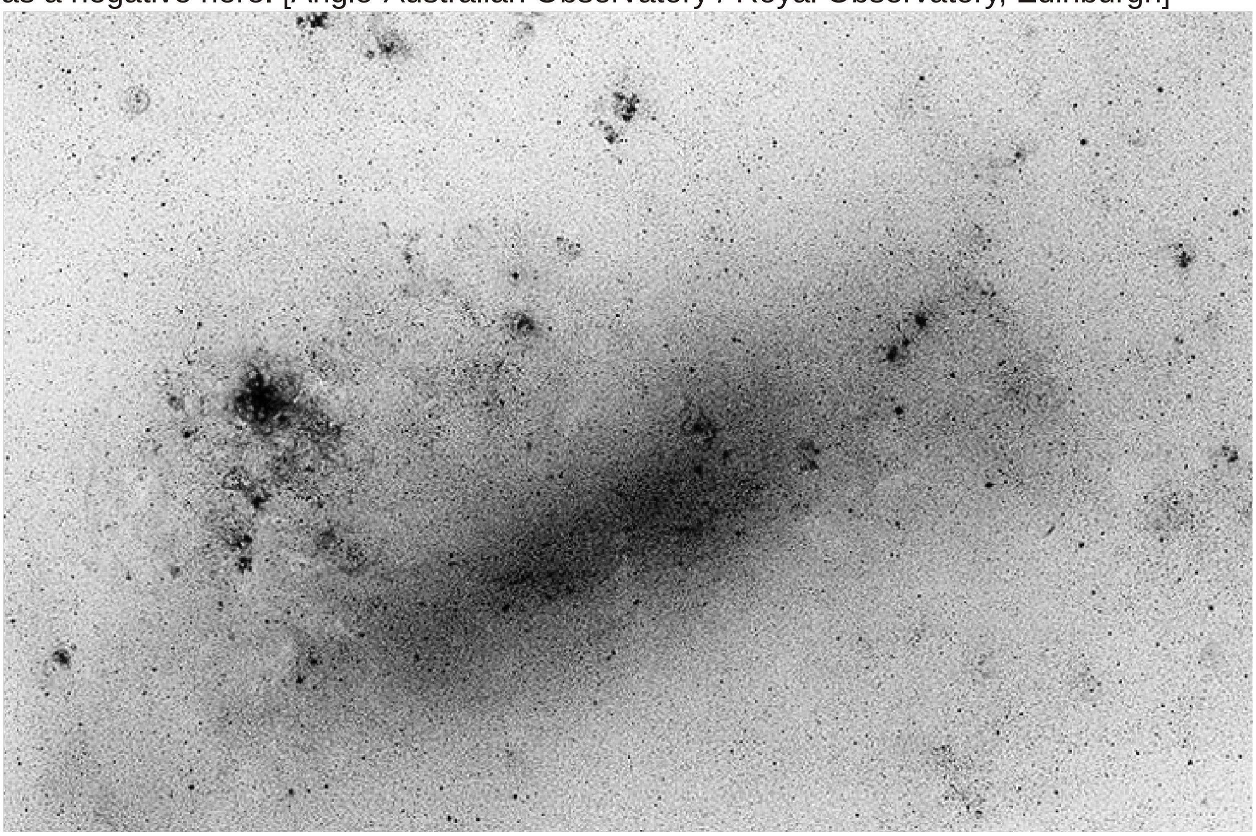
Supernova 1987A and the Distance to the Large Magellanic Cloud

