrights for this work, information about which is available at the listed URL.



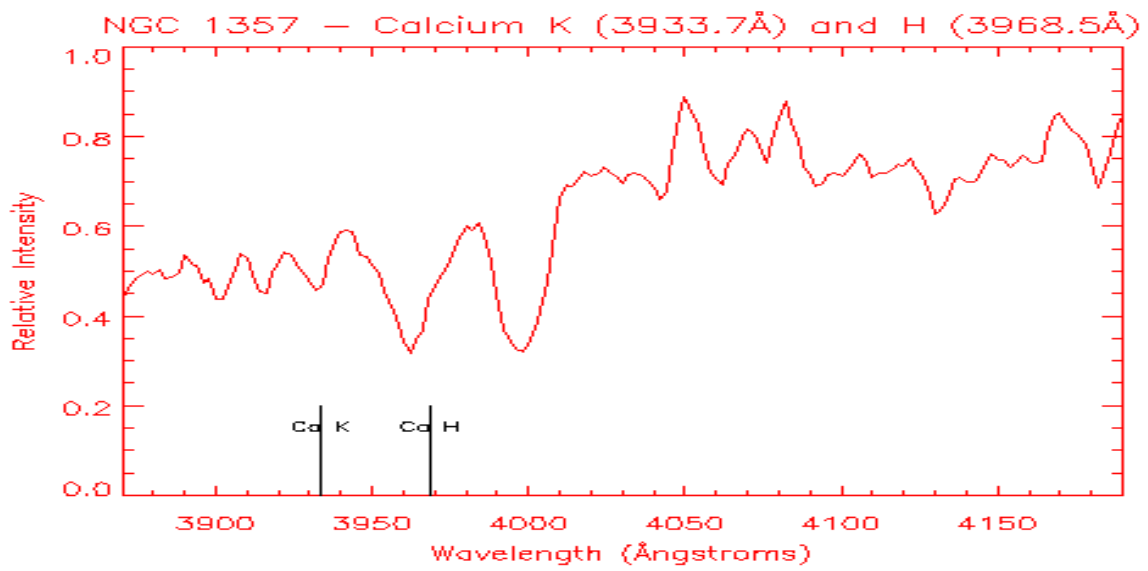
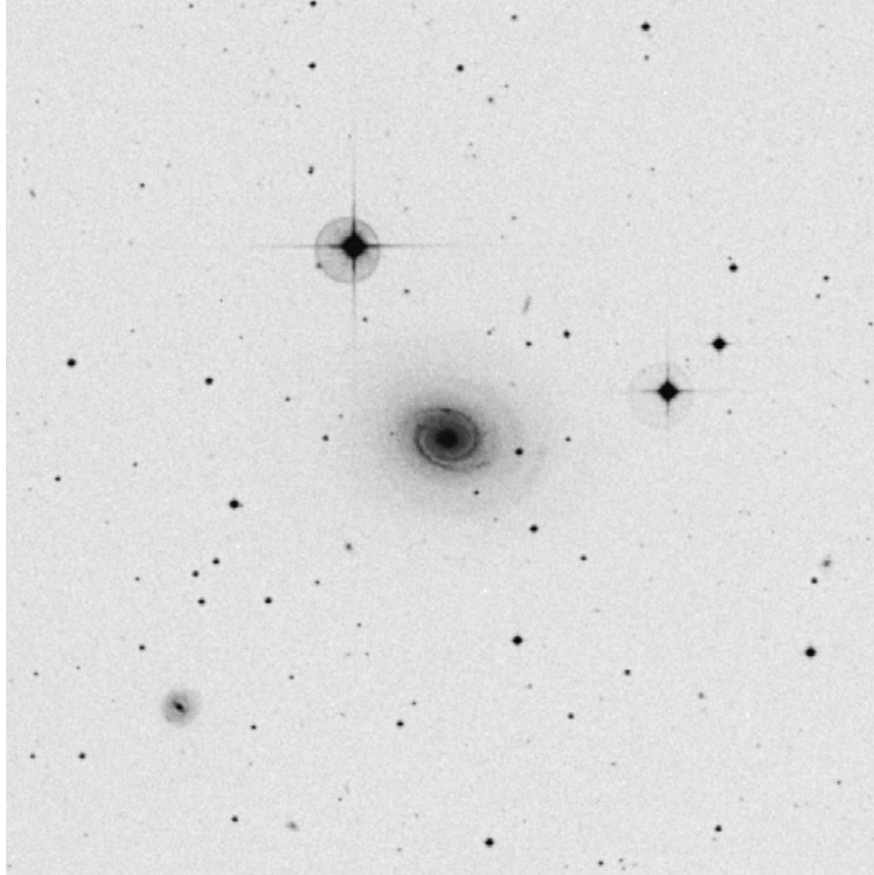


# The Hubble Relation

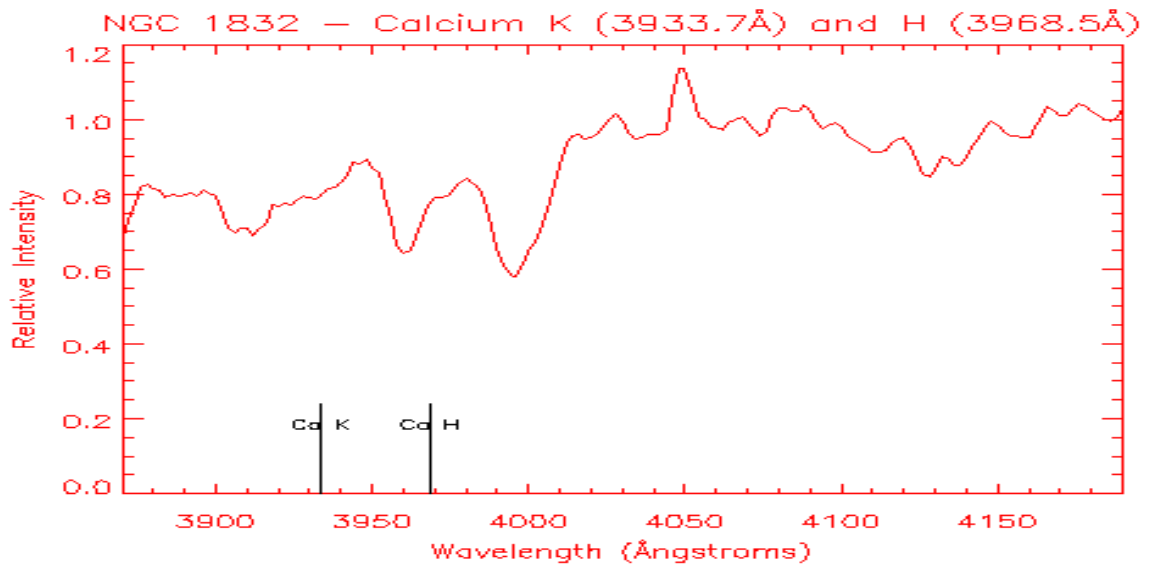
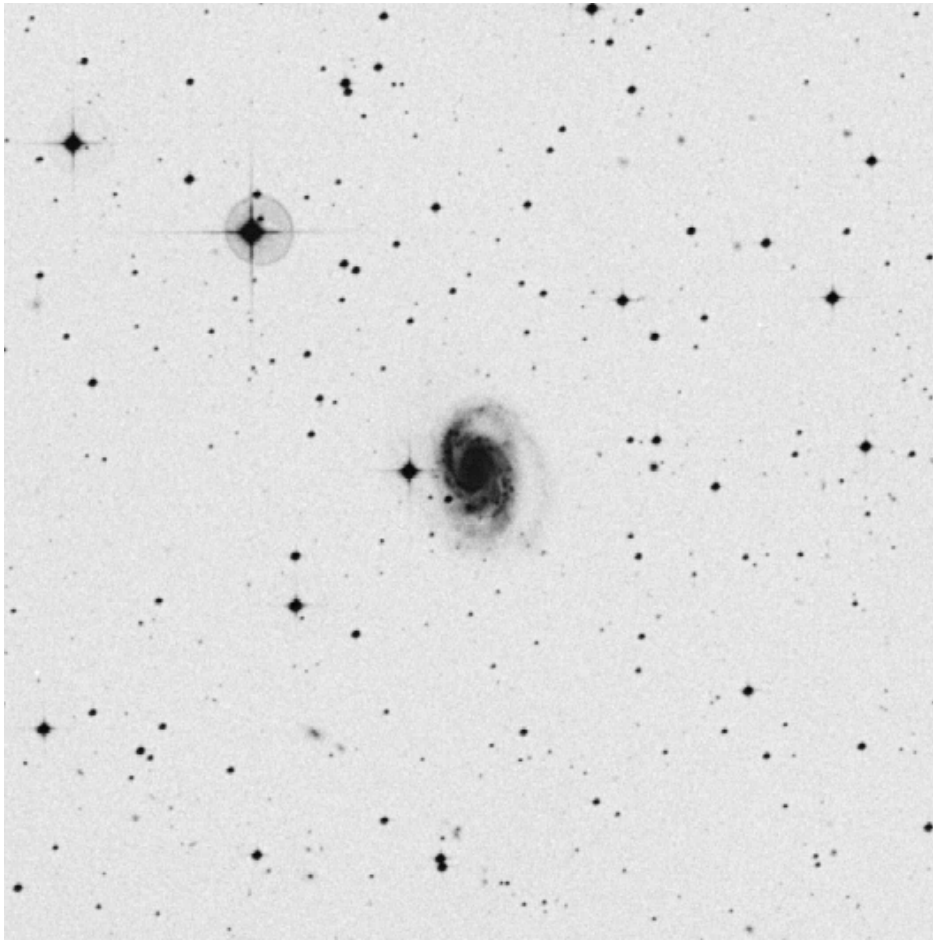


# Lab #10 Data

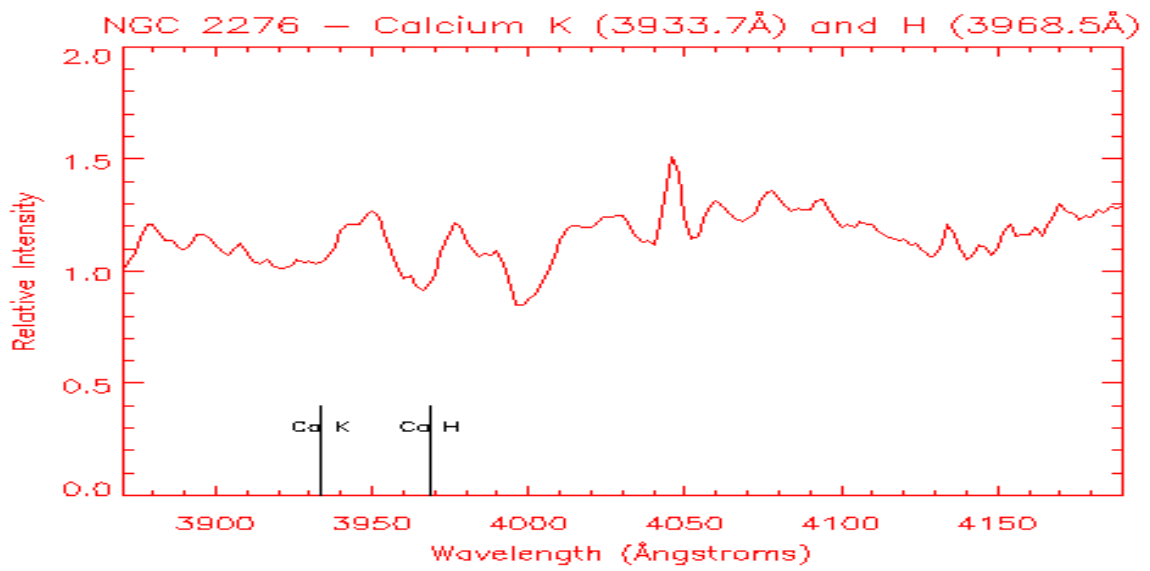
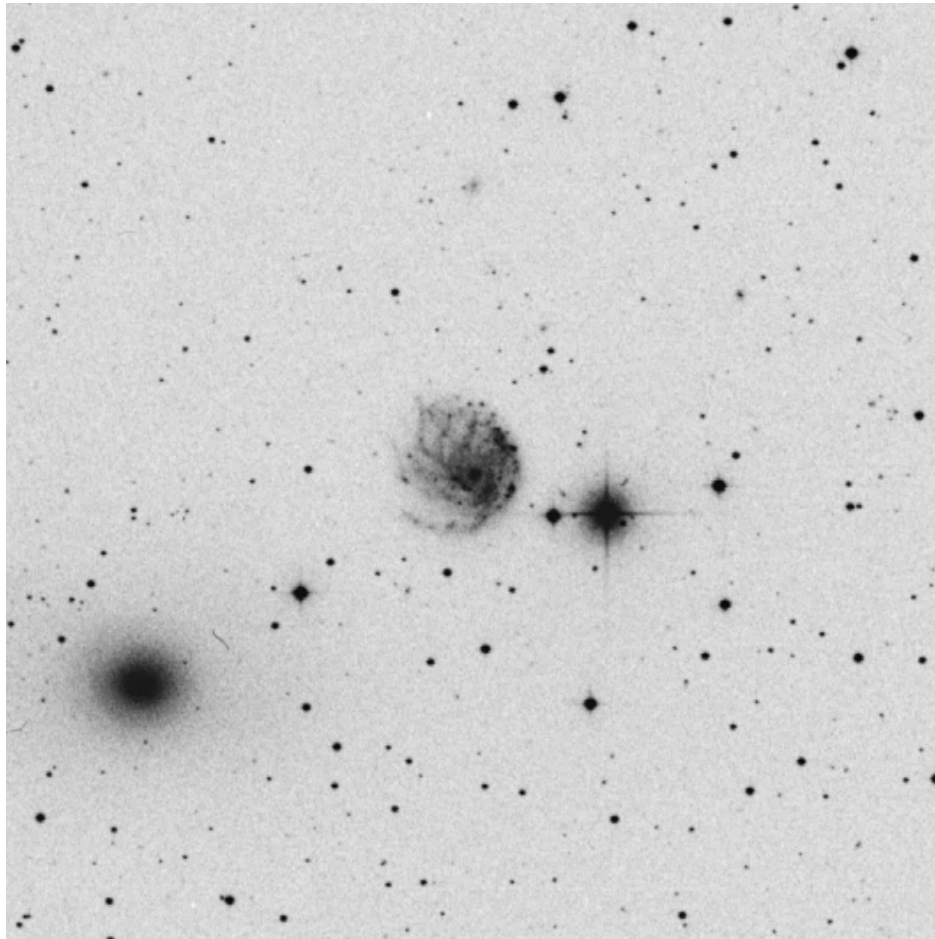
## NGC 1357



