# Physics 10263 Lab #10:
# 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:

Distance = Velocity * 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:

Distance = Velocity*Time

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

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

Velocity = 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.

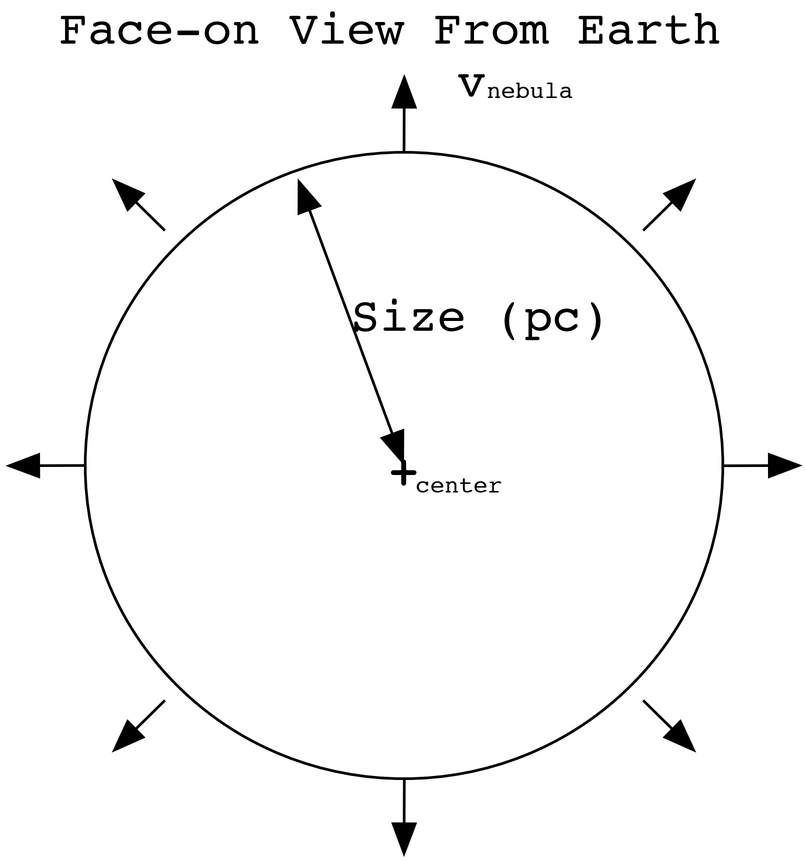
**Step 7**

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.




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

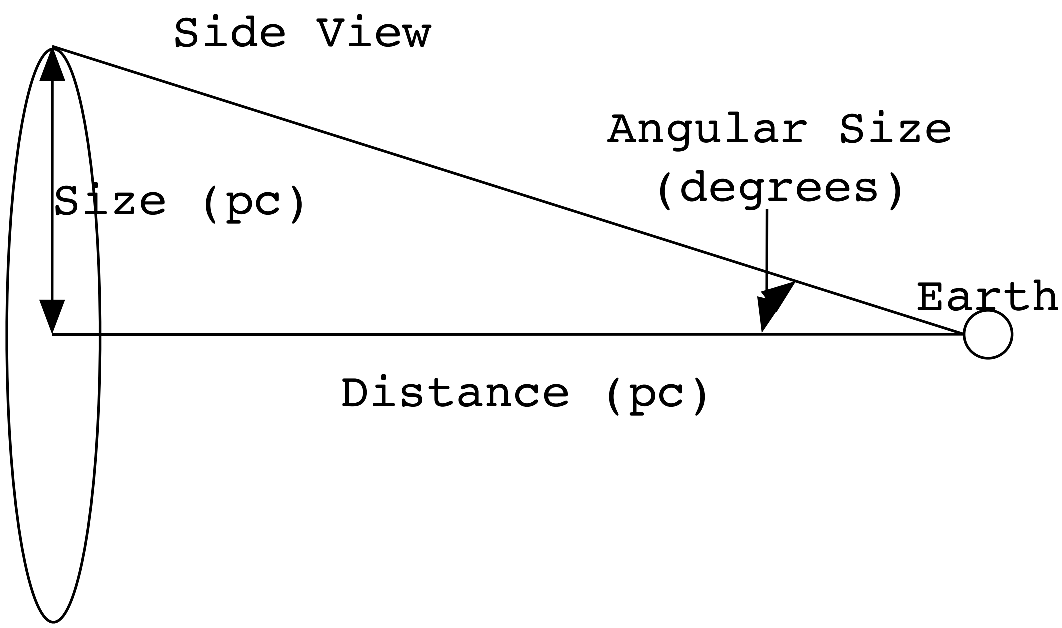
Nebula size (in parsecs) = (Nebula velocity) * (time of expansion)