Introduction

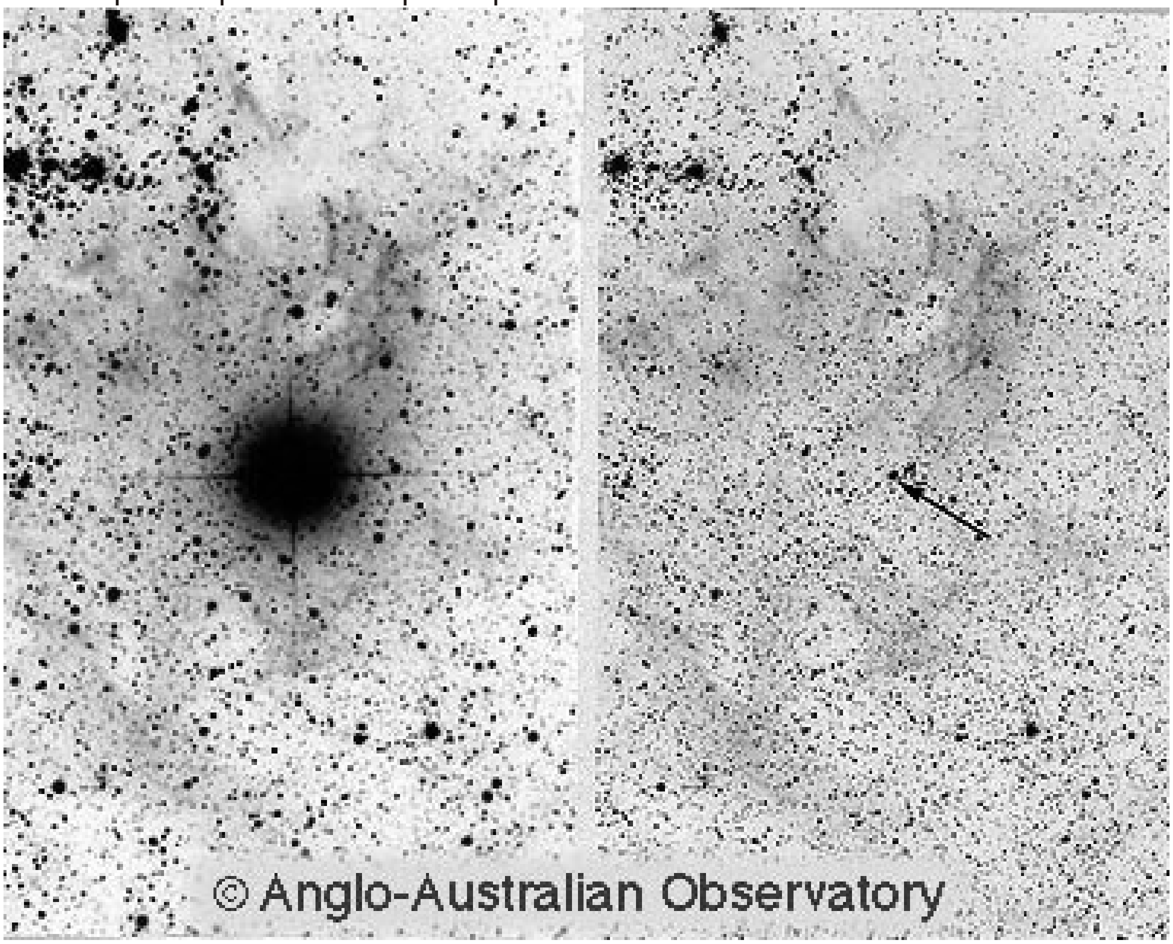
On February 24, 1987, astronomer Ian Shelton was making observations of the Tarantula Nebula in the Large Magellanic cloud at Las Campanas Observatory, when he noticed something strange on his image. After seeing this, he did something that astronomers haven't done for some time: he went outside and looked up. He saw the first supernova visible with the naked eye since 1604.

The Magellanic clouds are named for Magellan, the Portuguese navigator, who saw them in 1519. Here is a picture of the Large Magellanic cloud (LMC). It is about 8° wide, and was photographed using the United Kingdom Schmidt Tele scope. It is shown as a negative here. [Anglo-Australian Observatory / Royal Observatory, Edinburgh]