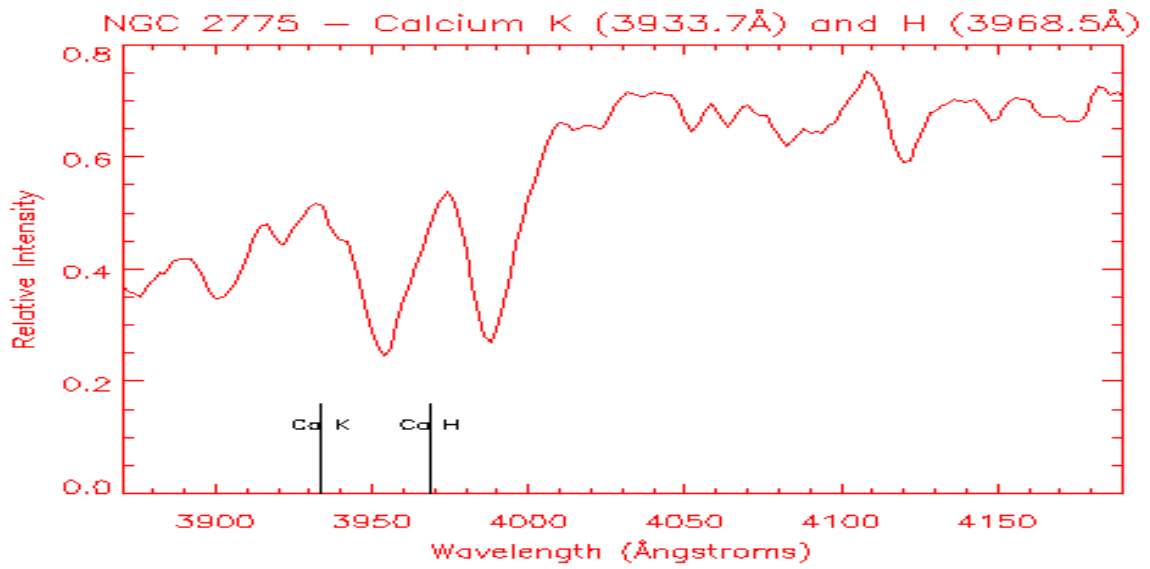
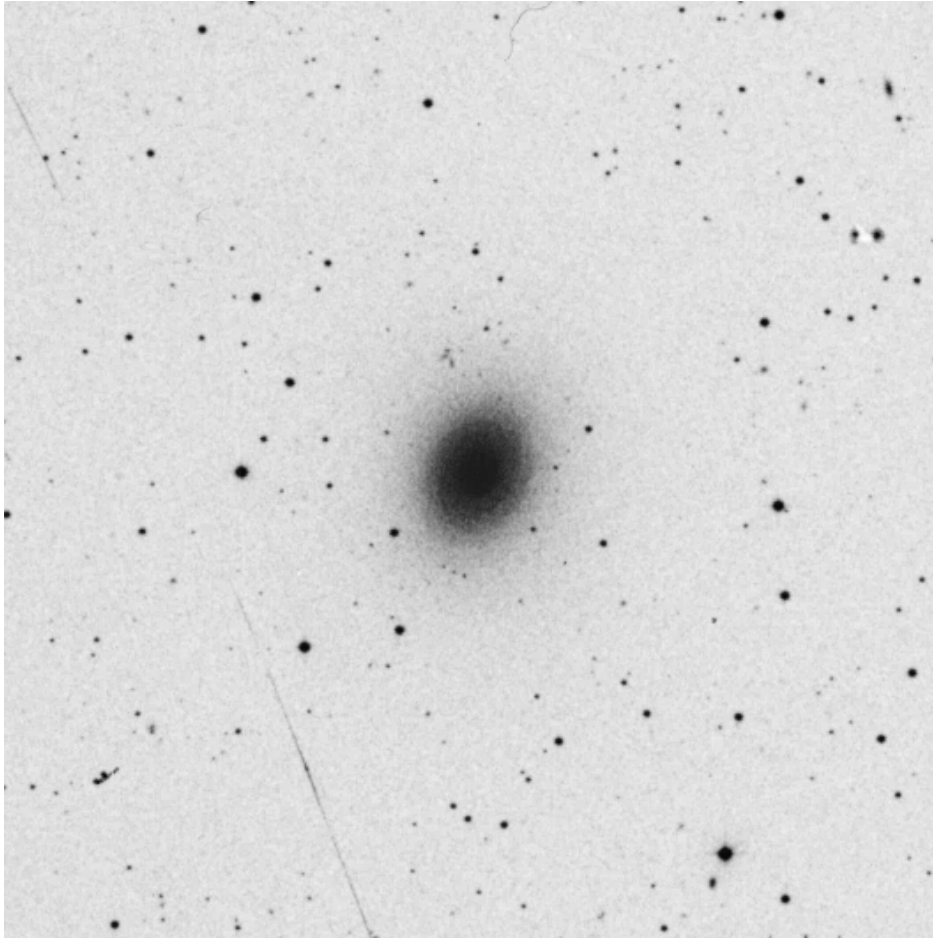
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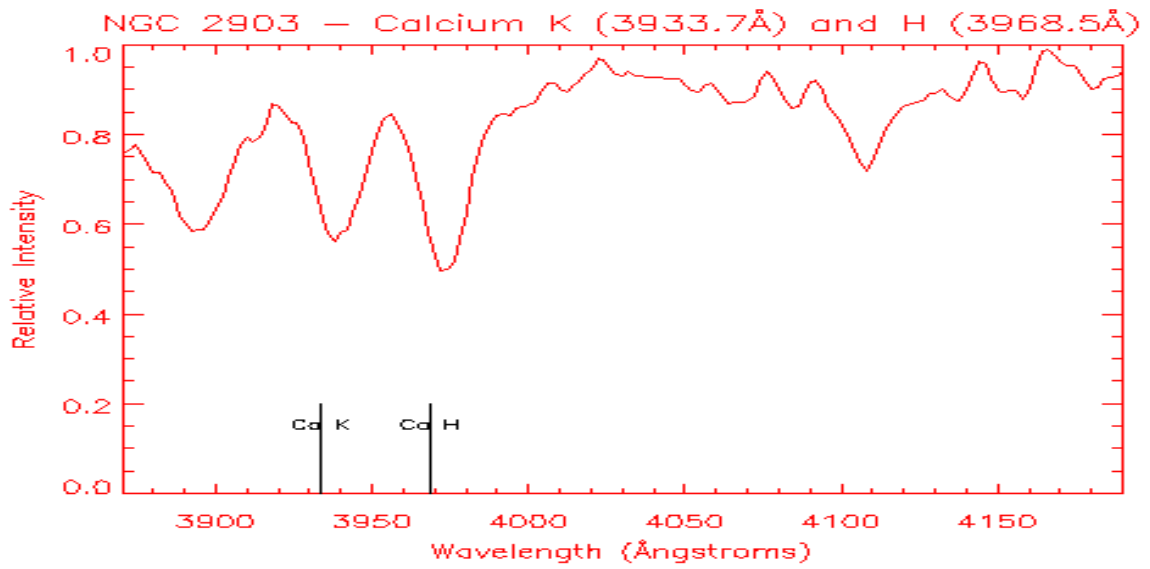
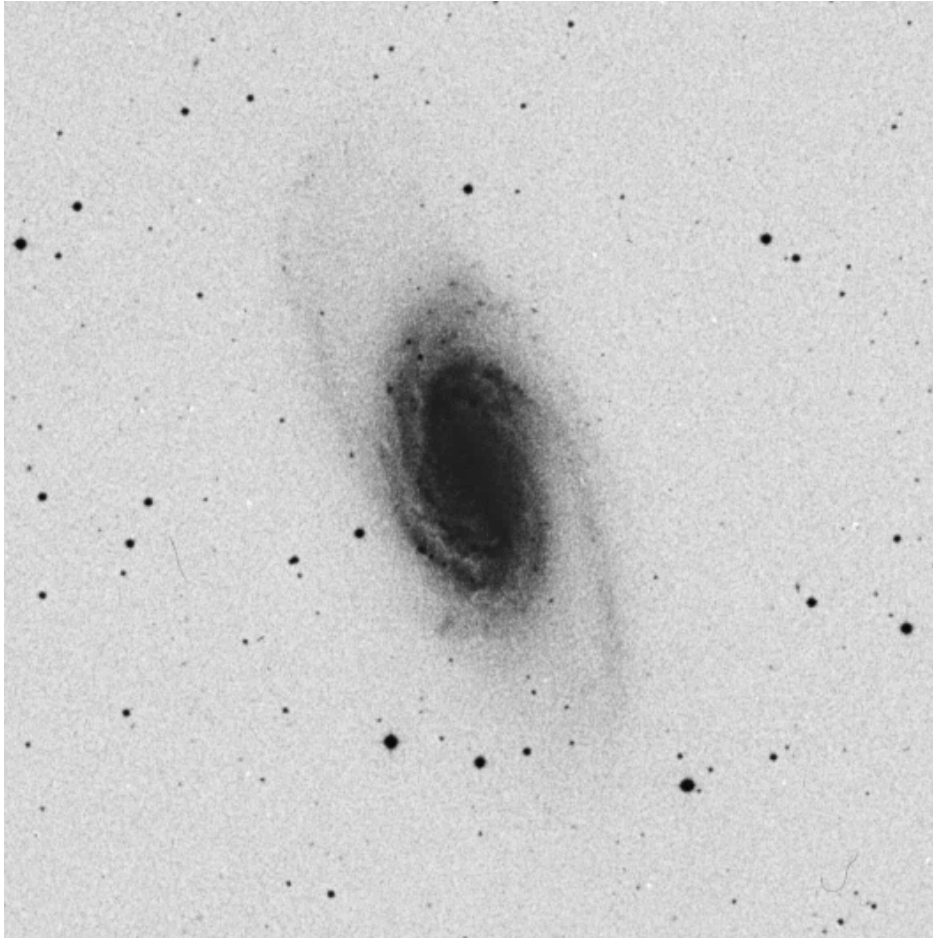
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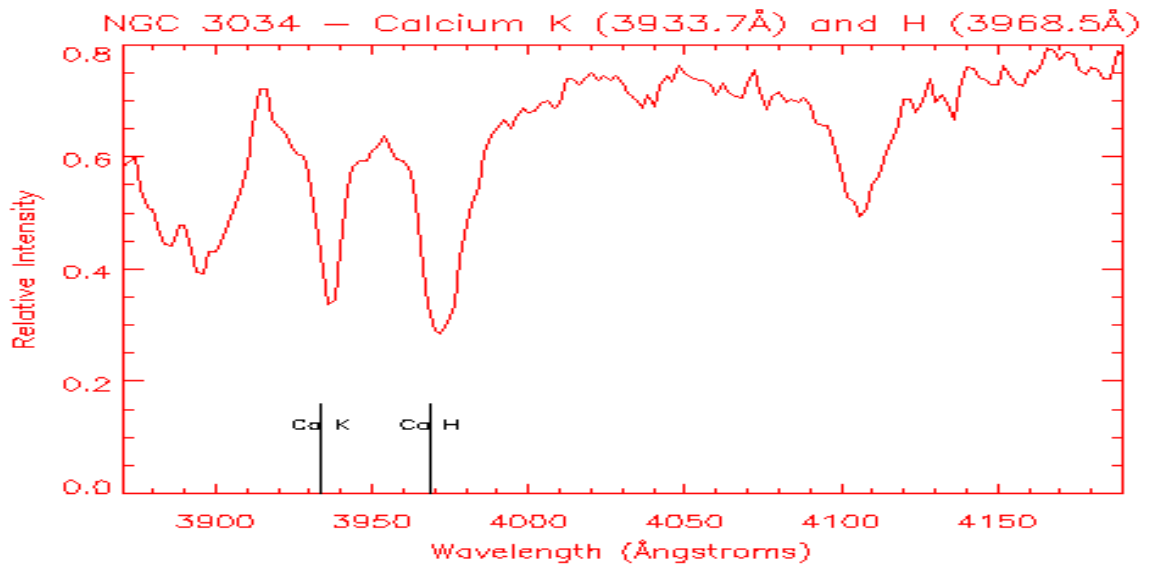
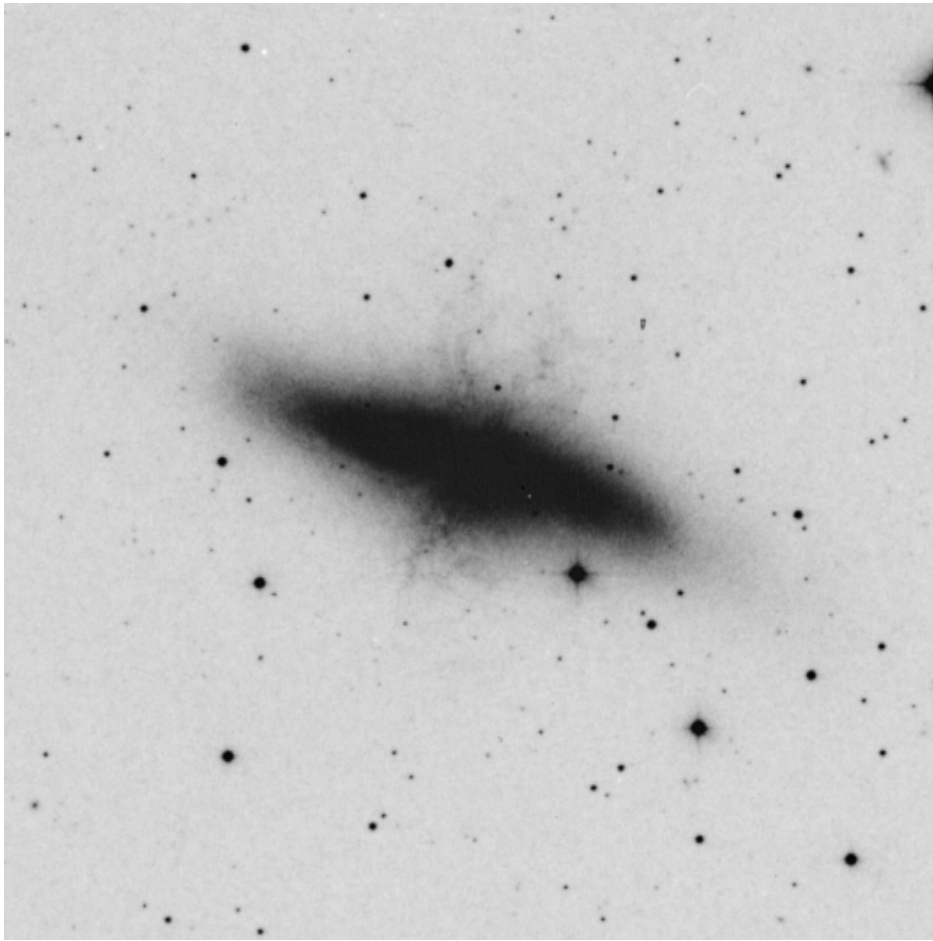
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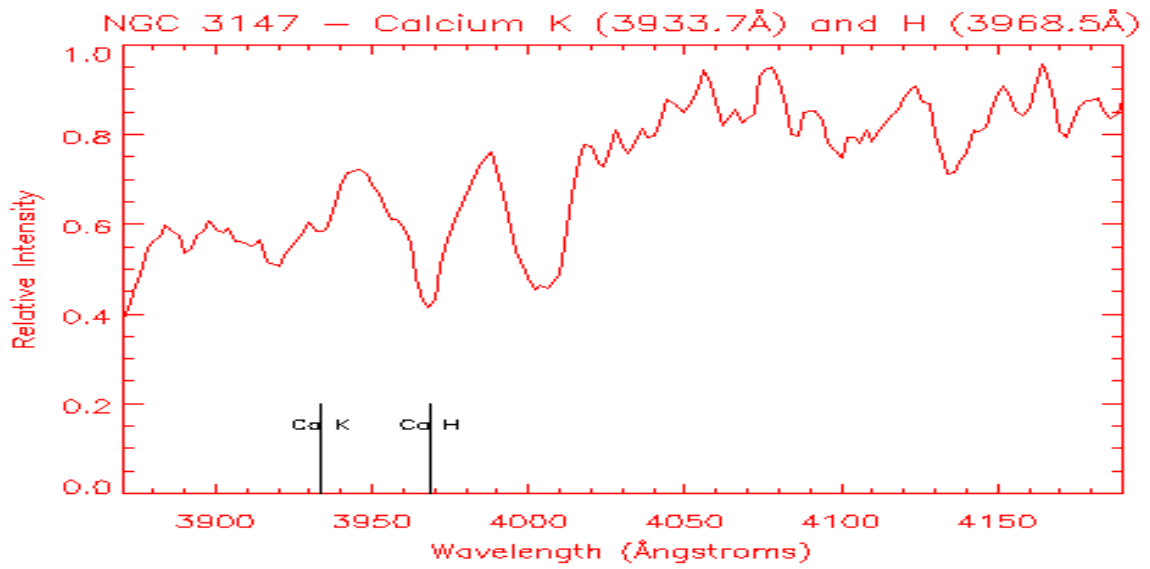
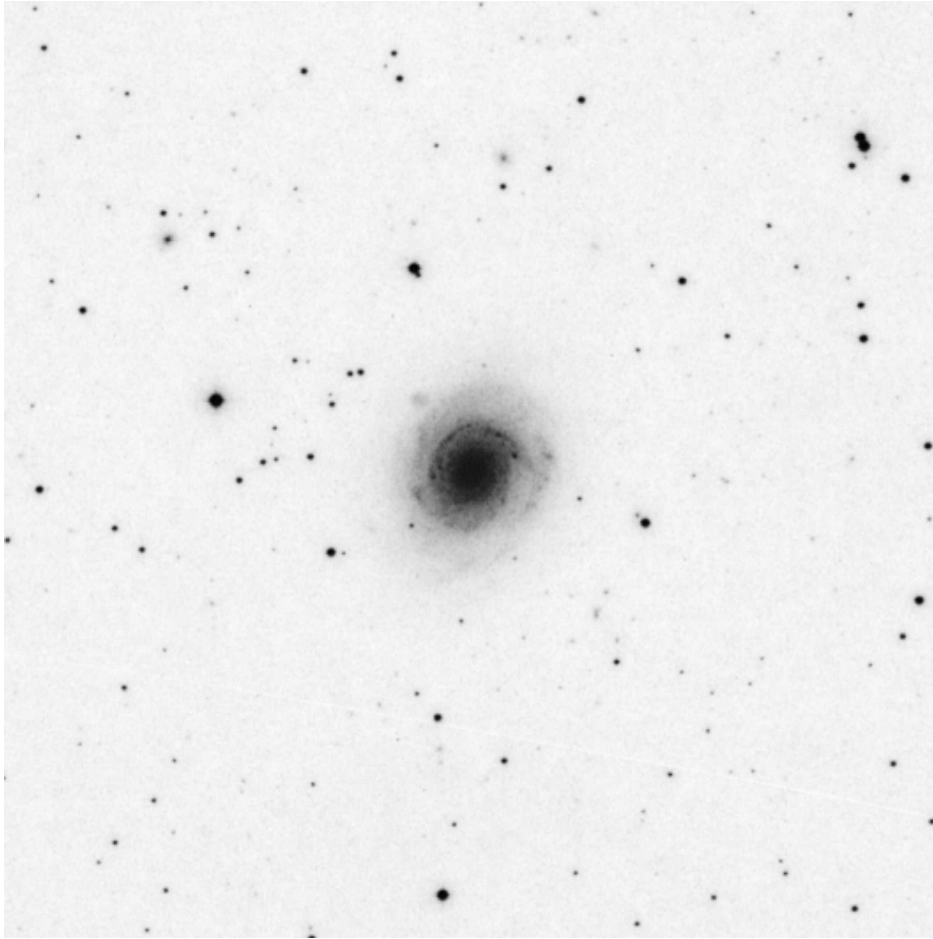
# NGC 2903



