THE ESA/ESO ASTRONOMY EXERCISE SERIES

Student exercises in astronomy using observations from the NASA/ESA Hubble Space Telescope and the ESO telescopes

Exercise 1

Measuring the Distance to Supernova 1987A

Based on Observations with the NASA/ESA Hubble Space Telescope

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The ESA/ESO Astronomy Exercise Series 1

Measuring the Distance to Supernova 1987A

Astronomy is an accessible and visual science, making it ideal for educational purposes. Over the last few years the NASA/ESA Hubble Space Telescope and the ESO telescopes at the La Silla and Paranal Observatories in Chile have presented ever deeper and more spectacular views of the Universe. However, Hubble and the ESO telescopes have not just provided stunning new images, they are also invaluable tools for astronomers. The telescopes have excellent spatial/angular resolution (image sharpness) and allow astronomers to peer further out into the Universe than ever before and answer long-standing unsolved questions.
The analysis of such observations, while often highly sophisticated in detail, is at times sufficiently simple in principle to give secondary-level students the opportunity to repeat it for themselves.

This series of exercises has been produced by the European partner in the Hubble project, ESA (the European Space Agency), which has access to 15% of the observing time with Hubble, together with ESO (the European Southern Observatory).

Figure 1: The NASA/ESA Hubble Space Telescope
The NASA/ESA Hubble Space Telescope has presented spectacular views of the Universe from its orbit above the Earth.

Introduction

SN 1987A is the name of a famous supernova. The first part of its name refers to the type of event – a supernova, then to the year in which it was first observed (1987) and finally the "A" denotes that it was the first supernova discovered that year.

Supernovae

A supernova is an explosion that signals the death of certain types of stars. There are basically two types of supernovae, but here we will only deal with the so-called Type II supernovae — massive stars that come to the end of their lives in a very spectacular fashion. SN 1987A was the explosion of one such massive star.

A massive star (typically more than five solar masses) may end its life in an explosion after a few million years. During the explosion most of the star's material is blown violently out into space. The velocity of the ejected material can reach 10^7 m/s (3% of the speed of light). The expanding shell of debris remains visible in interstellar space for thousands of years before it eventually fades into the interstellar medium, leaving a visible residue known as a supernova remnant. Within the surrounding nebula the central part of the original star is compressed to a neutron star.

All supernovae are very bright, with a brightness equivalent to the total emitted light of billions of Suns. They are believed to be among the brightest objects in the entire Universe. This makes them visible over large distances. However, there are very few supernovae and so the sky is not constantly lit by the spectacular deaths of stars. The rate at which supernovae occur is estimated to be only a few per century per galaxy.

Figure 2: The Large Magellanic Cloud (LMC)
The LMC is a small irregular galaxy, one of the nearest of the Milky Way's neighbouring galaxies. It is filled with stars, dust and gas and is teeming with star formation. SN 1987A appeared here in the LMC.
This image was taken with the Schmidt telescope at the European Southern Observatory's (ESO) La Silla Observatory.

Introduction

Figure 3: Apparition of SN1987A
In the left-hand image you can see the Tarantula Nebula after the supernova exploded. An arrow points to the supernova. The right-hand image shows the Tarantula Nebula in the LMC before the explosion of Supernova 1987A on February 23rd 1987.

Supernova 1987A

On February 23rd 1987 a supernova visible to the naked eye appeared in the Large Magellanic Cloud (LMC). The LMC is one of the nearest of the Milky Way's neighbouring galaxies. This was one of the most exciting events in the history of astronomy. SN 1987A was the first supernova visible to the naked eye for almost 400 years.

The Distance to the Large Magellanic Cloud

The determination of distances in the Universe is one of the most fundamental problems in astronomy. An accurate measurement of the distance to SN 1987A, situated within the LMC, can be used to determine the distance to the LMC itself.
All stars in the LMC are at approximately the same distance from us. If we can find the distance, D, to SN 1987A, we then simultaneously find the distance to all the other types of stars found in the LMC. Several other types of objects