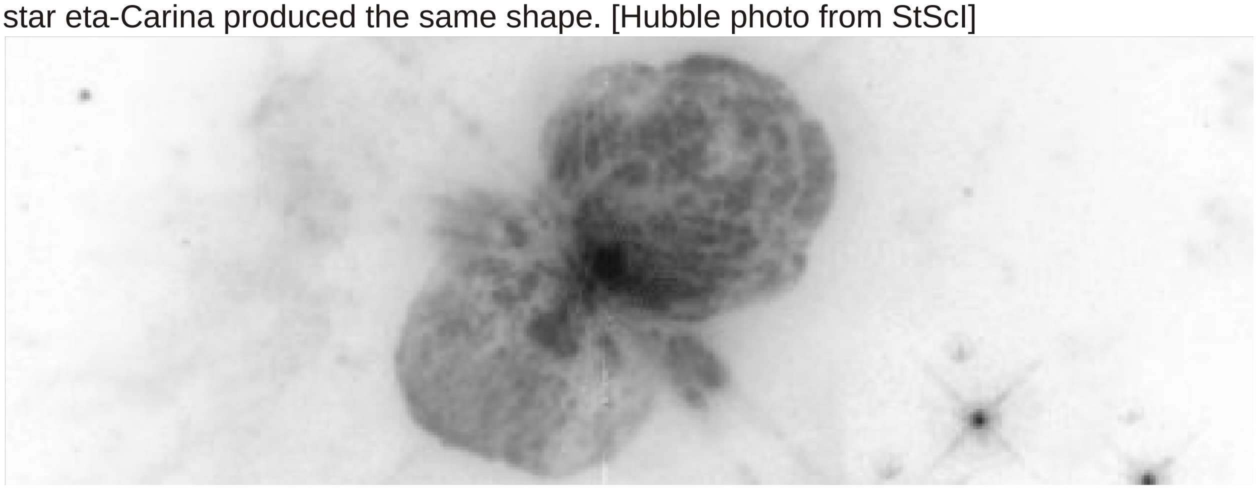


The LMC is a satellite galaxy of the Milky Way. In this experiment, we shall use the light from the supernova SN1987A to measure the distance to the LMC.

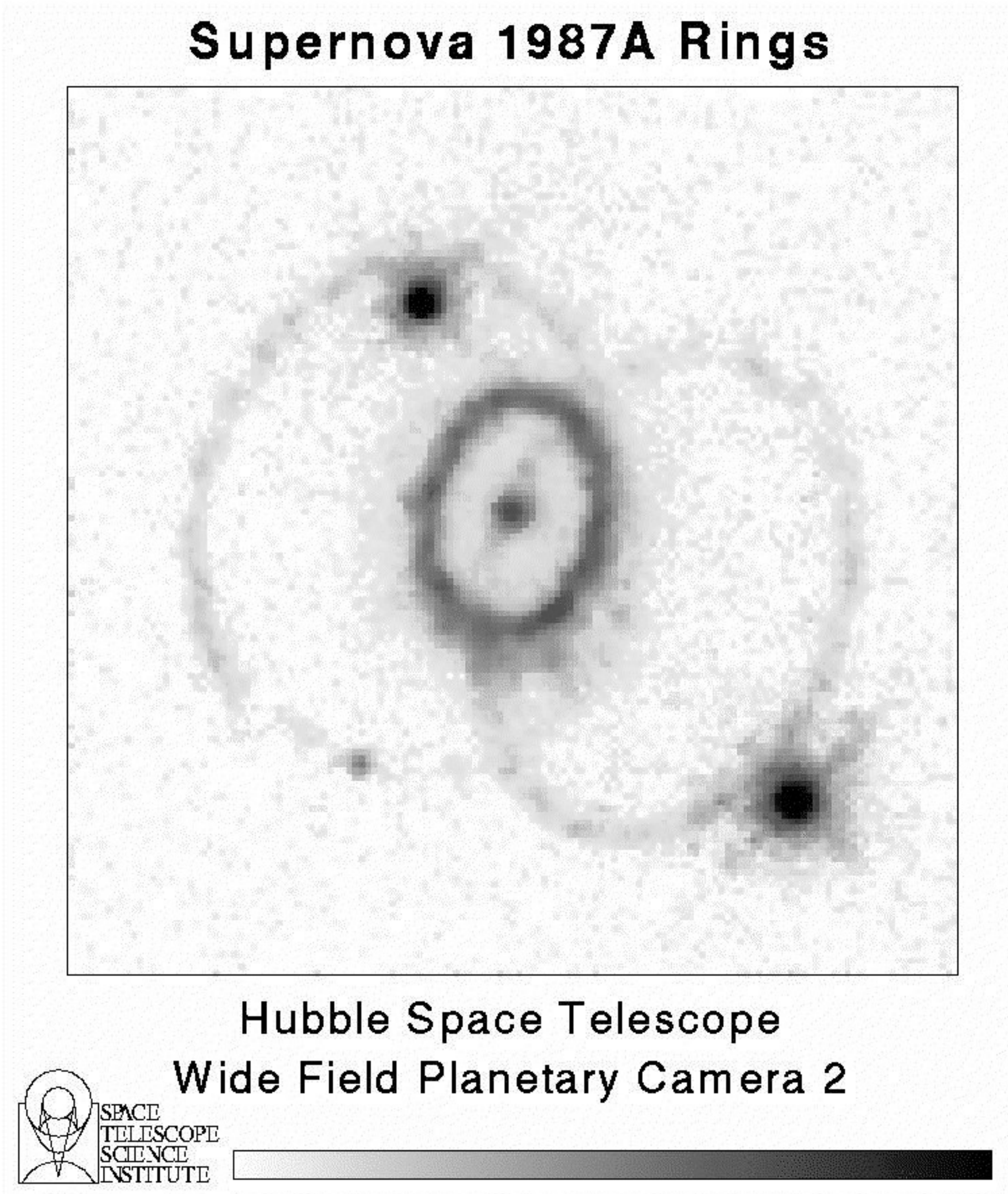
Here are pictures taken before and after the supernova explosion. An arrow on the right-hand picture points to the pre-supernova star.