# NGC 3034

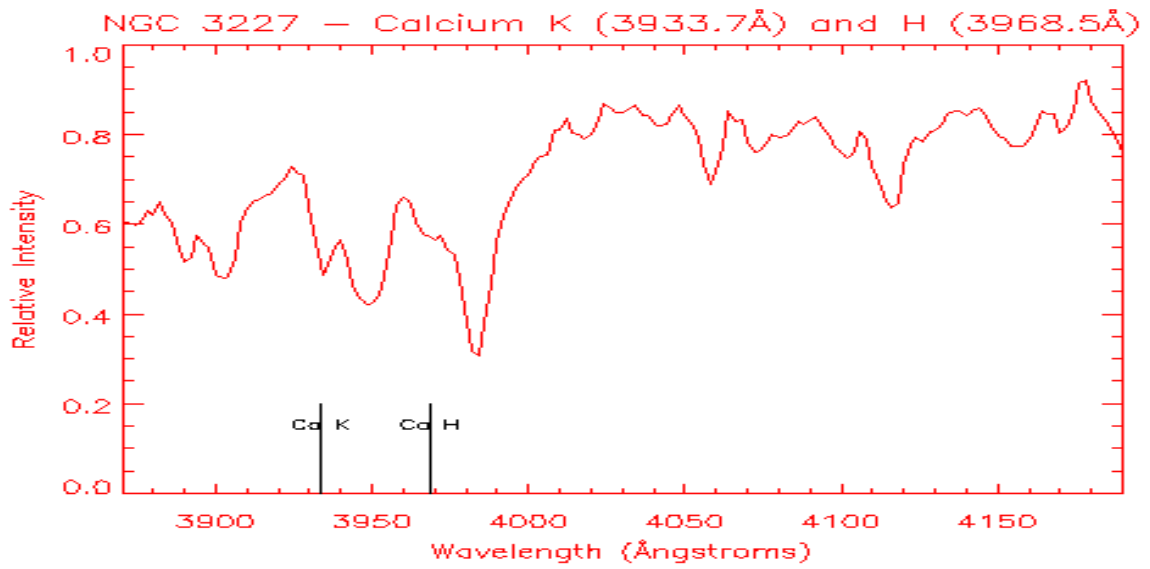
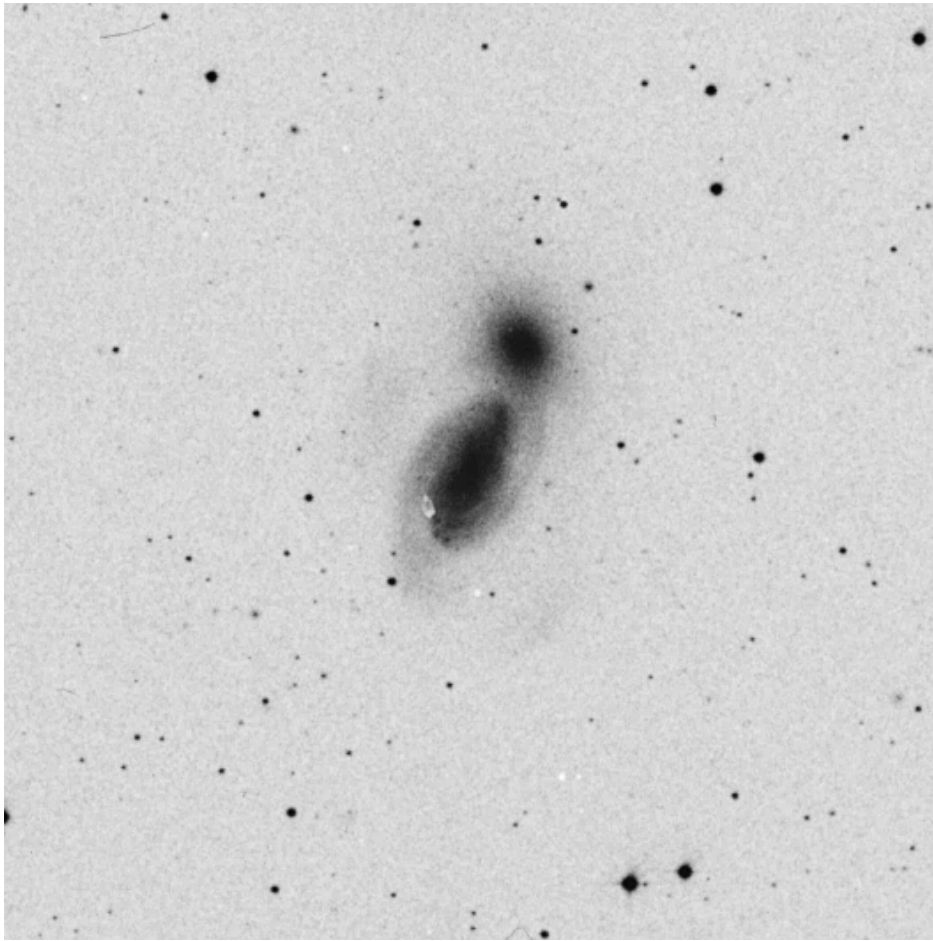


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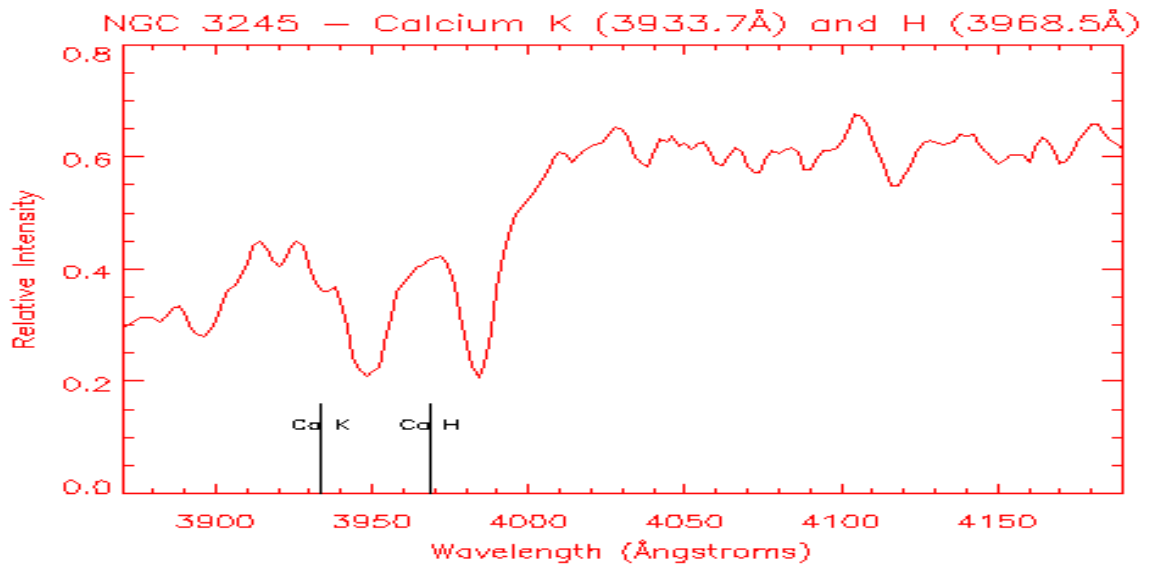
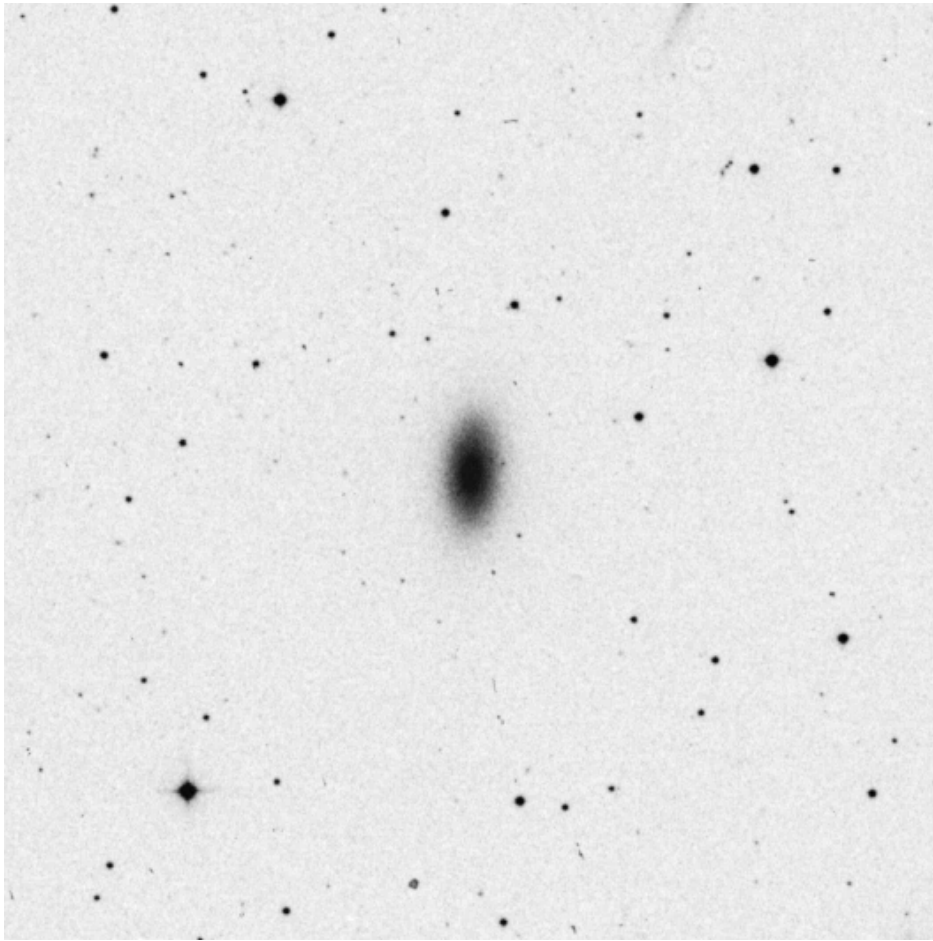