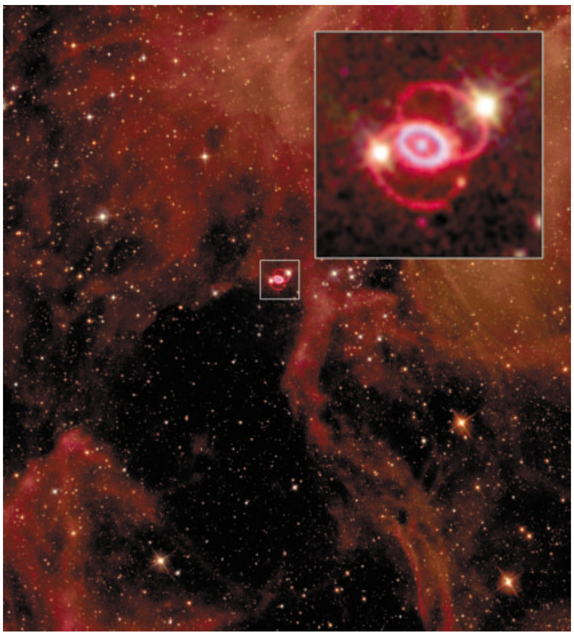


Figure 4: Supernova 1987A
SN 1987A in the centre (scaled up in the insert) left behind a residue of three rings of glowing gas in the LMC. In this exercise the small central ring is used to measure the distance to the supernova and thus to the LMC.

Many young — 12 million years old — blue stars are seen in the area as well as dust and gas (in dark red). This shows that the region around the supernova is still a fertile breeding ground for new stars.

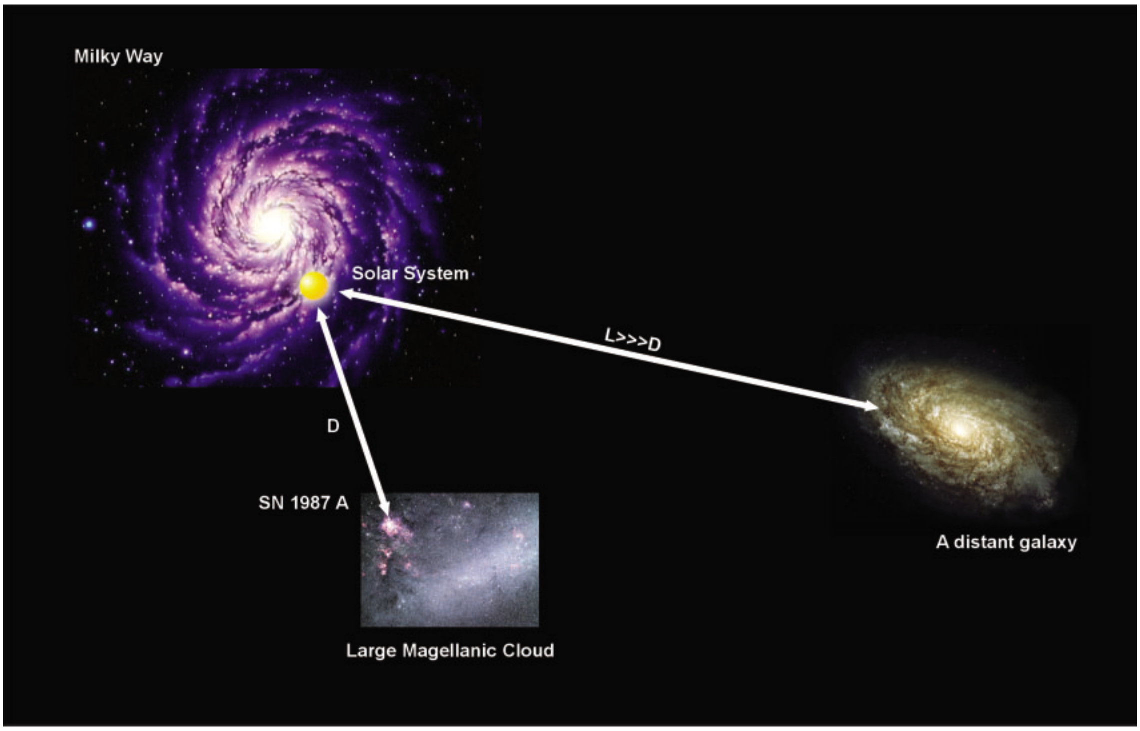


Figure 5: Measuring the distance between galaxies
If the distance of the LMC can be measured more accurately, then more precise distance measurements can also be made for other more distant galaxies.

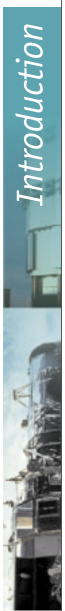
found in the LMC and in other more distant galaxies can also be used for distance measurements, so a more precise distance to the LMC would be a stepping-stone to more precise distance measurements for other, more distant galaxies.