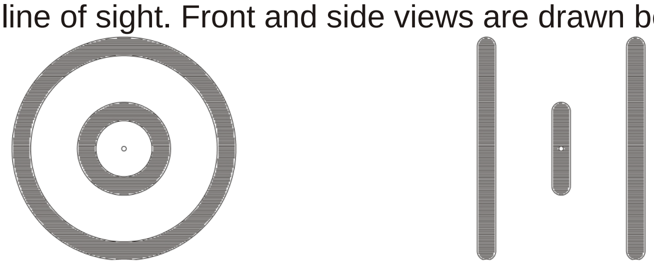
Long before the explosion, the pre-supernova ejected quite a lot of gas, perhaps when it was in some sort of red giant stage of its evolution. The shells were not spherical, but were in the forms of double lobes, plus an inner ring. Such structures are seen to day in many planetary nebulae, and an early 19th century explosion of the massive, unstable star eta-Carina produced the same shape. [Hubble photo from StScI]



Here is the supernova as seen ten years after the explosion.

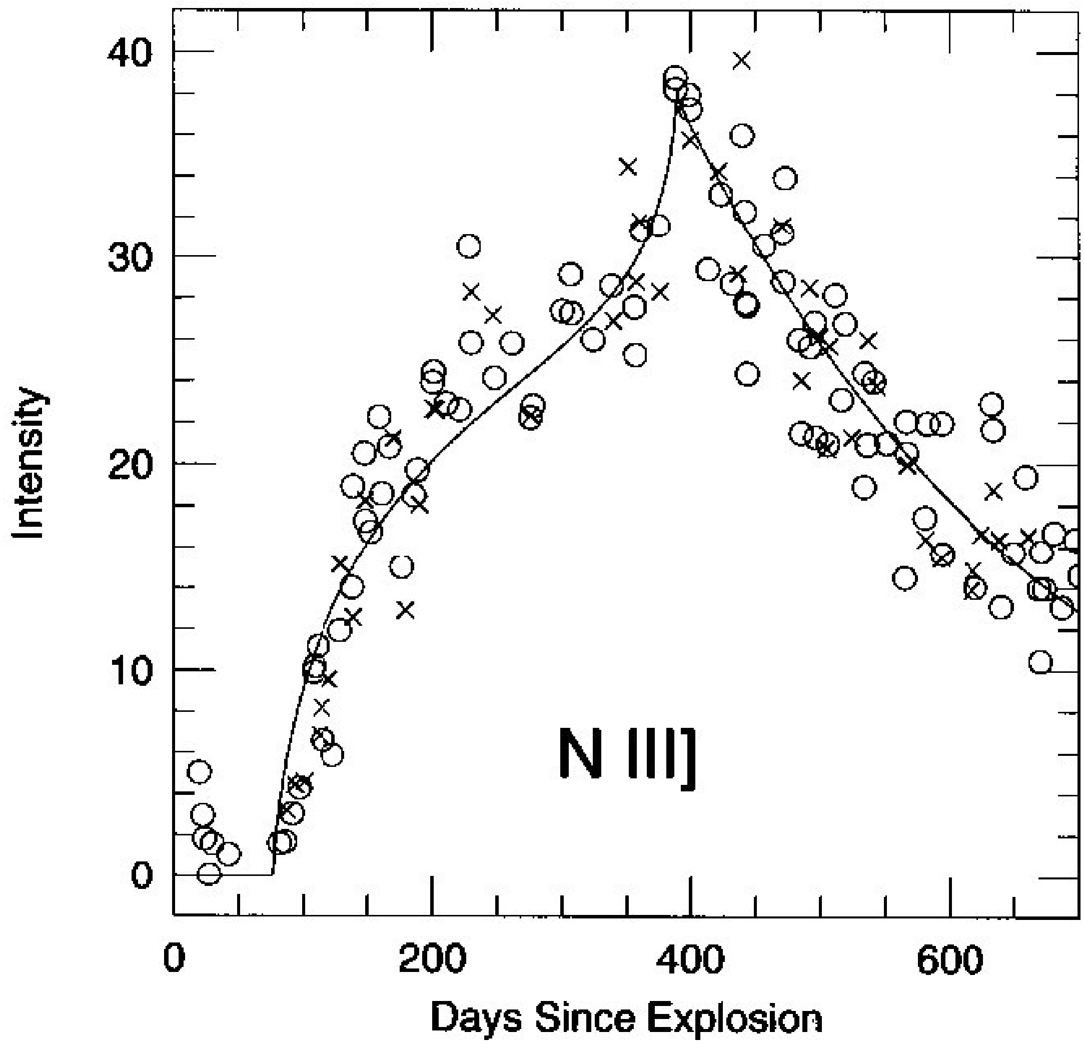


What do we see? The supernova remnant is still glowing, though no longer out shining other stars. The inner ring really is a ring, centered on the super nova. The outer rings are possibly sections of larger structures. The rings that we see have a common axis that is tilted from our line of sight. Front and side views are drawn below.