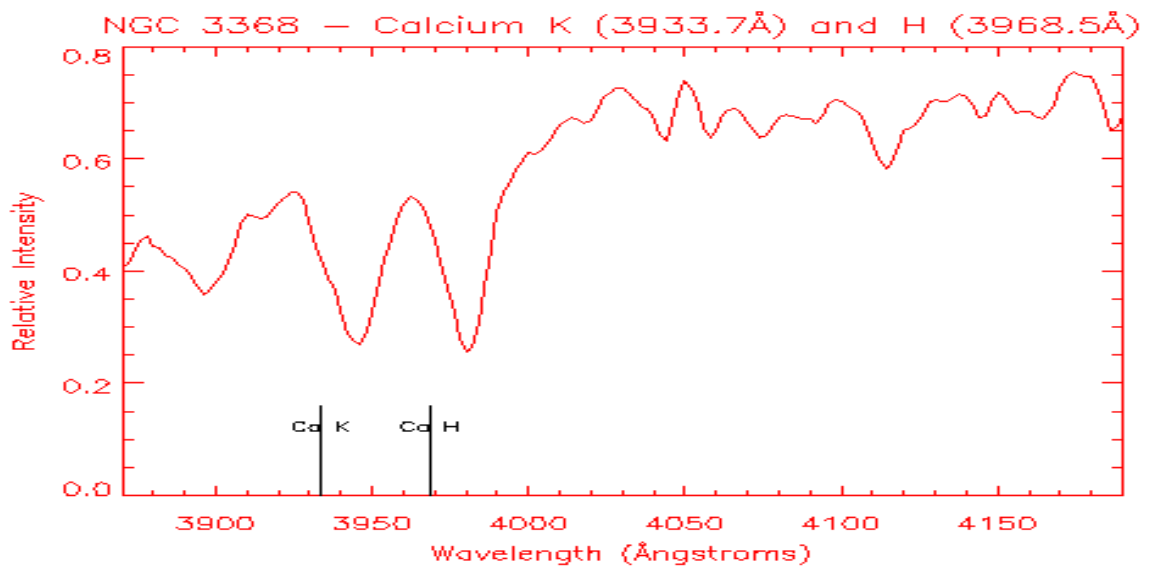
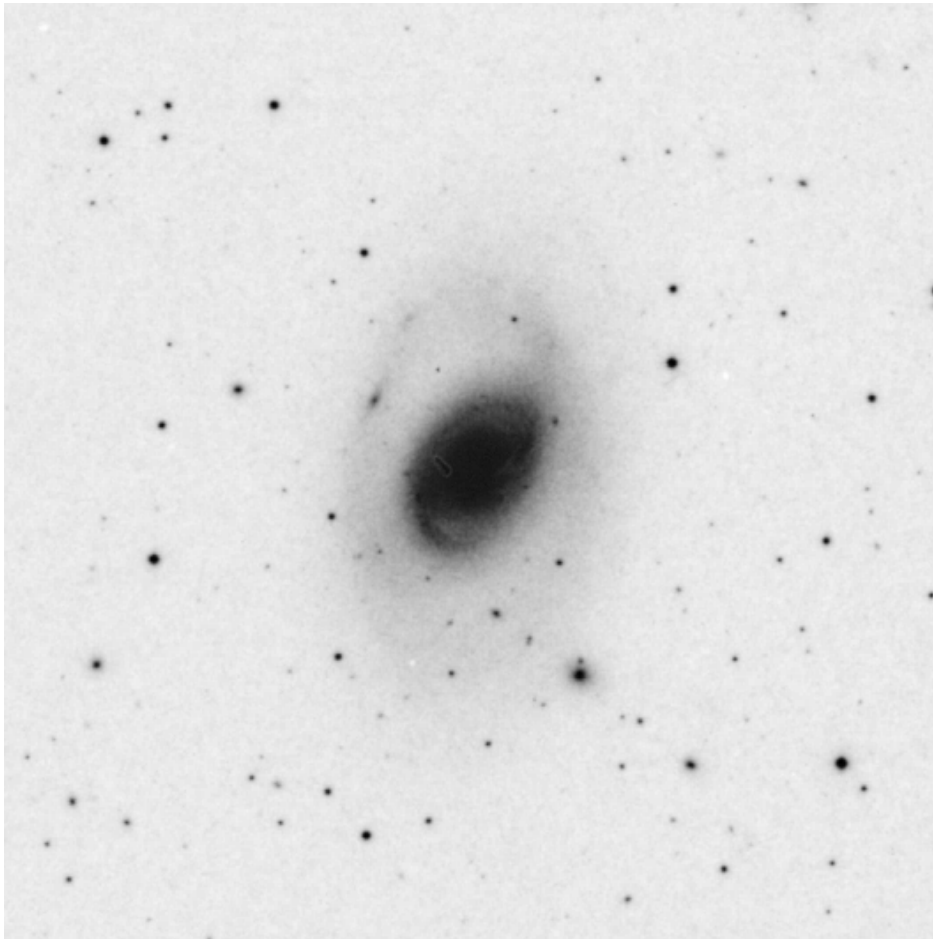
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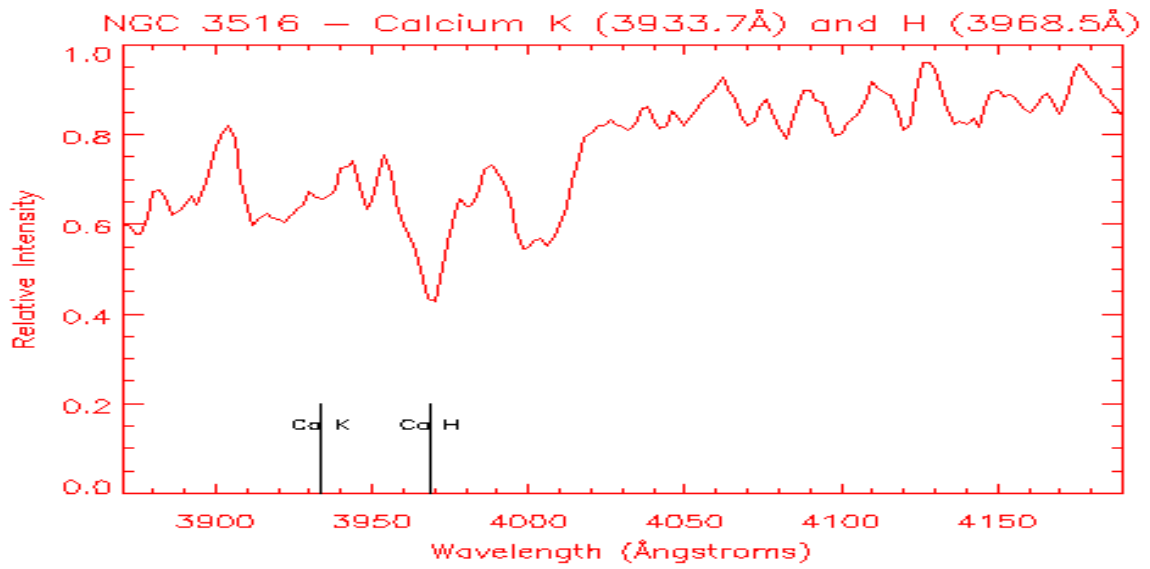
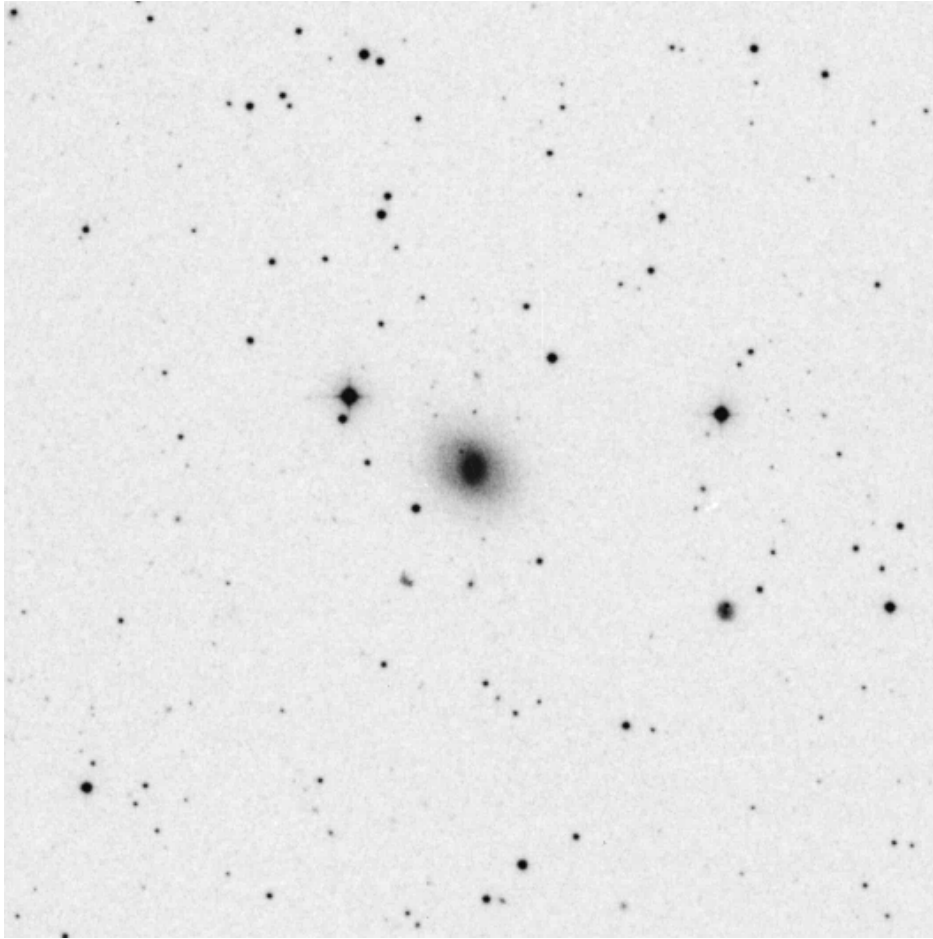
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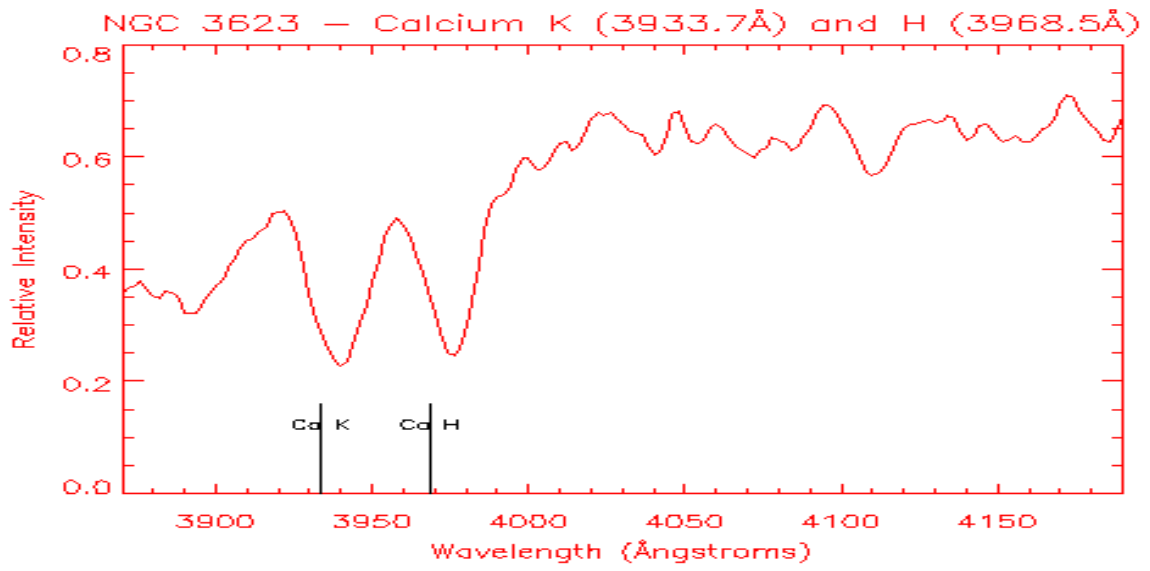
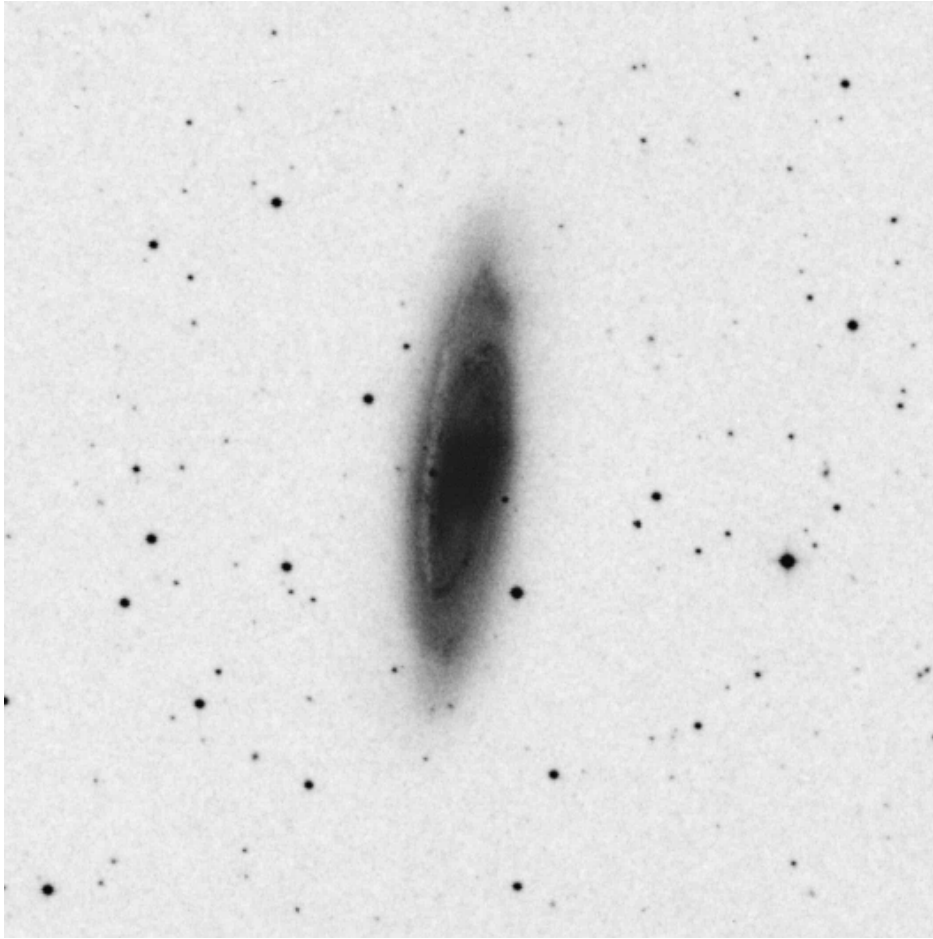
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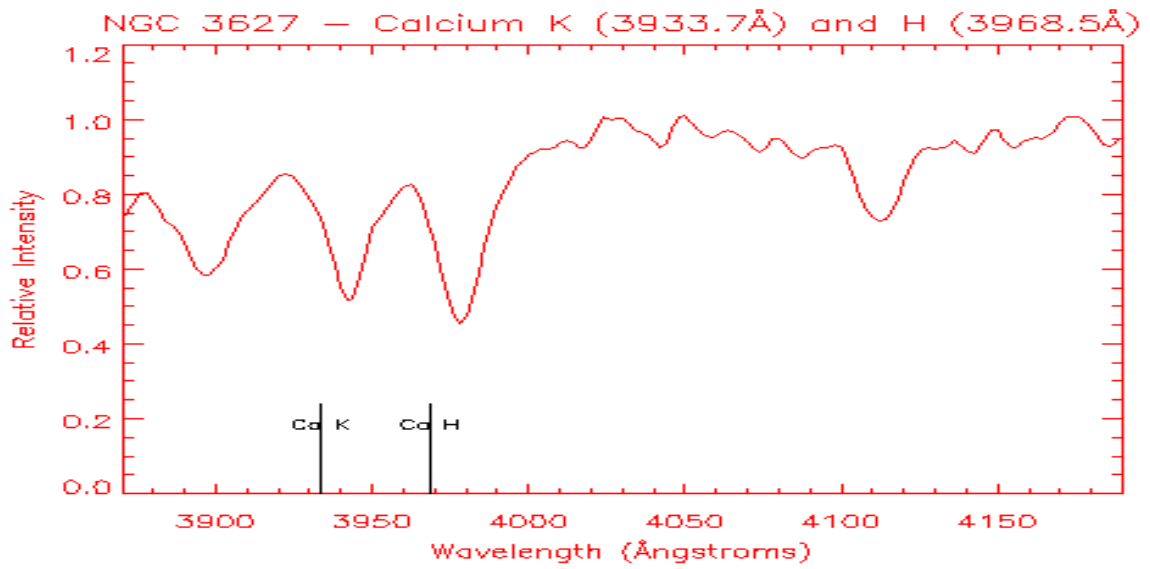
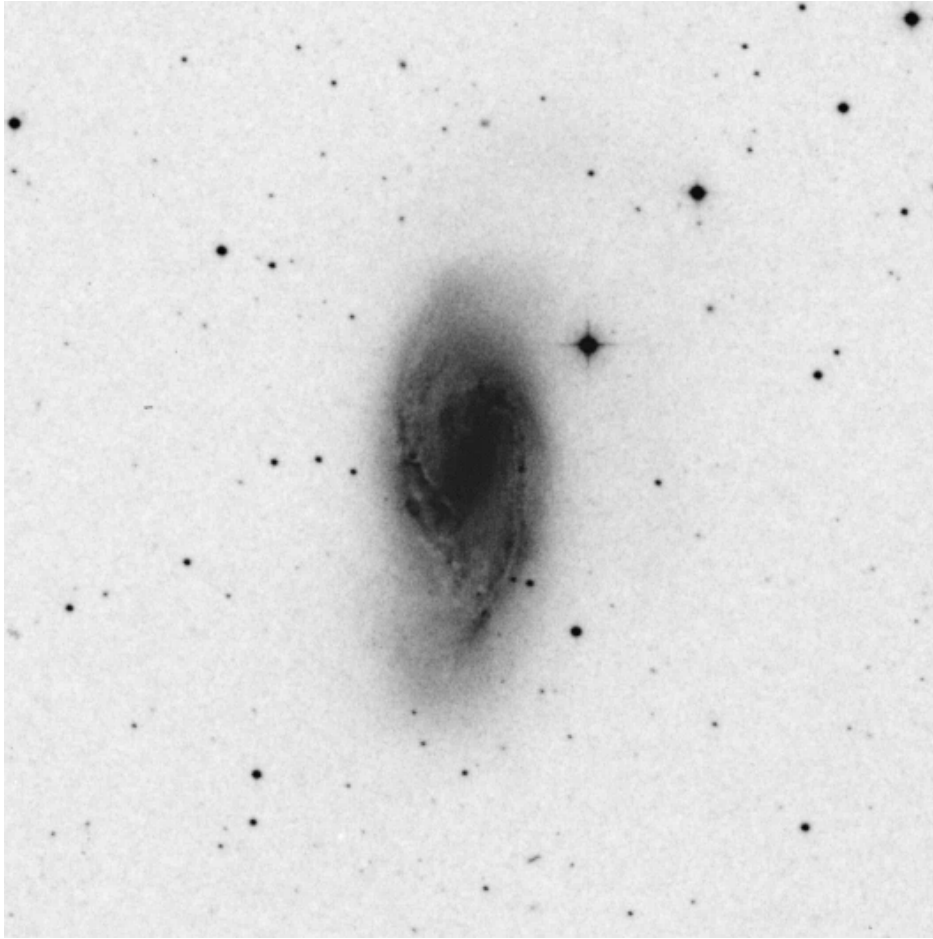
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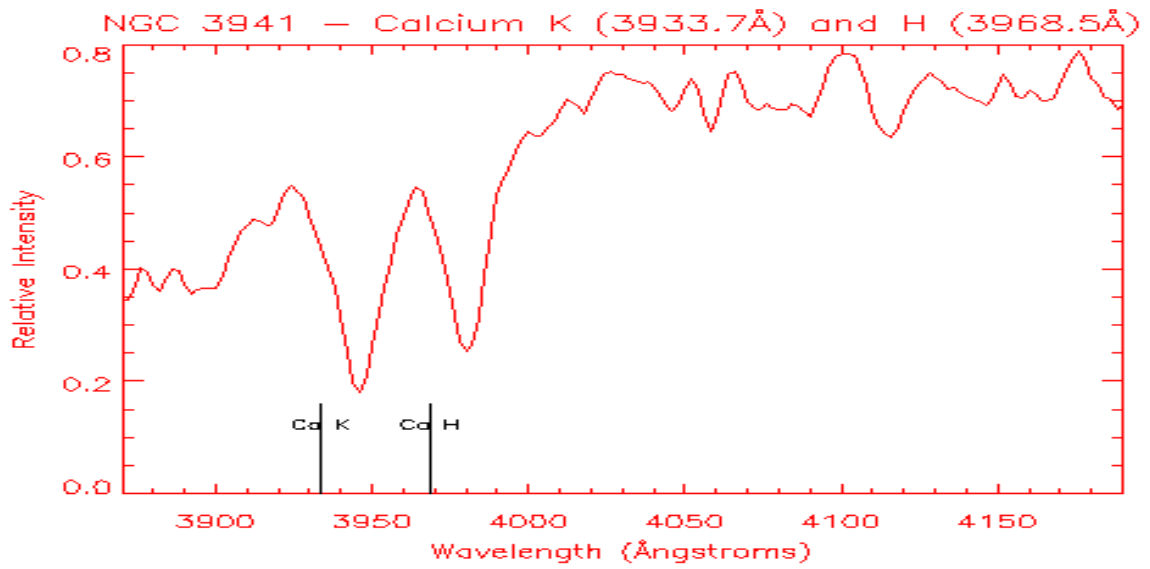
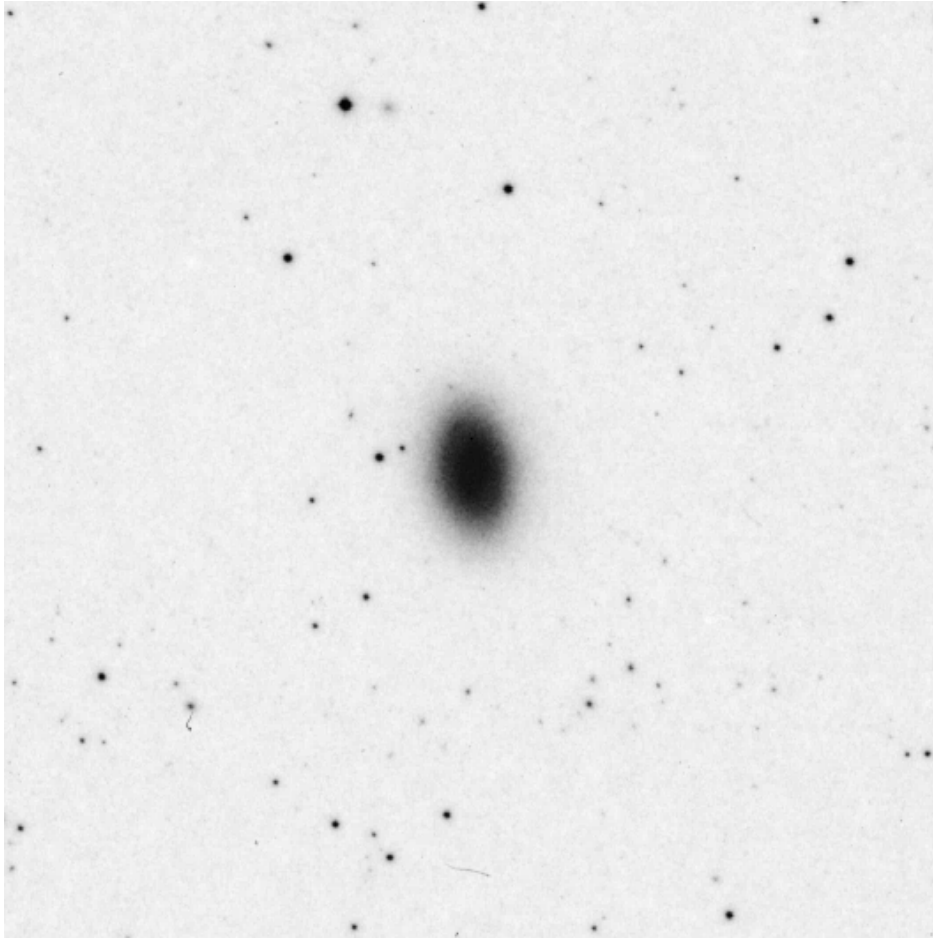
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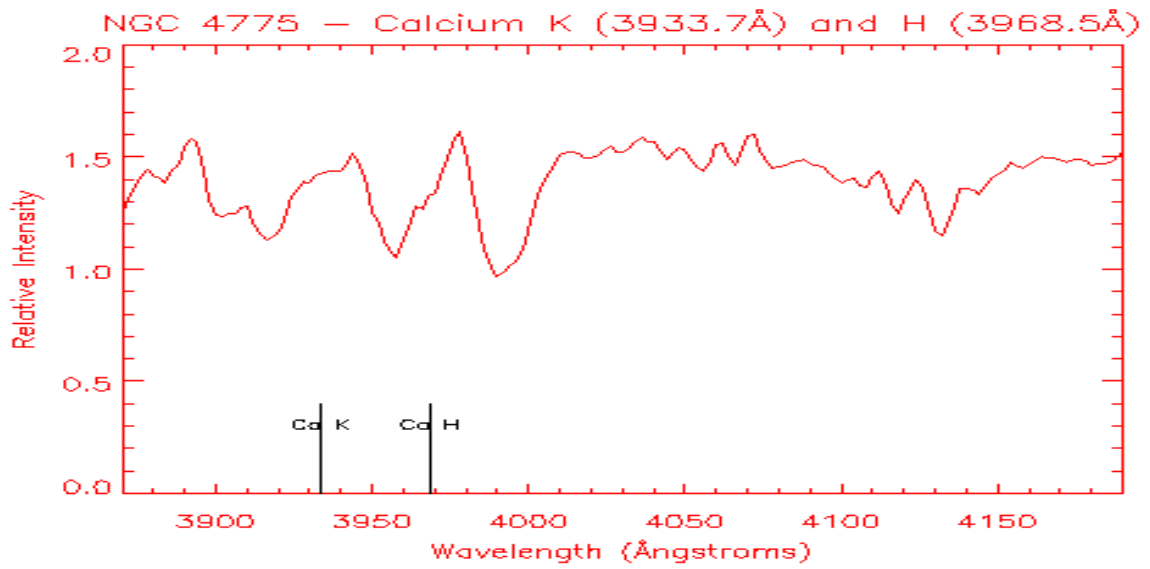
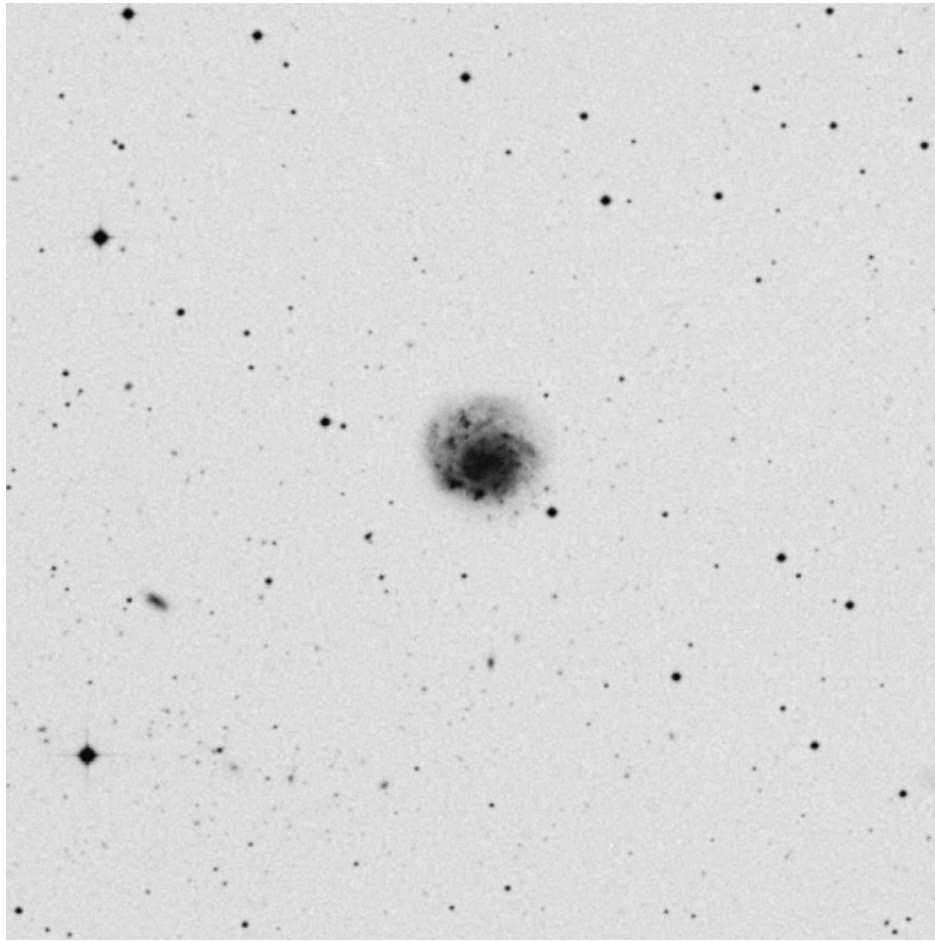
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# NGC 3941