The Ring

The first images of SN 1987A taken by the NASA/ESA Hubble Space Telescope were made using the ESA Faint Object Camera (FOC) on day 1278 after the outburst. Hubble was first launched in 1990 and then had to be set up in space, so that it was not possible to take images earlier. As well as being of great intrinsic interest, SN 1987A challenged even Hubble's very high resolution. The pictures of SN 1987A show three circular nebulae surrounding the supernova — an inner ring and two outer rings. In this exercise we use the inner ring only. The ring is too far from the supernova to be material ejected in the explosion. It must have been created earlier, probably as material from the dying star was carried out by the stellar wind during the last few thousand years of its life. It is not clear how the material was shaped into such a well-defined thin ring, but once formed, the material of the ring began to glow rapidly when a flash of ultraviolet light from SN 1987A reached it.

It is important to realise that the ring was present before the star exploded as a supernova. We will assume that the ring is a perfect circle, but inclined at an angle to a line joining Earth and the supernova so that we see an ellipse. If the ring were facing the observer all parts of the ring would have lit up simultaneously when the flash of light from the supernova reached it.

Introduction



However, as the ring is inclined, the nearer rim appeared to light up first (due to the finite speed of light) and then the light seemed to move around the ring, lighting the farthest point last (see Fig. 6). Note that the whole ring was actually illuminated at the same time, but that on Earth we *saw* the nearer rim light up first.

Since the gas continued to glow and only faded slowly after the light flash passed by, the total light emitted by the ring reached a maximum roughly when the whole circumference had been illuminated. This fact can be used to calculate the distance to SN 1987A.

The questions in the following tasks outline the steps to be taken to calculate the distance to the supernova using the angular size of the ring and a light curve that shows the evolution of the ring brightness with time after the explosion.

Figure 6: The Ring Lights Up
As this animation illustrates, the light from SN 1987A reaches the ring of matter around it and the ring lights up. The ring reached a maximum brightness around 400 days after the outburst. Note that even though the light reaches the different parts of the ring at the same time, we see the closest parts light up first (due to the finite speed of light). By measuring the observed time delay it is possible to derive the distance to SN 1987A. The images are taken from an animation sequence made by STScI/NASA.

Task 1

The first goal is to calculate the angular diameter of the ring, that is, the apparent diameter of the ring in arcseconds, as observed from Earth. This is the angle a.

The relative positions of stars 1, 2 and 3 in the image of SN 1987A (Fig. 8, p. 8), are given as angular separations (in arcseconds) in the data table below.

? Connect these values with direct measurements on the image to determine the scale of this image (in arcseconds/mm on the page).

Task 2

The ring around SN 1987A is assumed to be truly circular — the fact that it appears elliptical is due to the inclination or tilt of the ring (relative to the plane of the sky — the plane that is perpendicular to our line of sight to the supernova).

? You can measure the angular diameter of the ring in the image without knowing its inclination. Some people will say that this statement is obvious, while others will have to think it over to see that it is true. Explain why the statement holds. Look at Fig. 9 if necessary.

? Measure the diameter of the ring in mm in Fig. 8 and convert the answer to radians using the conversion factor you found in Task 1 and information in the Mathematical Toolkit.

	Distance (mm)	Distance (arcseconds)	Scale (arcseconds/mm)
Star 2 relative to star 1:		3.0	
Star 3 relative to star 1:		1.4	
Star 3 relative to star 2:		4.3	

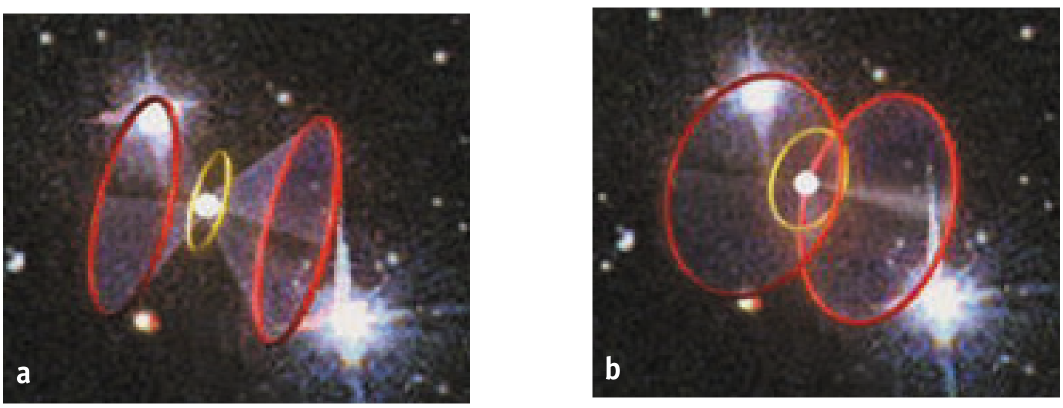


Figure 7: The rings
If we could view SN 1987A from a different angle we would see three circular rings with SN 1987A at the centre of the smaller one and the two biggest in parallel planes (Fig. 7a). However, from Hubble's point of view the three rings appear to be in the same plane (Fig. 7b) (courtesy of STScI/NASA).