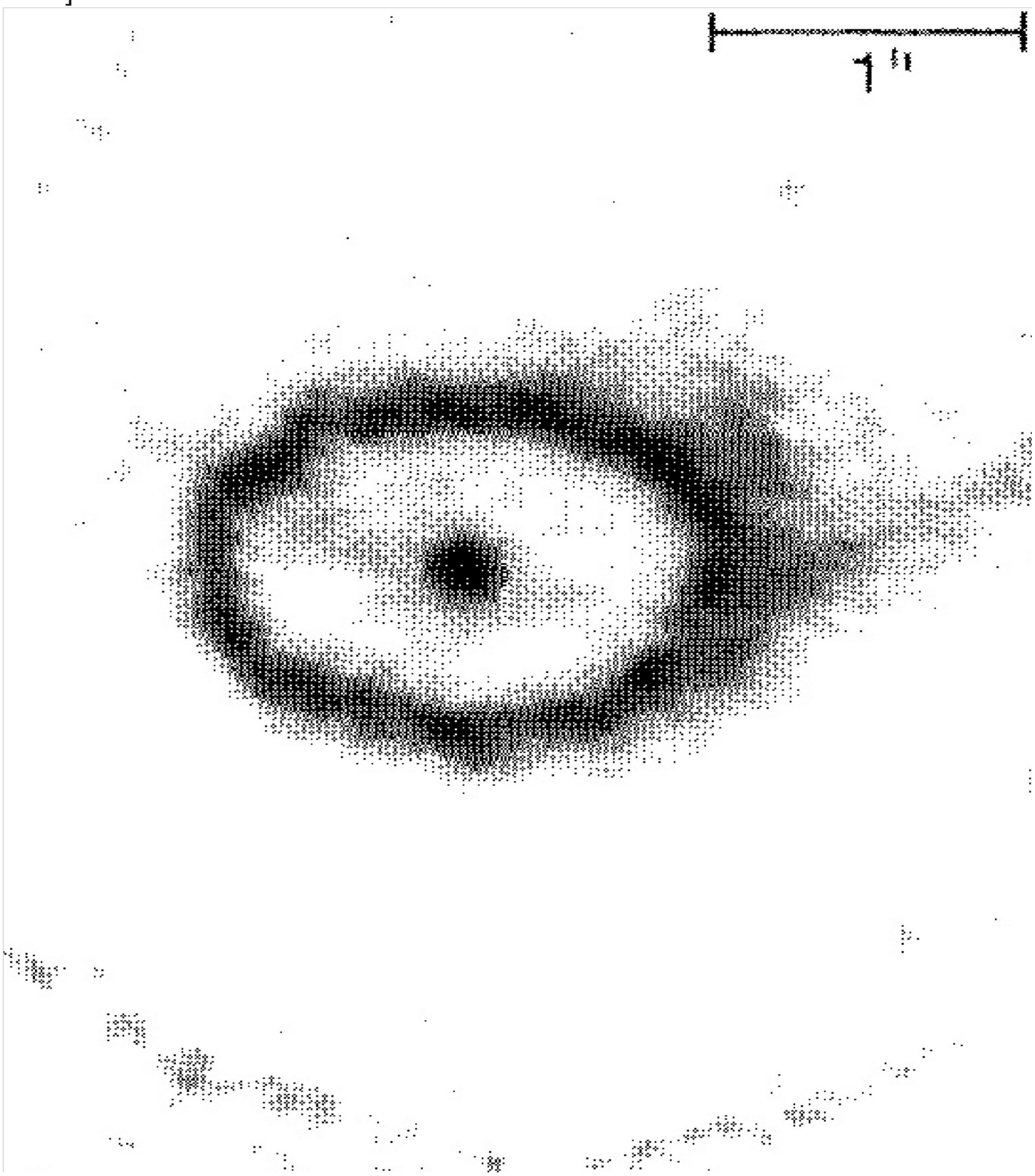
When SN1987A first went supernova, it gave off a flash in the far ultra violet. After a delay caused by the finite speed of light these energetic photons slammed into the inner ring, ionizing and heating the gas, which was then excited by thermal collisions and radiated at characteristic wave lengths. The whole ring would have lit up all at once, but that is not the way it would have been seen from Earth. The ring is inclined with respect to our line of sight, so one side of the ring is closer to us than the other side, and we would have seen the near side of the ring emitting light first. This light emission would be seen spreading around the ring until the entire ring was glowing. We do not have images of this happening, but we do have a record from the International Ultraviolet Explorer Satellite that recorded the ring emission.