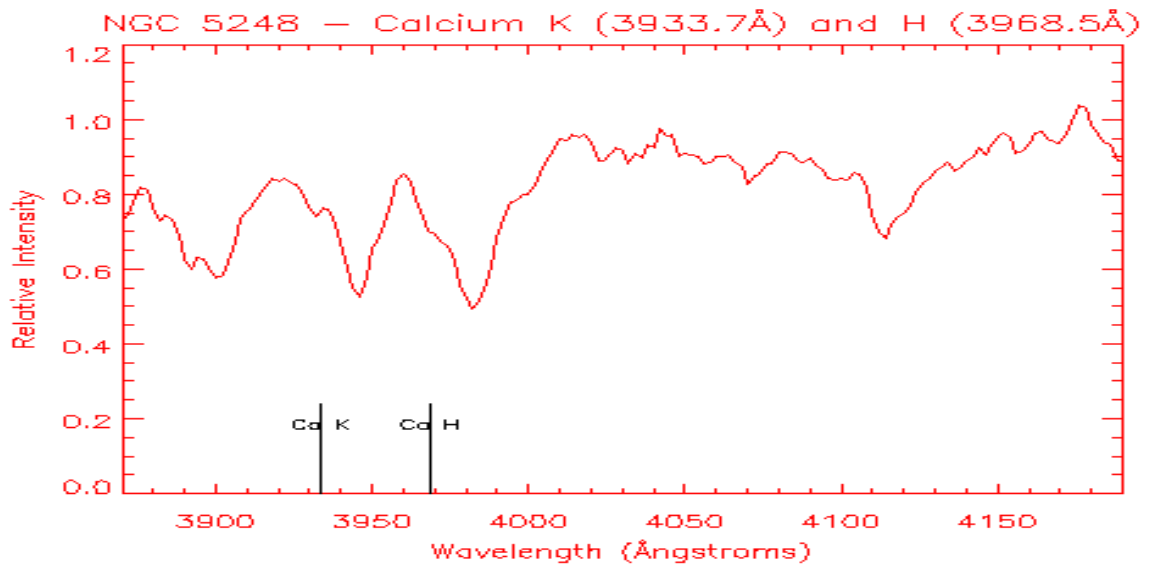
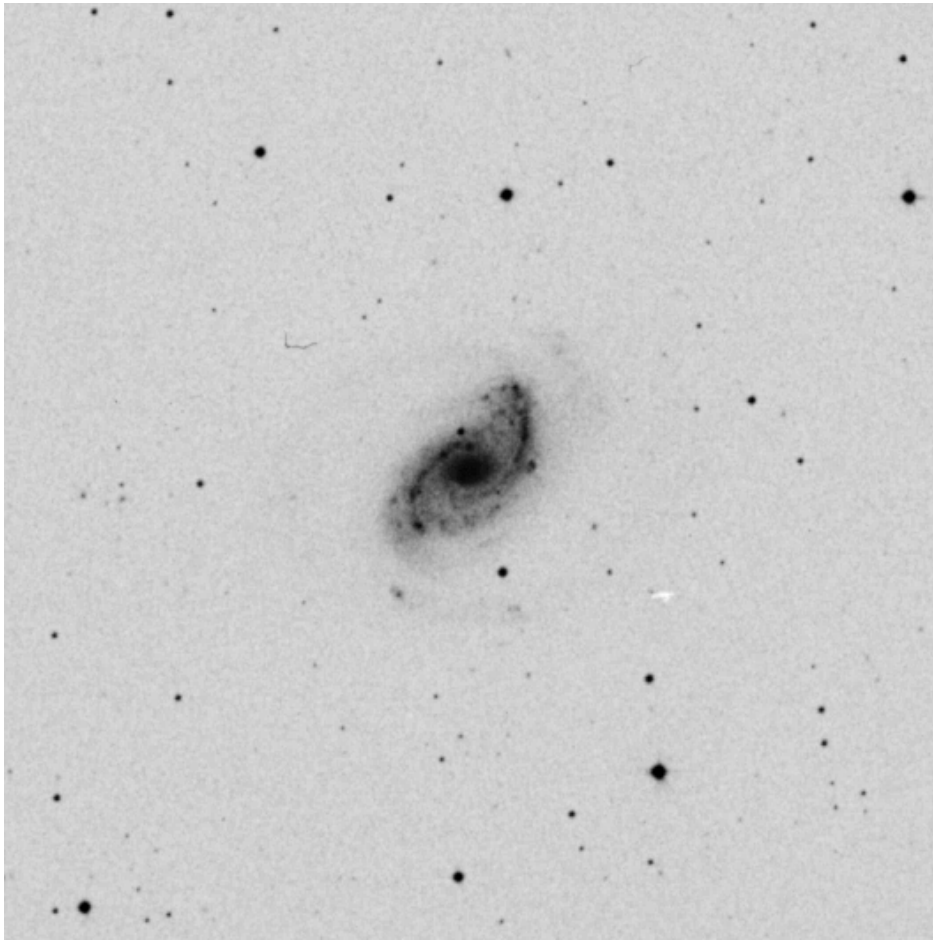