Astronomers use Doppler shift information to find out the typical velocity of gas clouds in the nebula moving radially (along our line of sigth) 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**

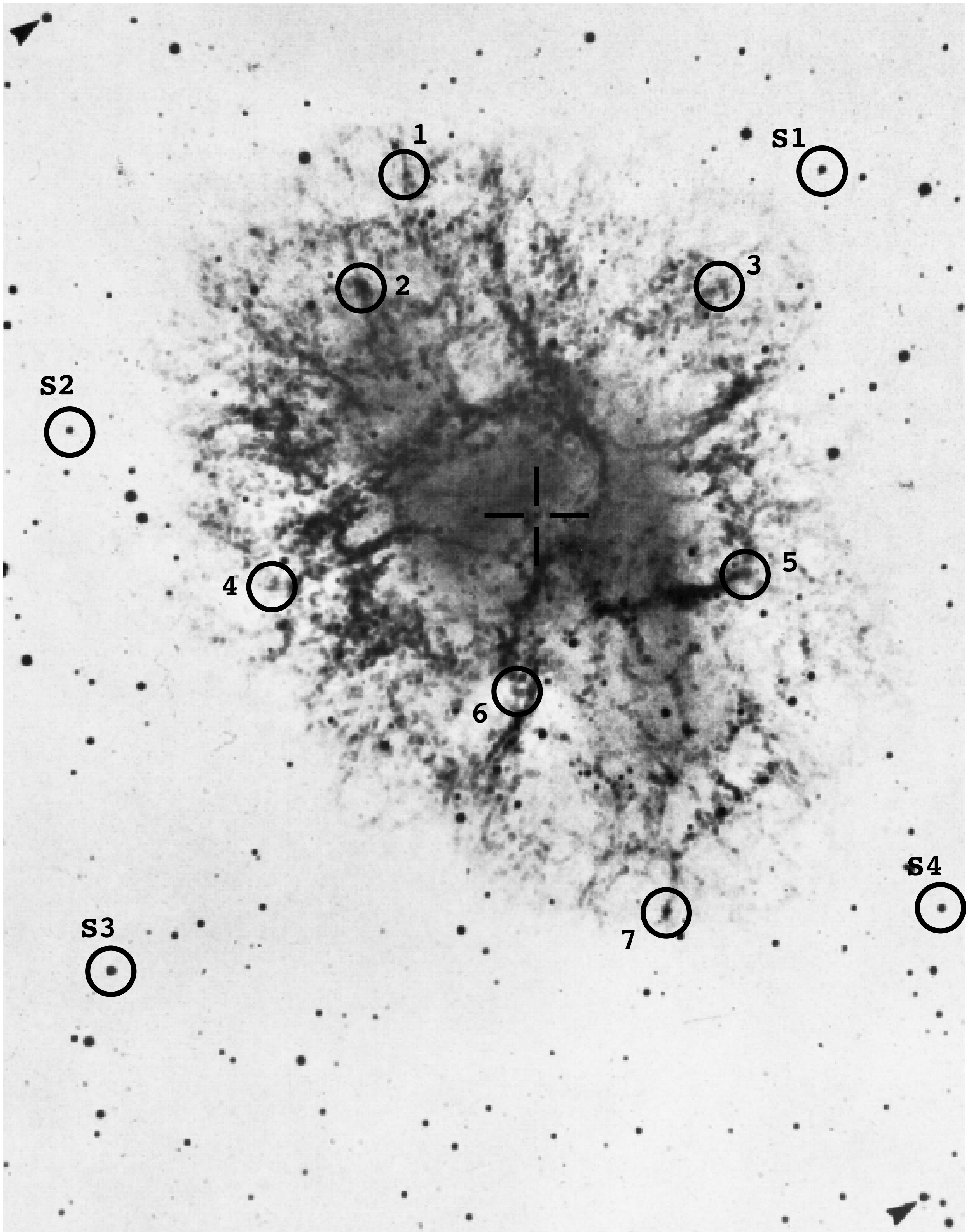
The purpose of this lab was straightforward: to determine the age and distance of the Crab Nebula. Your first paragraph should restate each of these two purposes separately along with a very brief two-sentence summary of how each purpose was accomplished. If you wish to redraw a diagram or two, feel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