Tasks

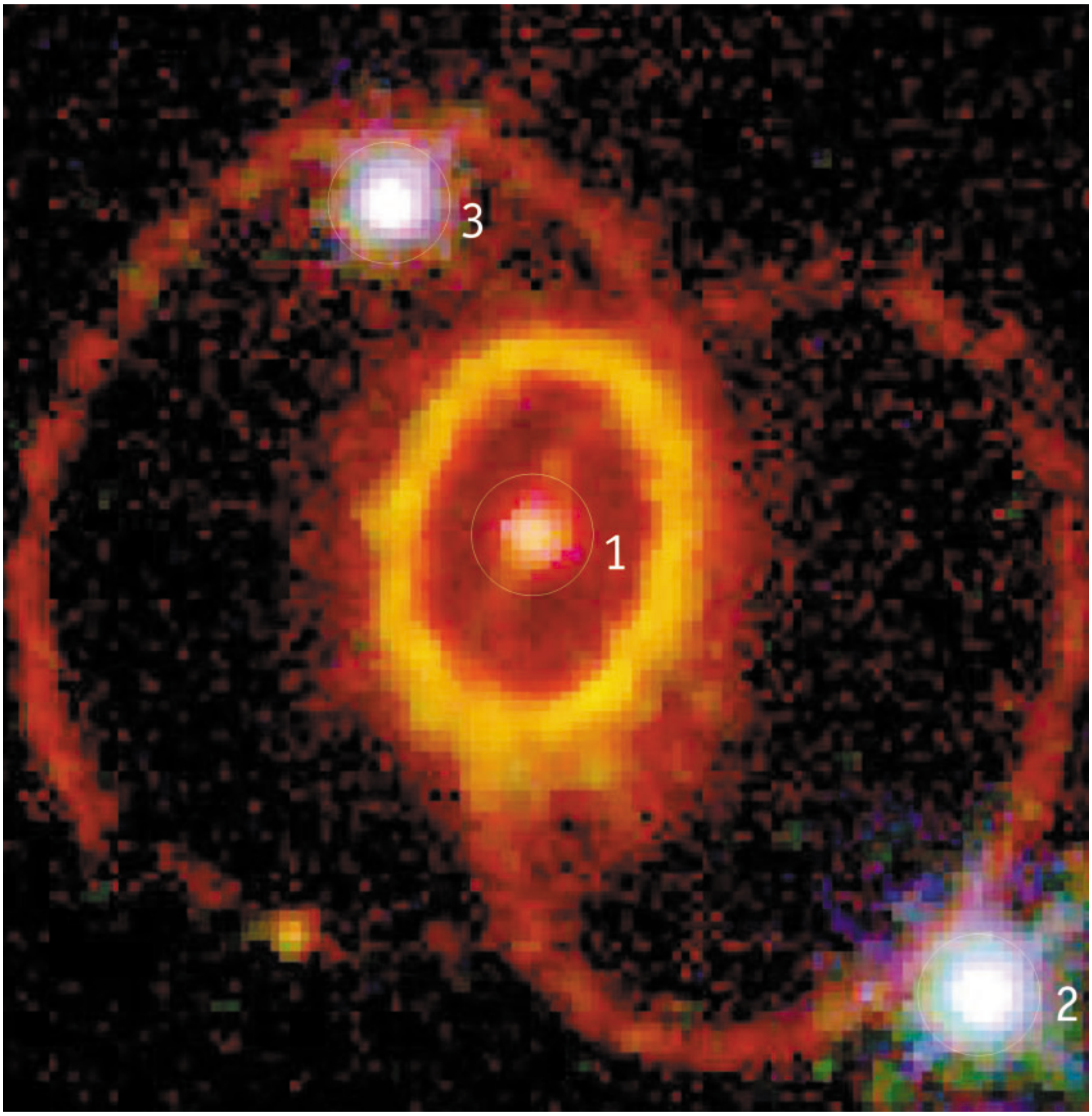


Figure 8: Stars around Supernova 1987A
This image was taken in February 1994 with the Wide Field and Planetary Camera 2 (WFPC2). WFPC2 has produced most of the stunning Hubble images that have been released as public outreach images over the years. Its resolution and excellent quality are some of the reasons that WFPC2 was the most used instrument during the first 10 years of Hubble's life. The filter used in the camera passes red light emitted by glowing hydrogen gas — the Balmer-α emission line.