# NGC 4775

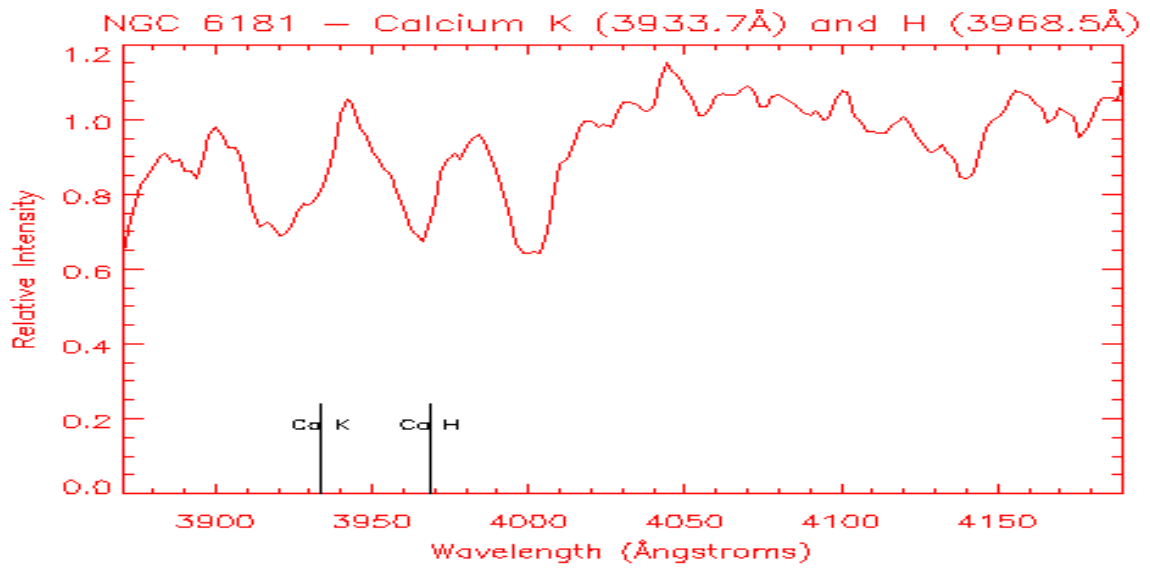
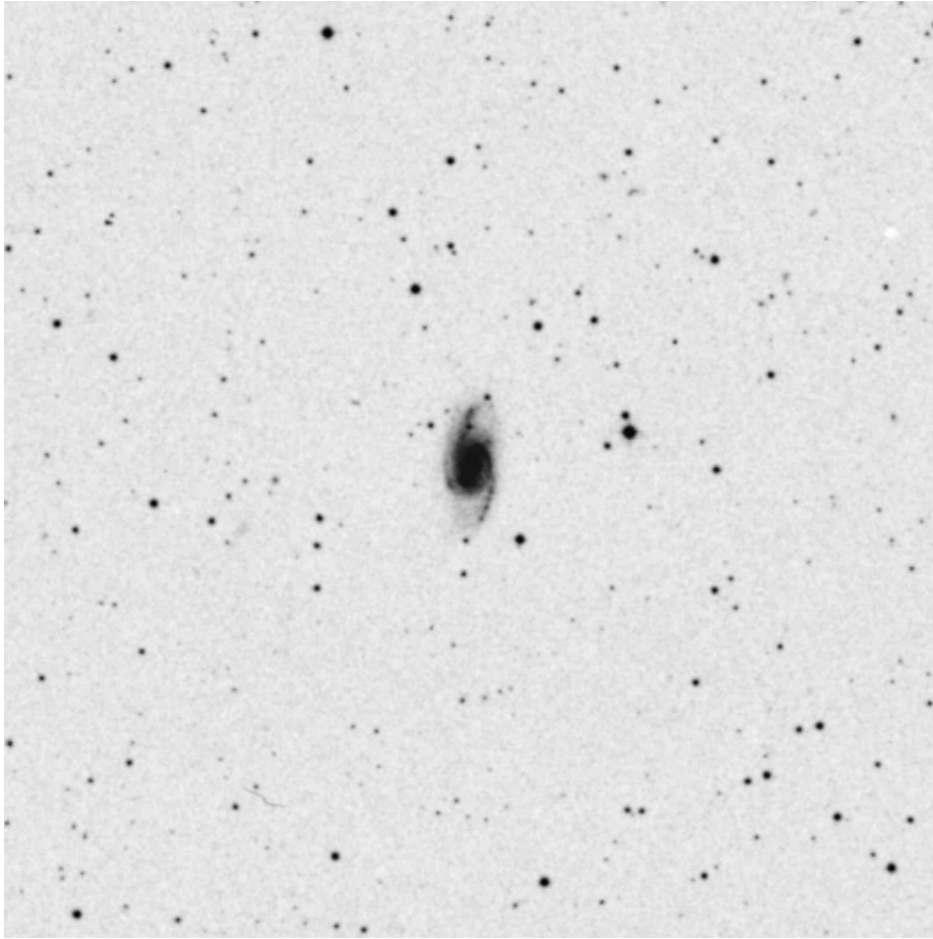




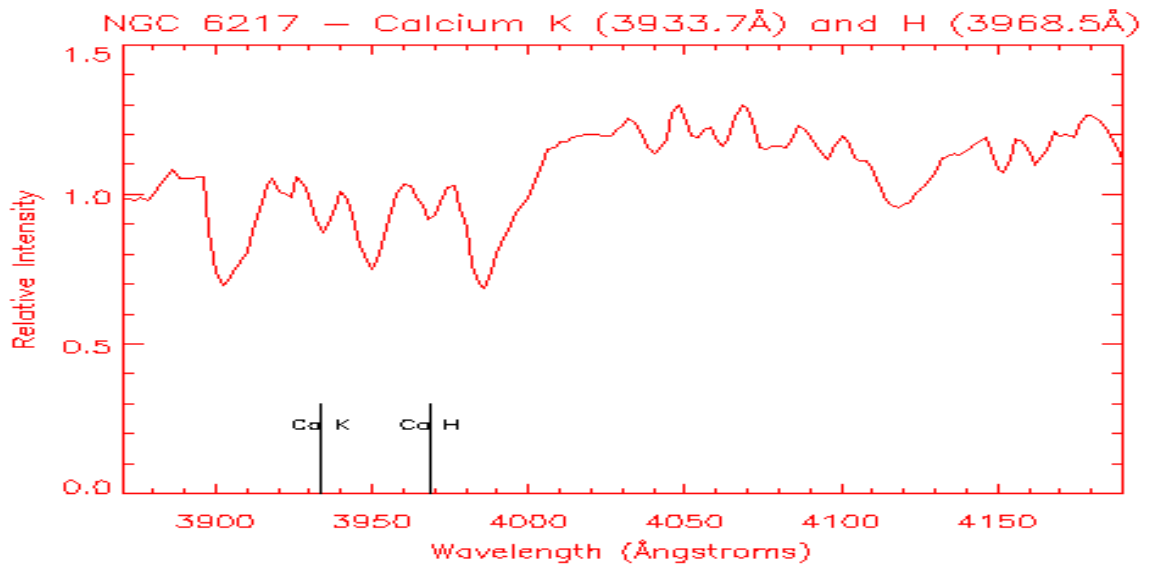
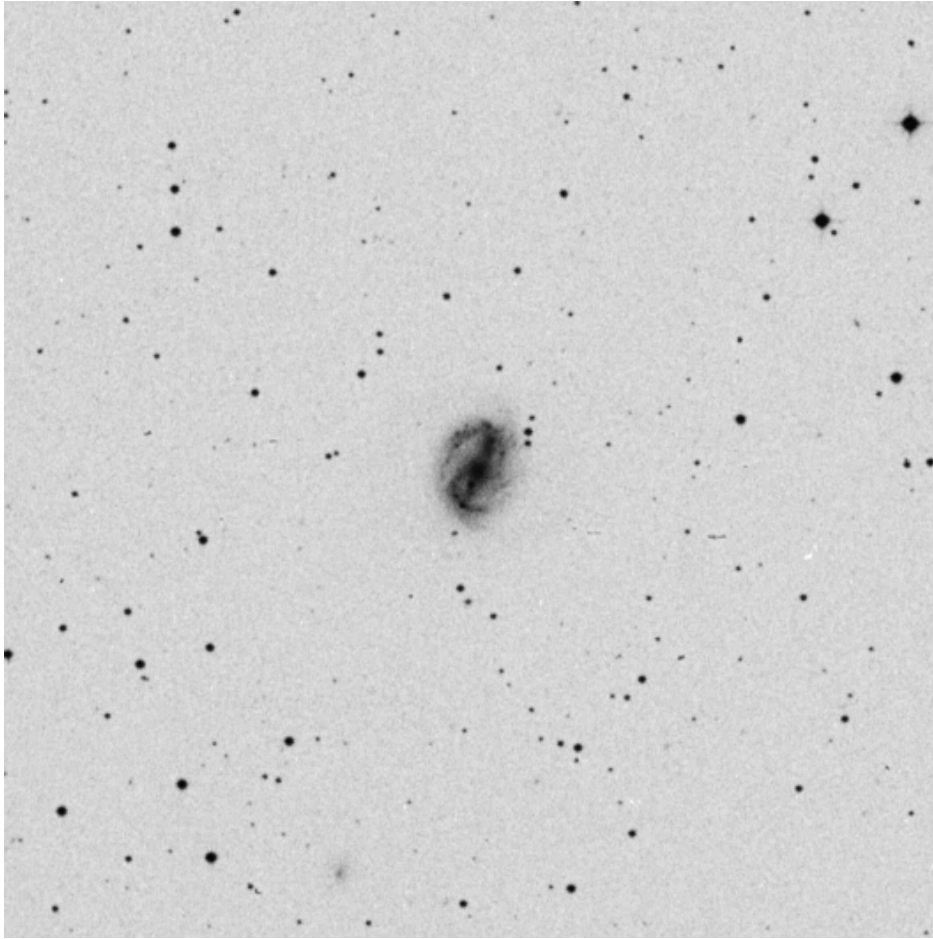
# NGC 5248