Here is the record for a spectrum line of nitrogen atoms stripped of two electrons. The wavelength is 175.0 nm. In the figure, observations are indicated by circles and crosses, while a computer model of the process is indicated by a solid line. [Andrew Gould, ApJ 452:189, 1995]



After an initial delay, the emission starts to rise, reaching a maximum when the ring is complete. At late times, emission falls as the gas cools off.

Here is an image of the complete inner ring. It was obtained with the ESA's Faint Object Camera on the HST through a narrow passband filter centered at 500.7 nm. The light is emitted by oxygen atoms ionized twice. This is an earlier picture than the one on page 3, and light from only parts of the outer rings has reached the Earth. In this heavily processed image, the arcs are clearly seen; one is 2.2 arc-seconds south of the supernova, the other crosses the inner ring of the super nova. [Plait, et. al., ApJ 439:730, 1995]



We now have all the data that we need for finding the distance to the supernova, but we are going to need some math and some physics.

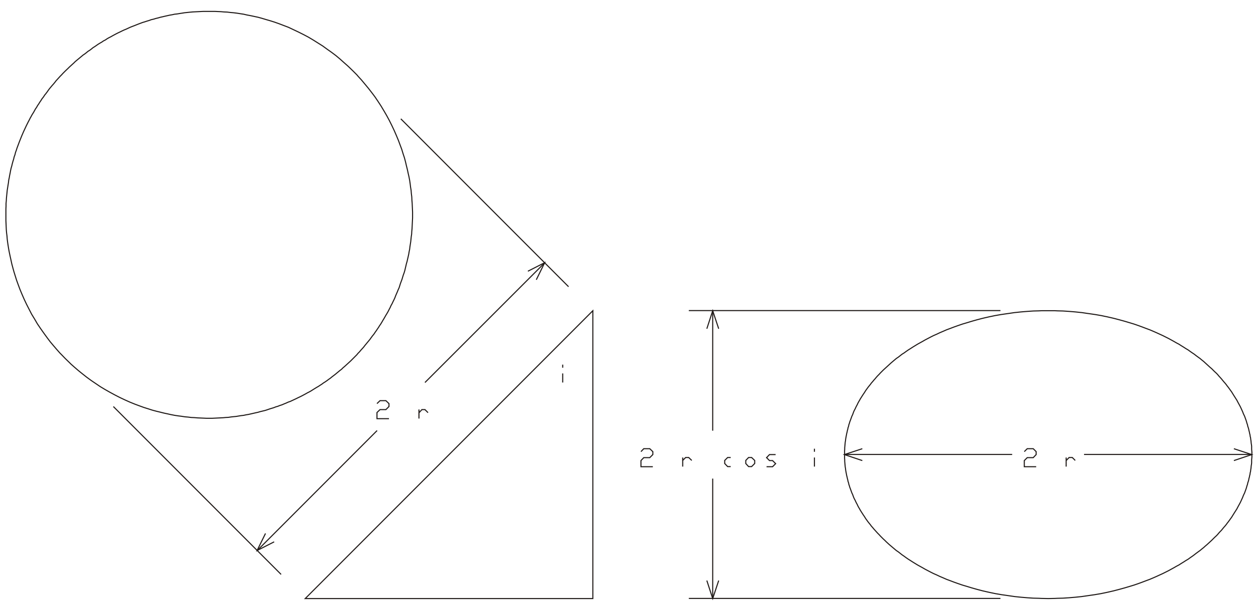
The physical principle that we need is