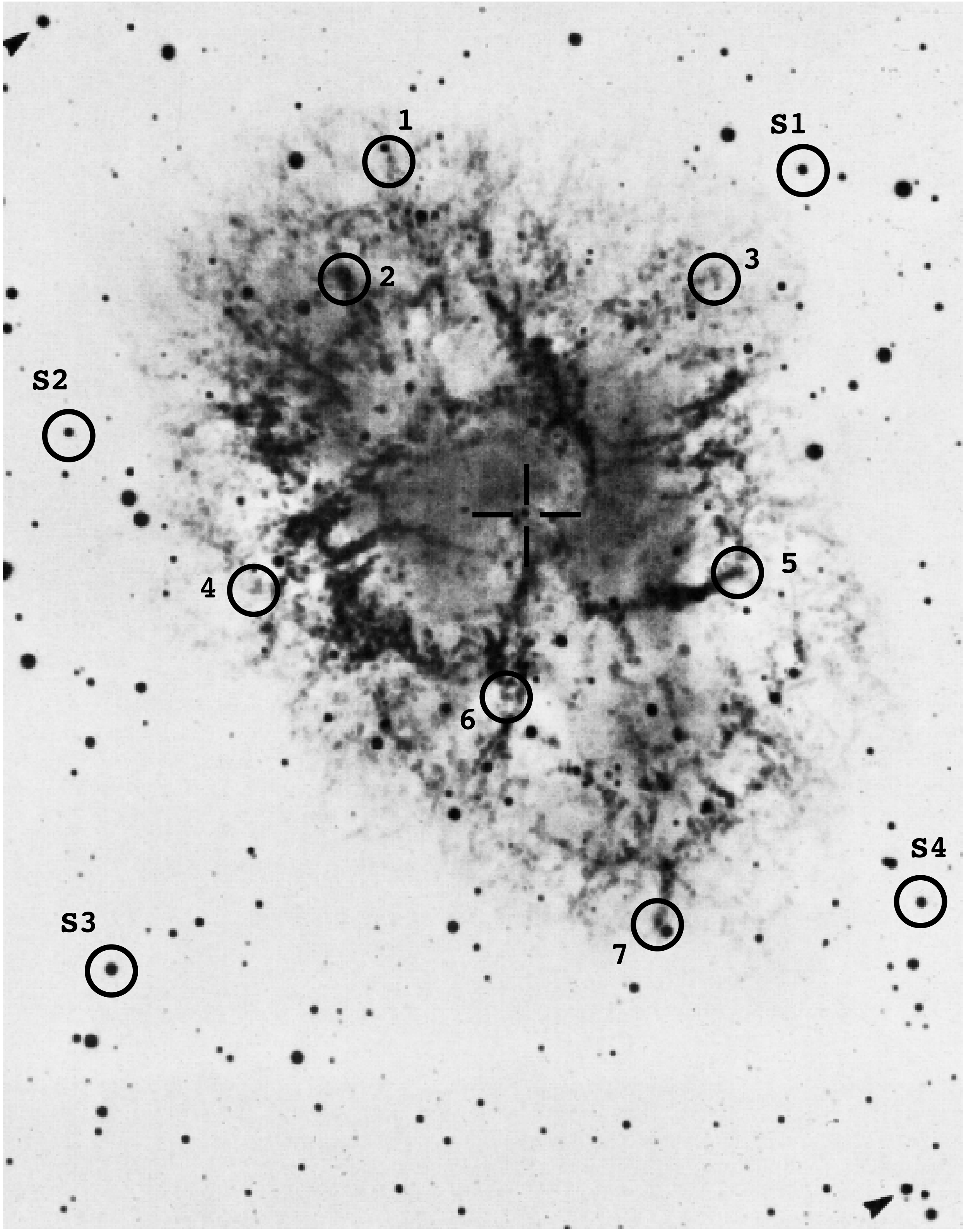
In steps (8)-(10), you derived a distance for the cluster. Assuming the given information was accurate, how could you make this measurement more trustworthy? Suggest an improvement to the outlined procedure. It is clear from the photograph that our assumption that the nebula is "roughly spherical" is 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 #10 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!