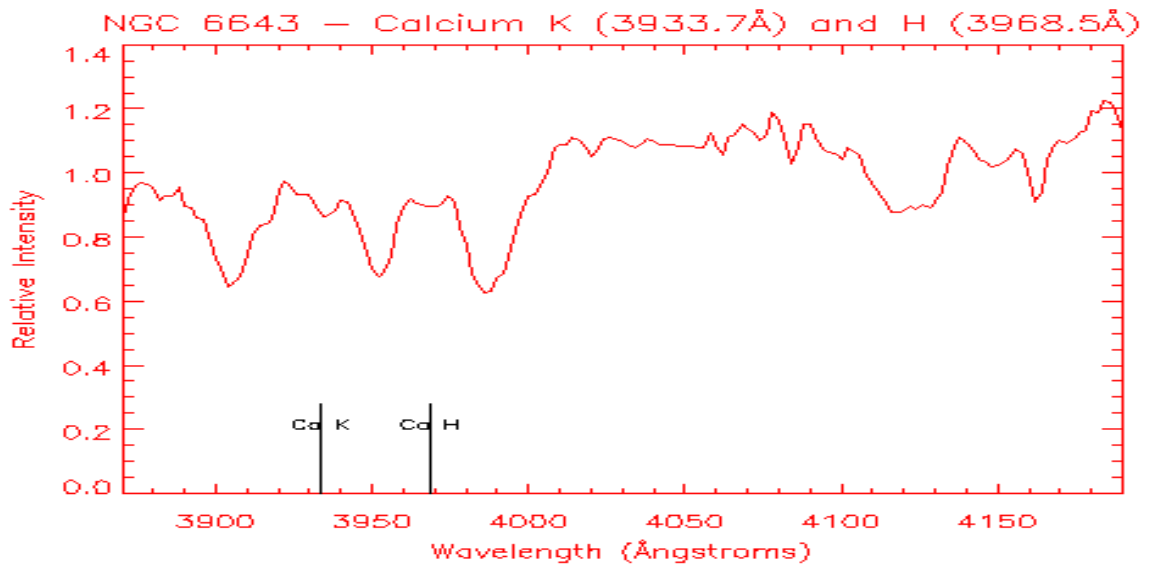
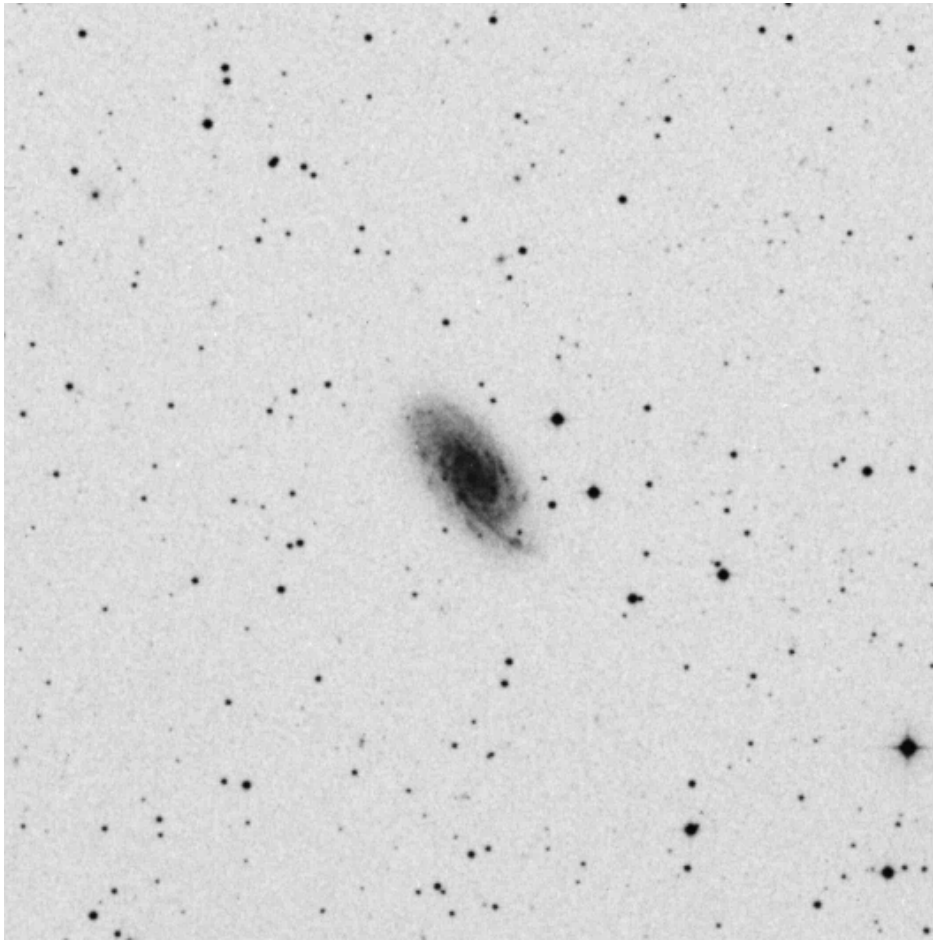
# NGC 6181



# NGC 6217



# NGC 6643



# Physics 10263 Lab #11:

## The Crab Nebula

### Introduction

The Crab Nebula is a beautiful cloud of gas and dust easily visible with a telescope in the constellation Taurus the Bull (it is fairly close on the sky to the Pleiades asterism we studied earlier, in fact). The Crab Nebula gets its name from English astronomer Lord Rosse, who observed it in detail in 1844. He published a sketch of the nebula made with his 72-inch telescope (which was one of the biggest in the world at the time), and in this sketch, the nebula looks somewhat like the claw of a crab (the image quality of the lens was fairly poor at the time).

Although better photographs of the nebula taken today reveal no such similarity, the name stuck. In 1921, astronomer John Duncan compared two photographs of the Crab Nebula taken over a time period of 12 years. Careful study of the knots in the nebula showed that they had uniformly changed position as if the nebula were expanding. Edwin Hubble later calculated the age of the expansion (he had a knack for this sort of thing, as you know by now) and discovered the date when this nebula began to expand coincided with the discovery in 1054 by Chinese astronomers of a supernova explosion in that part of the sky. It is clear today that the Crab Nebula is the expanding remnant of a supernova explosion.

In this lab, we will repeat Hubble's calculation and also attempt to estimate the distance to the Crab Nebula. To do this, we will use two photographs of the nebula, taken 34 years apart. The reproductions here aren't of the highest quality, but they are sufficient for our needs. Both images were taken with special red-sensitive plates (so that the emitting Hydrogen gas would stand out). The 1942 image is from Walter Baade of California's Mount Wilson observatory. The 1976 image was taken by William van Altena at Kitt Peak National Observatory in Arizona.

## **Hubble's Calculation**

We'll start with an overview of what we're about to do. The basis for the calculation of the age of the nebula is very simple. We start with the well-known equation:

$$\text{Distance} = \text{Velocity} * \text{Time}$$

In this lab, we will measure the distance travelled by several pieces of the Crab Nebula over a time interval of 34 years. By taking an average of these distances, we'll have a good idea of the average expansion velocity of the nebula.

Unfortunately, units present a problem. We'll be able to measure how many centimeters a cloud moves on paper in 34 years, but we'll need to convert this "paper" velocity into an angular velocity on the sky. By measuring the linear separation of two reference stars (whose angular separation is already known), we'll find the conversion from centimeters on paper to angles (in arcseconds) on the sky.

From there, we can find the velocity of each cloud in the nebula in arcseconds per year. If we know how fast each cloud is moving, then we can just measure how far (in arcseconds) each cloud is away from the center. We'll use  $d=vt$  again to determine how long ago each cloud was at the center, and that's the age of the nebula (in other words, when the expansion began).

### **Step 1**

First, let's establish the "plate scale" of the photograph. In other words, let's find out how many centimeters on paper is equal to an arcsecond on the sky. We'll do this by measuring the distance between the two stars marked by arrows on the photographs (one in the top left, the other bottom right). These two stars have had their positions carefully measured with a telescope, so we know that their angular separation is 576 arcseconds.

Measure the distance between the two reference stars to the nearest 0.05 cm on both photographs. Write down these distances on your worksheet. Divide both distances by the angular separation (576 arcsec) to get the plate scale (# of cm per arcsec) for the two photographs.

## **Step 2**

Now fill in the table on your worksheet by carefully measuring the indicated distances to the nearest 0.05 cm. You'll be measuring the distance from the center of the nebula (a small neutron star in the center marked with crosshairs) to the seven circled pieces of the nebula as well as the four reference stars numbered S1 through S4.

If you can't see the small star located near the center of the crosshairs, use a very dark pen or pencil to mark a spot near the center of the crosshairs and use this as the central point of the nebula for your measurements. Your measurements from the center to a given cloud will be delicate. You can't necessarily just measure to the center of a blob on the photograph, because that isn't well-defined. A better idea is to choose an edge of the feature easily visible on both photographs.

The reference stars, on the other hand, have well-defined shapes, so you can simply measure to the centers of these shapes.

## **Step 3**

In the next two columns of your table, use the plate scale for each image from Step 1 to convert your measurements in cm to angles on the sky. Simply divide your measurements of photographic distances by the plate scales of the two images (they should be slightly different!) to determine the angular distances in arcseconds for each photograph respectively. Your answer should have 3 significant figures.

As a check, you should find that the angular distance from the center of each of the four comparison stars (S1, S2, S3, S4) should be nearly identical in both frames (though there may be some small measurement error). If this isn't the case, ask your TA for assistance.

## **Step 4**

In the fifth column of your table, determine the angular distances travelled by each blob. Simply subtract the (lower) angular distance in column 3 from the (higher) angular distance in column 4. Since the nebula is expanding, all of your values for angular distance should be positive (if they aren't, you made a mistake and should go back and remeasure). Your answer should be precise to within 0.05 cm.

### **Step 5**

If we divide the angular distances in column 5 of the table by the amount of time that passed between the photographs (34 years), then we'll have an angular velocity for each cloud (in arcseconds per year). Please perform this calculation. Divide your angular distance values in column 5 by 34 and put this answer in column 6. Your answer should have 3 significant figures.

### **Step 6**

We now know the angular speeds of the various parts of the nebula. We'll use these to work backwards to find out how long ago the nebula began to expand. We know that:

$$\text{Distance} = \text{Velocity} * \text{Time}$$

can be applied here. We'll assume the following for each cloud

$$\text{Distance} = 1976 \text{ angular distance of cloud from center of nebula (in other words, the values from column 4)}$$

$$\text{Velocity} = \text{Velocity of the cloud, in arcseconds per year (in other words, the values from column 6)}$$

Thus, the total amount of time that has passed since the nebula began expanding from the center is just Distance/Velocity, or column 4/column 6! For each of the clouds, do this simple calculation and put the result in column 7. Your answers should all be rounded to three significant figures.

### **Step 7**

Now let's estimate how long the whole nebula has been expanding (as of 1976, anyway). Determine the average value of all seven entries in column 7 and write that average on your worksheet. For this answer, assume 3 significant figures.

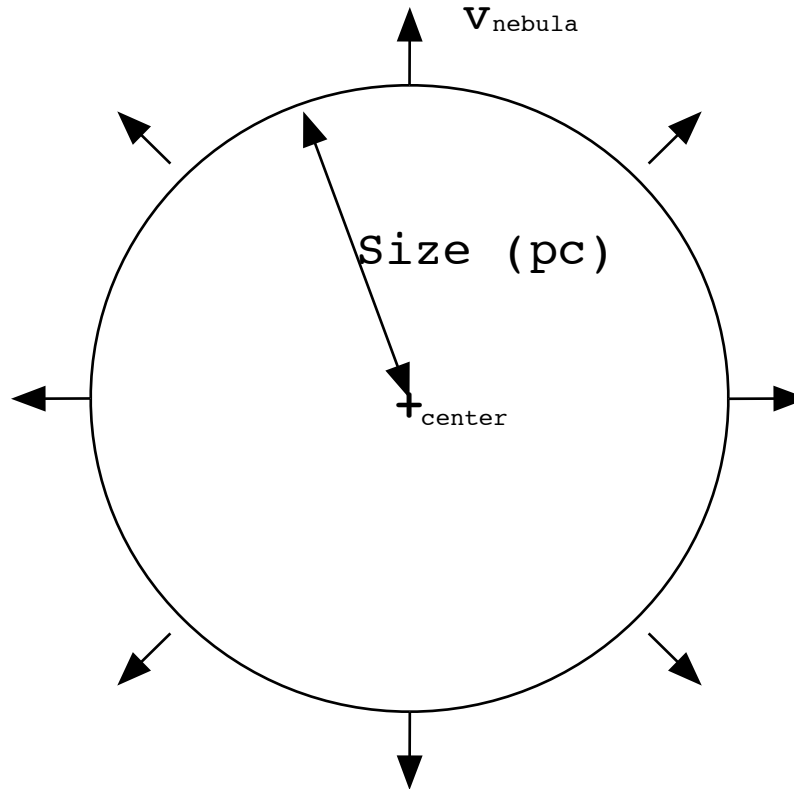
The correct value for the nebula's age (as of 1976) is simple to calculate since we know from historical records that the supernova went off in the year 1054. Write down the true value for the nebula's age (as of 1976) on your worksheet and calculate your percentage error.