$$Rate \times Time = Distance$$

Rate here is the speed of light, c. This will permit us to convert light delay times into distances.

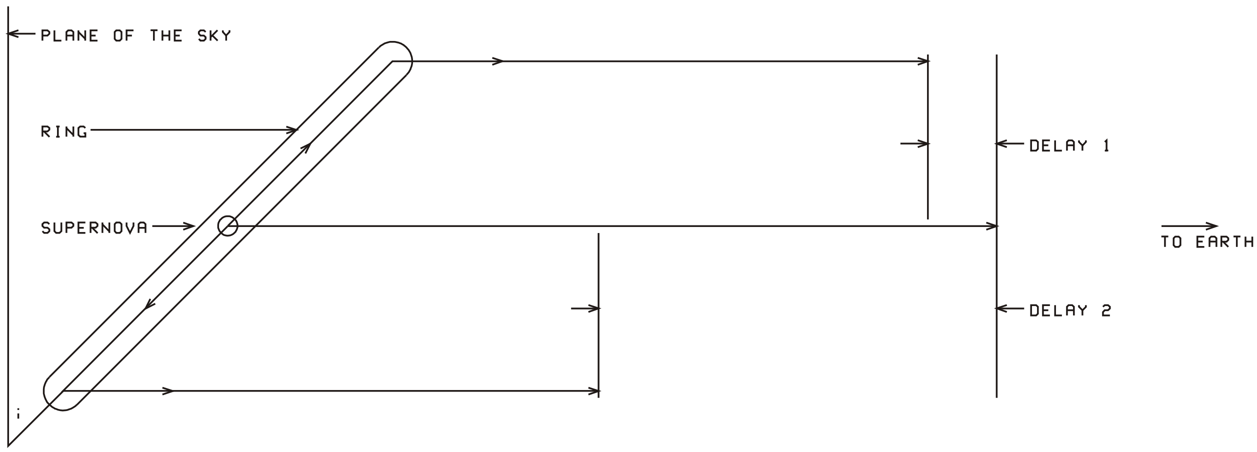
The ring structure is seen as an ellipse because it is tilted with respect to our line of sight. Let r = the apparent semi-major axis of the ellipse. Then the apparent semi-minor axis of the ellipse is r cos(i), where i equals the angle of inclination. The major axis is 2 r and the minor axis is 2 r cos i. The cosine of the angle i can be found from

$$\frac{semi-minor\ axis}{semi-major\ axis}=\frac{2r\cos i}{2r} = \cos i$$



The values of r and i are found from the photograph on page 5.

Next, we consider the actual distances traveled by light along three paths:



In the figure above, the supernova and the ring are on the left, while the Earth is off towards the right. We are interested in three light paths:

1) Light from the supernova hits the top (nearest) part of the ring, and then light from the ring travels towards the Earth.

2) Light from the supernova hits the bottom (farthest) part of the ring, and then light from the ring travels to wards the Earth.