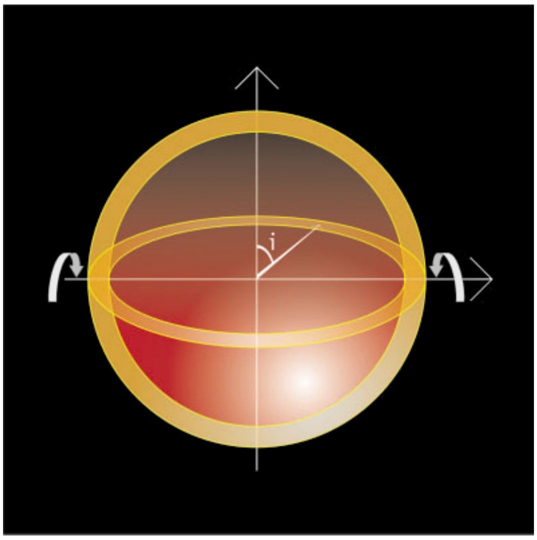


__Figure 9: An inclination__
An inclination angle, i, describes the tilt of an object, e.g. a ring, away from the plane of the sky.

Task 3

The inclination angle is called i. If i = 0° or i = 180° we see a circle, and a line if i = 90°. For any other value of i between 0° and 180°, we see an ellipse.

? How can you determine i from the measurement of the major and minor axes of the ellipse? Figs. 9 and 10 might help in deriving this relationship.

__Figure 10: Determination of the inclination angle, i__
Imagine that we are now looking at the system from the side, so that we see the ring with an inclination angle, i, relative to the plane of the sky (this plane is perpendicular to the observer's line of sight).
The inclination angle can be derived from a simple relation between the minor and major axes of the observed ellipse. The nearest part, A, and the furthest part, B, of the ring are indicated.

? Measure the major and minor angular diameters of the ellipse and calculate the inclination angle, i, from the relationship you just found.

Task 4

Now we have the angular diameter of the ring and its inclination. We still need to find the true diameter in the plane of the sky, d, to determine the distance.
The key to finding the true diameter of the ring is our knowledge of the speed of light.

When the supernova explodes, it emits a very bright flash of light. This flash expands into the surrounding space at the speed of light, c. Later, at some time, t seconds after the explosion, the flash will illuminate the ring. Since we have assumed that the ring is circular and we will also assume that its centre coincides with that of the supernova, all parts of the ring will be illuminated simultaneously, as seen from the supernova.
Consider how this will appear as seen from Earth. Although all parts of the ring 'see' the supernova flash at the same time, we do not see

the whole ring light up simultaneously because the ring is inclined. The part of the ring that is inclined towards us will appear to brighten first as light from this point has a shorter distance to travel to reach Earth. Only when the whole ring is illuminated as seen from Earth, will the light curve reach its maximum. The difference in the distance between the near and far points of the ring can then be calculated from the elapsed time between these events in the light curve. So the time it takes from when we first see the ring illuminated until the light curve reaches its maximum is closely related to the difference in distance between the nearest and the furthest points of the ring. The light curve for the ring of SN 1987A is shown in Fig. 12.

? Measure this time t from the light curve of the ring of SN 1987A.

? Had the inclination angle been 90 degrees, it would have been very simple to relate this time to the diameter of the ring — why?

Task 5

To do the next calculation we have to use another approximation (see Fig. 13a and 13b). We

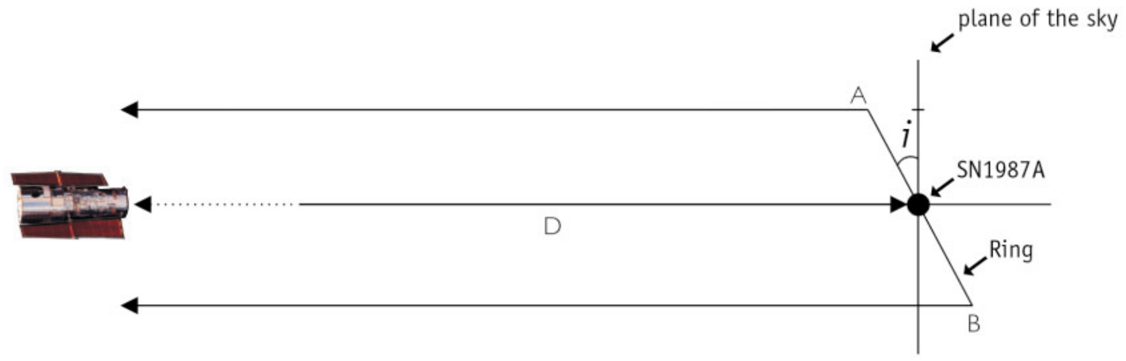


Figure 11: The journey of the light
The flash from SN 1987A hit the whole ring at the same time. So the nearest part, A, and the furthest, B, were illuminated at the same time and they simultaneously radiated light towards the observer on Earth. The light emitted from B had further to travel due to the inclination of the ring.