### Step 8

Let's go one step further than Hubble and use some other information to try to calculate the distance to the Crab Nebula. Once again, we'll be using  $d=vt$  but in a new way.

### Face-on View From Earth



If we assume the nebula is roughly spherical, then we can say:

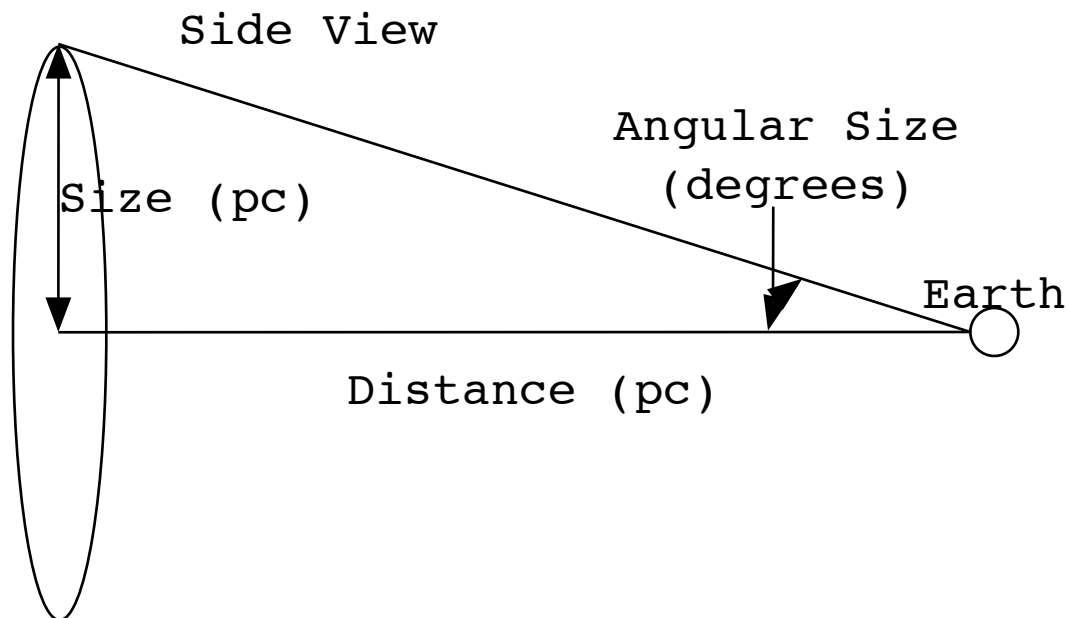
Nebula size (in parsecs) = (Nebula velocity) \* (time of expansion)

Astronomers use Doppler shift information to find out the typical velocity of gas clouds in the nebula moving radially (along our line of sight) either toward or away from us. Without going into the details of this calculation, we will assume that the velocity of the gas in the nebula is 0.0014 parsecs/year. On your worksheet, use this velocity and the true value of the expansion time from part (7) to determine the nebula size. You simply need to multiply these two quantities since the units will work out correctly.

### Step 9

Now that we know the nebula size (in parsecs), we can use our knowledge of the angular size of the nebula (in arcseconds) and some simple geometry to find the distance to the Crab Nebula. As you can see from the triangle in the diagram below, we can use simple trigonometry to find:

$$\text{Tan (Angular size)} = \frac{\text{Size (pc)}}{\text{Distance (pc)}}$$



Use the angular distance of cloud 3 in 1976 (in arcseconds, from column 4 of your table) as an estimate for the angular size of the nebula. On your worksheet, calculate the angular size in degrees (simply divide the value in arcseconds by 3600), then take the tangent of that angle and divide that into size from step (8). In other words, we're rewriting the equation above to read:

$$\text{Distance (pc)} = \frac{\text{Size (pc)}}{\text{Tan (Angular size)}}$$

Write down your estimate of the distance to the Crab Nebula. This should be good to an accuracy of 3 significant figures.

### **Step 10**

The true value for the distance to the Crab Nebula (good to 2 significant figures) is 2000 pc. On your worksheet, calculate your percentage error (it is all right to be off by as much as 50% -- the calculation is very sensitive to how you measure the location of cloud 3).

### **Essay**

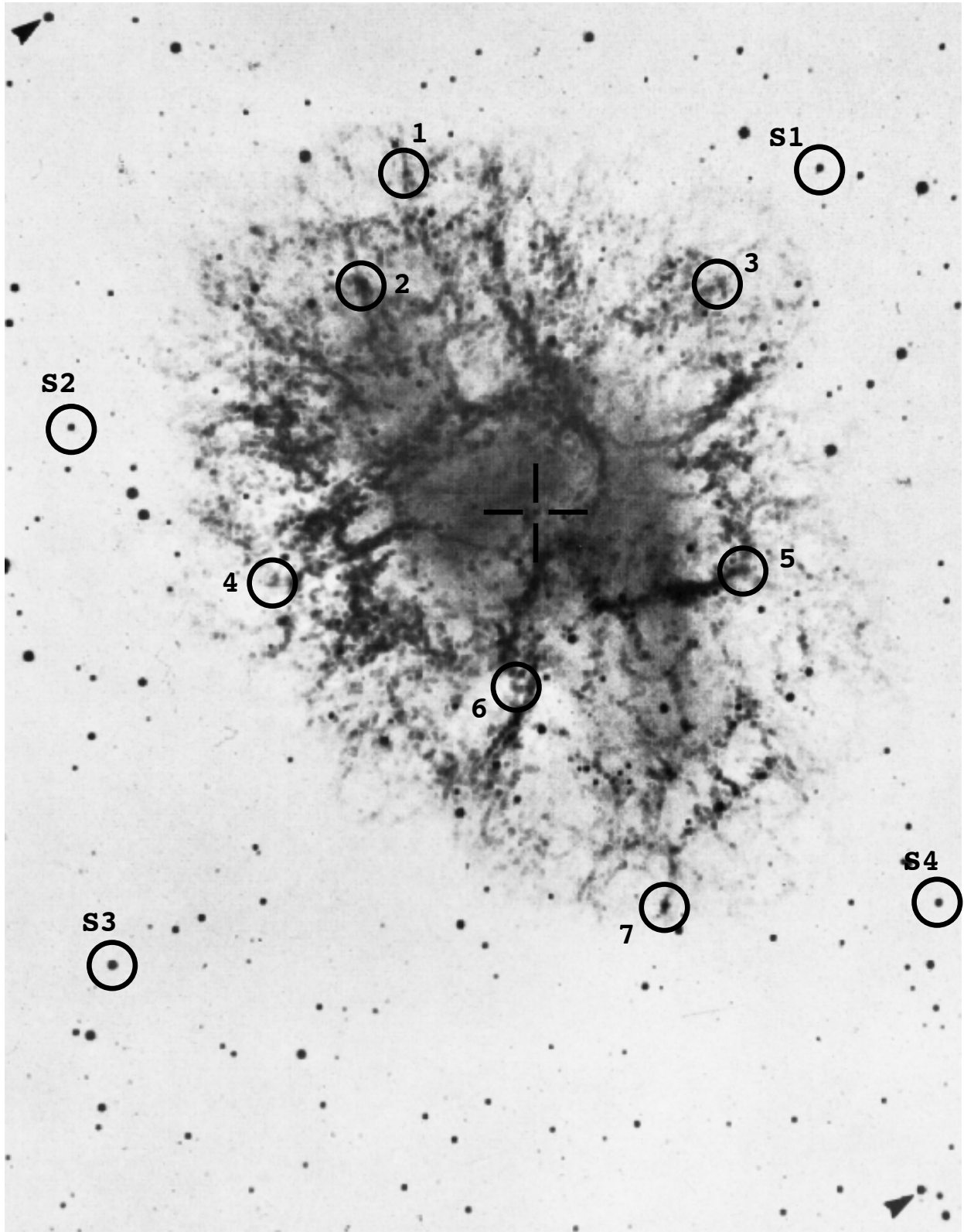
The purpose of this lab was straightforward: to determine the age and distance of the Crab Nebula. Your first paragraph should restate each of these two purposes separately along with a very brief two-sentence summary of how each purpose was accomplished. If you wish to redraw a diagram or two, feel free. So the first paragraph is a combination purpose/procedure paragraph.

Your second and third paragraphs should restate conclusions and discuss your error analysis. In steps (1)-(7), you got a value for the nebula's age that was probably a bit different from the true value. Carefully discuss the errors in the ruler measurements you made. Are some clumps easier to measure than others? Explain. If you had measured more clumps, would your result be more reliable? Explain.

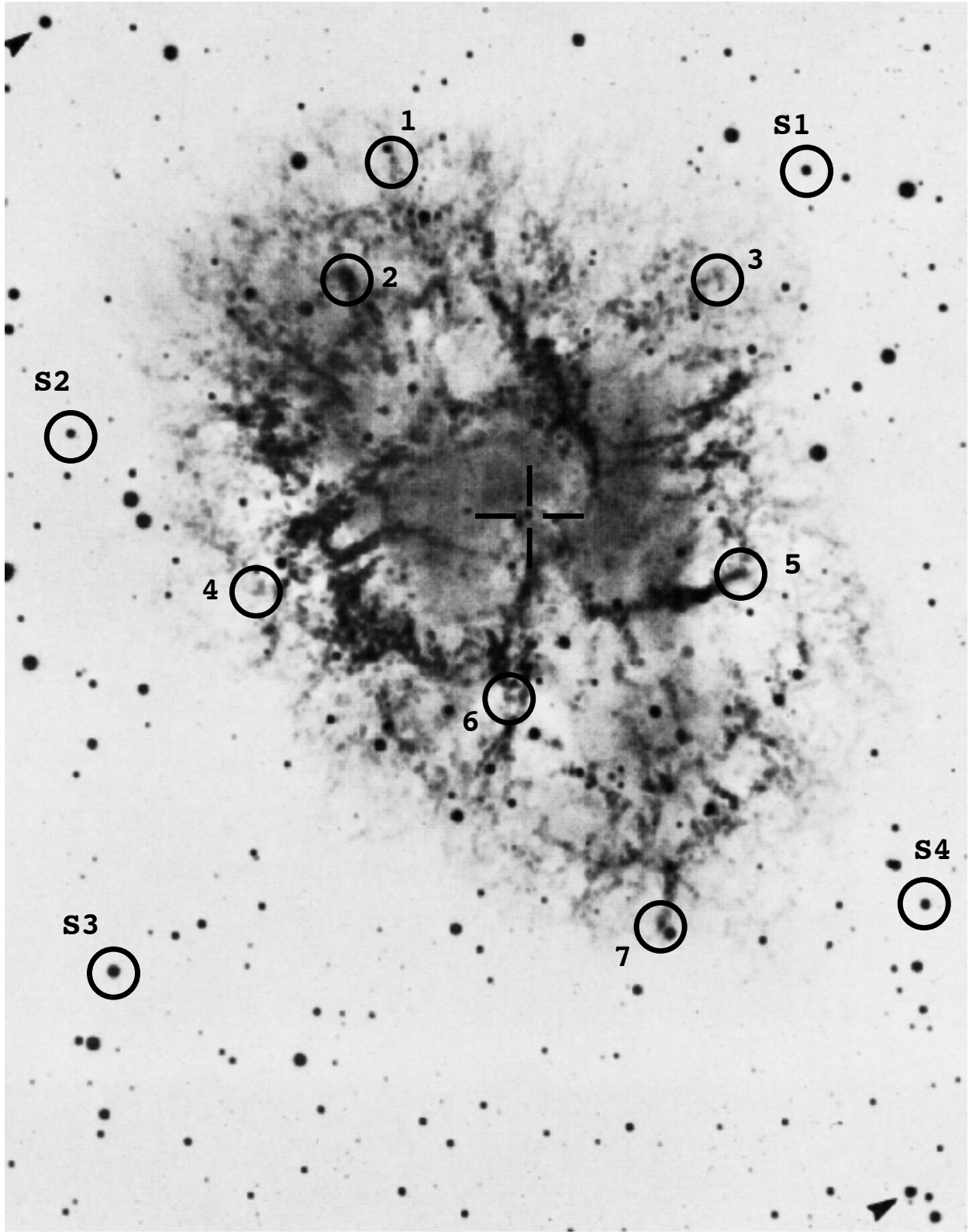
In steps (8)-(10), you derived a distance for the cluster. Assuming the given information was accurate, how could you make this measurement more trustworthy? Suggest an improvement to the outlined procedure. It is clear from the photograph that our assumption that the nebula is "roughly spherical" is false. If we had picked cloud 7 (which is further from the center of the nebula than cloud 3), explain either mathematically or in words how our estimate of the distance to the Crab Nebula would change (would it increase or decrease?).

### **Credits**

Much of the original procedure in this lab has been summarized from the original description in the "Sky and Telescope" laboratory exercise "The Crab Nebula" by Owen Gingerich, 1977. The two images of the Crab Nebula are also reproduced from the text of that exercise.



The Crab Nebula in 1942



The Crab Nebula in 1976



# Lab #11 Worksheet

**Name:**

**Home TA:**

**Step 1**

Distance between the two reference stars (in cm):

In 1942 photo: \_\_\_\_\_ In 1976 photo: \_\_\_\_\_

Plate scale of the two photos (in cm/arcsec):

1942 photo: \_\_\_\_\_ 1976 photo: \_\_\_\_\_

**Steps 2-6**

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
Object	1942 distance (cm)	1976 distance (cm)	1942 angular distance (arcsec)	1976 angular distance (arcsec)	angular distance covered (arcsec)	angular velocity (arcsec/year)	time of cloud's motion (years)
Cloud 1							
Cloud 2							
Cloud 3							
Cloud 4							
Cloud 5							
Cloud 6							
Cloud 7							
Star S1							
Star S2							
Star S3							
Star S4							

**Step 7**

The average cloud motion time (hence, the best estimate of the age of the nebula as of 1976) is:

\_\_\_\_\_ years

The true value of the age of the nebula (as of 1976) is:

\_\_\_\_\_ years

The percent error in your calculation is:

\_\_\_\_\_ %

**Step 8**

The size of the nebula (in parsecs) is:

\_\_\_\_\_ pc

**Step 9**

Using cloud 3 as a marker for the edge of the nebula, the angular size of the Crab Nebula (in **degrees**) is:

\_\_\_\_\_ degrees

Using the formula from the notes, the estimated distance to the Crab Nebula is:

\_\_\_\_\_ parsecs

**Step 10**

The percent error in your calculation is:

\_\_\_\_\_ %

**Essay**

Please read the special instructions in the student notes regarding the essay for this lab, and write your essay on a separate sheet of paper. In your essay, be sure to answer the specific underlined questions posed in the essay instructions!