3) Light from the supernova travels in a straight path towards the Earth.

The three paths are indicated in the figure above. The lengths of the light paths are all equal, indicating how far light has gone after a certain time. The light rays following the broken paths 1 and 2 lag behind light traveling along path 3. The lag distances are labeled DEL AY 1 and DELAY 2.

The light travel times corresponding to DEL AY 1 and DE LAY 2 are the time delays of initial rise and maximum emission measured from the graph on page 4, which plotted ring emission vs. time. The distance unit we will use is the light day, the distance light travels in one day.

$$1 \text{ light day} = \frac{1}{365.25} \text{ light year} = 173.14 \text{ AU}$$

After measuring the two delay times, we calculate the delay distances in light days, which is no calculation at all:

$$\text{delay distance in light days} = \text{delay time in days} \times 1 \, \frac{\text{light day}}{\text{day}}$$

The light delay distances depend on the radius of the ring and it's angle of inclination, marked as "i" on the page 7 diagram. Algebraically, we let r equal the radius of the ring and solve the following simultaneous equations for the unknowns i and r. (In the computer program, you will do this graphically.) Note that you have found the inclination angle two ways.
This provides a test of the assumption that the inner ring is actually round.

$$\text{DELAY1distance} = r\,(1 - \sin i)$$

$$\text{DELAY 2 distance} = r\,(1 + \sin i)$$

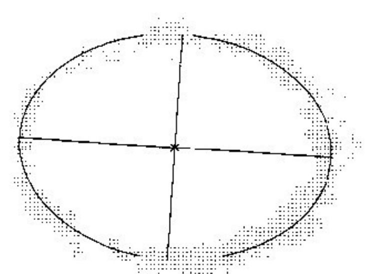
Next, we double the radius to get the diameter of the ring in light days. Then, we convert light days to astronomical units (AU) by multiplying by the conversion factor, 173.14 AU per light day.

We now have a diameter of the ring in AU and an apparent diameter in arc-seconds. We find the distance to SN1987A in parsecs using the definition of a parsec.

$$\text{distance in parsecs} = \frac{\text{ring diameter in AU}}{\text{apparent ring diameter in arc-seconds}}$$

Procedure

1) Start the program "SN1987A". Instructions appear at the top of the wind ow.
2) Type in your name(s) and left button mouse click on the "OK" button.
3) View a series of photographs.



4) Find the delay times in days from the graph of ring emission vs time, as on page 4.
5) Find the apparent geometry of the ring by fitting an ellipse to the photo on page 5. When done, the computer screen will look something like the above.
6) Find the physical diameter of the ring and the inclination angle from a graphic that looks like the one on page 7.
7) If a printer is available, print your results. If not, copy the data to the data sheet.
8) Use a scientific calculator to perform the required computations.
9) Answer the questions on the print out or data sheet and hand it in. Note: If you are working with a partner, circle your own name on the printout.

Data Sheet, SN1987A

Name ______________________________

Partner's Name ______________________________

Date ____________

Step 1 Data

Path 1 delay time, in Days ____________

Path 2 delay time, in Days ____________

Step 2 Data

Apparent ring major axis, in arc-seconds ____________

Apparent ring minor axis, in arc-seconds ____________

Apparent ring tilt, in degrees ____________

Step 2 Calculations

$$\cos i = \frac{apparent\ minor\ axis \in arc - seconds}{apparent\ major\ axis \in arc - seconds}$$

Inclination angle, in degrees, computed from Cos I ____________

Step 3 Data

Inclination angle, in degrees ____________

Ring radius, in light days ____________

Ring diameter, in light days ____________

(Continued on next page)

Step 3 Calculations

$$\text{ring diameter in AU} = \text{ring diameter in light days} \times \frac{173.14\ \text{AU}}{\text{light day}} = \underline{\hspace{3cm}}$$

$$\text{distance in parsecs} = \frac{\text{ring diameter in AU}}{\text{apparent ring diameter in arc-seconds}}$$

$$= \underline{\hspace{3cm}}$$

Questions

1) The data in the program is printed with an unrealistic number of significant figures. Estimate a realistic number of significant figures for your data and for the distance.

2) Compare your distance to SN1987A with the literature value of the distance to the LMC, 50 kpc.

3) Explain why the two measurements of the ring's inclination angle were independent.