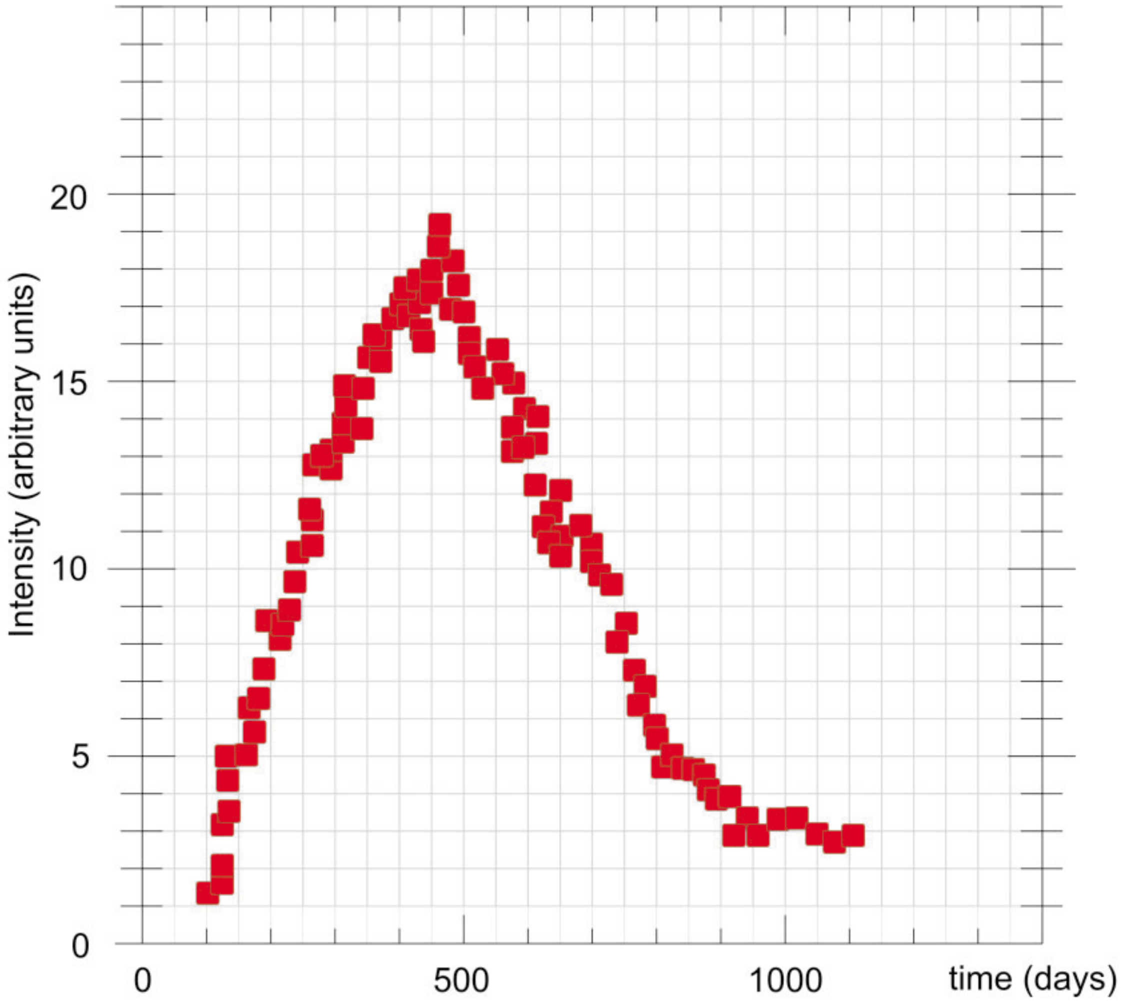


Figure 12: Light curve for the ring
Here we show measurements from the total light of the ring as it lit up in the months after the supernova exploded. The total intensity of the ring starts to increase as the light from the nearest parts of the ring reaches us. When the ring is fully lit (as seen from Earth) the light curve reaches its maximum. These measurements were made with the International Ultraviolet Explorer (IUE) — another space-based observatory.

will assume that the lines connecting the Earth to the points A and B, the furthest and nearest points to Earth on the ring, are parallel. This is a valid assumption since the angular diameter of the ring, a, is so small compared to the distance, D. Hence the angles i and j are equal.

? Look at the diagram (Fig. 13) and use it to find a relationship between:

1. The difference in the distance travelled by light coming from the nearest point, A, on the ring and from the furthest point, B. We call this distance d_p.

2. The true diameter of the ring, d

3. The inclination angle, i (calculated in task 3)

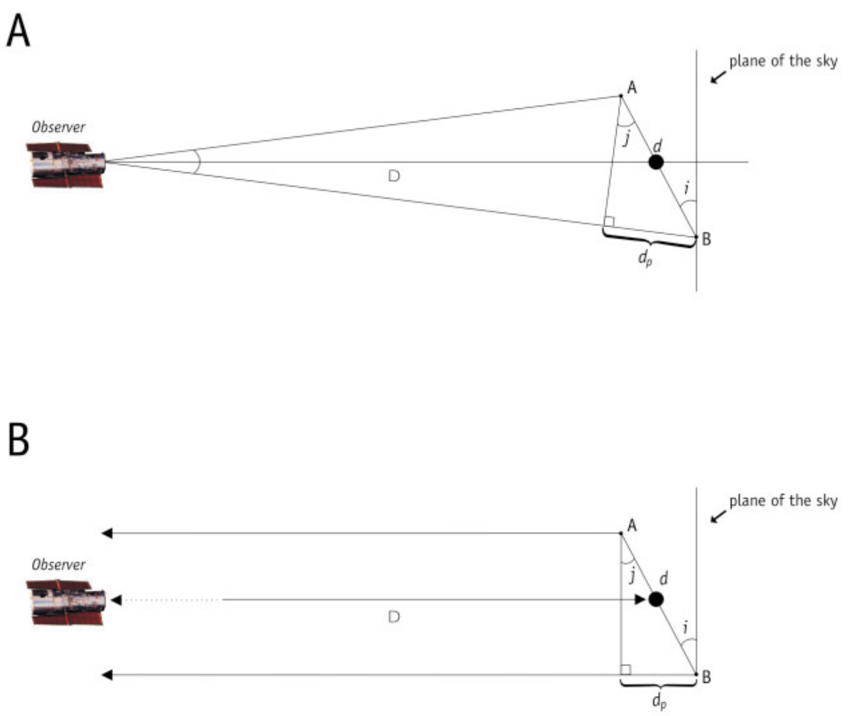


Figure 13: Finding the true diameter
With the help of this figure and values found previously, it is possible to determine the true diameter, d, of the supernova ring. In 13a a schematic shows the real situation, but due to the large distance to LMC it is reasonable to assume that the lines connecting Earth with A and with B are parallel. This assumption is illustrated in Fig. 13b.

- ? Then find a relationship between the difference in distance, d_p, the speed of light, c, and the time, t.

- ? Combine these two expressions to find an expression for the true diameter of the ring, d.

- ? Enter the values that you have previously either calculated or measured into this expression and find the true diameter, d, of the ring.

Task 6

You are now ready for the grand finale!

- ? Use the values of d and the angle a (calculated in task 2) to determine the distance to the supernova, D (use the small-angle approximation in the Mathematical Toolkit). Give the answer in kiloparsecs using the conversion factor given in the Mathematical Toolkit.

A clue to check your answers...

The distance to the supernova has been calculated by Panagia et al. (1991) from the original versions of this data. The value they find is D = 51.2 ± 3.1 kpc and they have measured the inclination angle as i = 42.8 degrees ± 2.6 degrees.

If your answers are within a 20% margin of error, you have made accurate measurements as well as thorough calculations and can be very proud of your work.

- ? Can you think of some reasons why your results differ from the scientists' result?

This task does not address the question of the two outer rings.

- ? Can you speculate on the origin of these?

Further Reading

Scientific Papers

- Fransson, C., Cassatella, A., Gilmozzi, R. Kirshner, R. P., Panagia, N., Sonneborn, G., and Wamsteker, W., 1989, Ap.J., 336, 429-441: *Narrow ultraviolet emission lines from SN 1987A Evidence for CNO processing in the progenitor.*

- Gould, A., 1994, Ap.J., 425, 51-56: *The ring around supernova 1987A revisited. 1: Ellipticity of the ring.*

- Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H.M., Kirshner, R.P. 1991, Ap.J., 380, L23-L26: *Properties of the SN 1987A circumstellar ring and the distance to the Large Magellanic Cloud.*

- Jakobsen, P., Albrecht, R., Barbieri, C., Blades, J. C., Boksenberg, A., Crane, P., Deharveng, J. M.,Disney, M. J., Kamperman, T. M., King, I. R., Macchetto, F., Mackay, C. D., Paresce, F., Weigelt, G., Baxter, D., Greenfield, P., Jedrzejewski, R., Nota, A., Sparks, W. B., Kirshner, R. P., Panagia, N., 1991, ApJ, 369, L63-L66: *First results from the Faint Object Camera – SN 1987A.*

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http://www.astroex.org/

Colophon

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Teacher's Guide

Quick Summary

The geometry of the nearest ring around Supernova 1987A (SN1987A) is introduced. We then define the scale of the Hubble image of the supernova so that the angular diameter of the ring and also the inclination of the ring relative to the plane of the sky can be found.
Observations from Earth show how light from the supernova reached the different parts of the ring. Using light intensity measurements and the speed of light, the physical dimensions of the ring can be found. Once both the angular and the physical size of the ring have been determined, we can determine the distance to SN 1987A itself.

This teacher's guide contains solutions to the problems together with comments and discussion of any approximations and simplifications that have been made. The aim is to maximise the usefulness of the exercise and to assist the teacher in preparing a teaching plan.

Task 1

Example measurements, made by hand, using a ruler on a 149 mm × 152 mm version of the printed image (the printed size depends on the printer):

	Distance (mm)	**Distance (arcseconds)**	**Scale (arcseconds/mm)**	**Average Scale (arcseconds/mm)**
Star 2 relative to star 1:	89 mm	3.0	0.03371	
Star 3 relative to star 1:	50 mm	1.4	0.02800	0.03111
Star 3 relative to star 2:	136 mm	4.3	0.03162	

Task 2

The angular diameter of the ring is found by measuring the largest dimension of the ellipse seen. The projection of a circle will always display the diameter somewhere, no matter how the circle is tilted.

The measured apparent diameter of the ring: 51 mm.
Conversion to radians:

$a = 51 \text{ mm} \times 0.03111 \text{ arcsec/mm} \times 4.848 \times 10^{-6} \text{ rad/arcsec} = \mathbf{7.6917 \times 10^{-6} \text{ rad}}$

Task 3

Some people have difficulties with spatial perception in 3D when looking at a 2D diagram — i.e. to 'de-code' a diagram that simulates perspective (for example an isometric projection) using a view in cross-section. Take care with this topic and comment on the diagrams if necessary. The approximation that considers light rays as parallel when the source is far from the Earth is generally well known by students (it is often used for light rays coming from the Sun).

Every ellipse can be thought of as the projection of a circle tilted at an angle, i (the inclination) to the plane of the sky (this plane is perpendicular to the line of sight). The major axis is equal to the diameter of the circle and the minor axis is cos(i) times the major axis.
It follows that:
$\cos i = \text{minor axis} / \text{major axis} = 37 \text{ mm} / 51 \text{ mm}$

$i = \cos^{-1}(37/51) = 0.7591 \text{ rad} = \mathbf{43.49 \text{ deg}}$

Task 4

On the graph you can measure the distance on the time-axis between the beginning of the highlighting of the ring and the maximum intensity. We read **t = 399 days** from the graph — it is pure coincidence that the elapsed time is close to a year.

Had the inclination been 90 degrees, the ring would appear as a line. In this case the difference in time between the moment when we see the first light and the moment when we see the furthest edge light up is just the diameter of the ring divided by the speed of light.

Task 5

$\sin i = d_p/d \Rightarrow d = d_p/(\sin i)$
$d_p = c \cdot t$

Combined:

$d = d_p/(\sin i) = (c \cdot t)/(\sin i) = (2.997 \times 10^8 \times 399 \times 24 \times 3600)/(\sin(43.49)) = \mathbf{1.5012 \times 10^{16}\ m}$

Task 6

$D = d/a = (1.5012 \times 10^{16})/(7.6917 \times 10^{-6}) = 1.9517 \times 10^{21} = \mathbf{63.2\ kpc}$

The distance calculated by Panagia et al. from the original data (using a more sophisticated method of calculation) is D = 51.2 ± 3.1 kpc. (The value we obtain is within a reasonable margin of error.)

Sources of error

It is possible to use this question to introduce a more formal calculation of margins of error by asking students to repeat the calculation using the smallest and largest possible measurement values. Here are the trends:

Too large an angular diameter, a => too small D (the closer something is, the larger it looks)

Too large an apparent diameter => too small D

Too large a conversion factor => too small D

Too small t => too small D

Too large i => too small D

It is a good exercise for the students to work out these trends for themselves.

The origin of the two outer rings

The question of the origin of the outer rings is a good example of a simple scientific question with no clear answer (these occur quite often in a front line science like astronomy).
The scientific community does not agree on their origin, but it is known that the rings were expelled from the progenitor star more than 20,000 years before it exploded as a supernova. Why they are so well defined is a complete mystery. It is believed that a red giant star normally ejects its outer layers uniformly in all directions.

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