DISTANCE TO THE CRAB NEBULA

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Within this use case you learn about supernovae, exploding or exploded stars. In particular you will use information on the Crab Nebula (the 1054 aD supernova registered by Chinese astronomers) to derive its distance: an example of how some very important information may be gained from very simple arguments and geometry.

If used in the classroom this use case requires a very basic knowledge of the relation between angles and sides of triangles. If used in more advanced classes it may be a good demonstration of the power of trigonometry.

1 Introduction

The Crab Nebula (M1) is a supernova remnant observable in the constellation of Taurus. The bright supernova "SN1054" that originated the remnant was recorded by Chinese and Arab astronomers in 1054 A.D.
The fact we know the year of the explosion allow us to compute the expansion rate of the gas shell, and then, by comparison between angular and real dimensions of the nebula, obtain its distance.

2 The Crab Nebula

In visible light, the Crab Nebula consists of a oval-shaped mass of filaments that are the remnants of the progenitor star (fig. 1).

Fig. 1: Optical image of the Crab Nebula.

At the center of the nebula lies the Crab Pulsar, a rotating neutron star, which

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emits pulses of radiation from gamma rays to radio waves.
At the beginning of 20th century, the analysis of early photographs of the nebula taken several years before revealed that it was expanding. Moreover, tracing the expansion back revealed that the nebula must have become visible on Earth about 900 years ago. Historical records reported that a new star bright enough to be seen in the daytime has been observed in the same part of the sky by Chinese and Arab astronomers in 1054 A.D. Given its large distance, the daytime "new star" observed by the Chinese and Arabs could only have been a supernova.
Thanks to the recorded observations of 1054, the Crab Nebula became the first astronomical object connected to a supernova explosion.
The nebula was independently rediscovered in 1758 by Charles Messier as he was observing a bright comet. Messier catalogued it as the first entry in his catalogue of nebular objects.
In our Milky Way and in the nearby galaxies few tens of supernova remnants similar to the Crab Nebula have been observed. The most famous are the remnants of supernovae SN1006, SN1572 (observed by Tycho), SN1604 (observed by Keplero) and SN1987A (exploded in the Large Magellanic cloud).

X-ray astronomy

The Crab Nebula is a beautiful example of an astronomical object that emits radiation along all the electromagnetic spectrum. In particular, some of its features are observable only at high energies, for example in the X-ray wavelengths.
X-rays are absorbed by Earth atmosphere, so astronomers have to put their high energy telescopes in orbit around the Earth. X-ray astronomy was born in the 60s, with the launch of the first rocket with a X-ray detector onboard. Since then have been launched many X-rays satellites that mapped the X-ray sky.
X-ray astronomy improved our knowledge of pulsar (rotating neutron stars) and many other astronomical objects, like black holes and supernovae.

3 Aladin

Aladin is an interactive sky atlas developed and maintained by the Centre de Donnèes astronomiques de Strasbourg (CDS) for the identification of astronomical sources through visual analysis of reference sky images. It is available for download here: https://aladin.u-strasbg.fr/java/Aladin9.0.jar.
Aladin allows the user to visualize digitized images of any part of the sky, to superimpose entries from the CDS astronomical catalogues and tables, and to interactively access related data and information from various data servers (like SIMBAD, NED, VizieR). In this usecase we use Aladin in the *undergraduate* mode (developed in the framework of the EuroVO-AIDA European project).

4 Linear size of the nebula

The simplest method to obtain the linear size of the nebula is to multiply the expansion velocity by the time passed since the explosion.
We know, from spectroscopic measurements, that the Crab Nebula is currently expanding at about 1500 km/s.
In this tutorial we analyse an image of the Crab Nebula as recent as possible and consider the expansion constant. This simplification gives us an approximated result, but enough accurate for our aims.

Start Aladin and switch to the undergraduate mode from the menu:

edit -> user preferences -> profile -> undergraduate.

Restart Aladin in order to validate the new configuration.
Open the server selector window:

File -> Load astronomical image
-> Aladin image server

In the field “target” enter “M1” and press “submit”. The list of available images appears (fig. 2): look at the dates of the images and load in Aladin the most recent one (taken in 1998).
We use this Crab Nebula image in the next step, when we will compute its projected angular size.

Now we need only to know the year the image has been taken. We calculate the time passed since the explosion (1054):

(1998 - 1054) yr = 944 yr = $2.97 \cdot 10^{10}$ s.

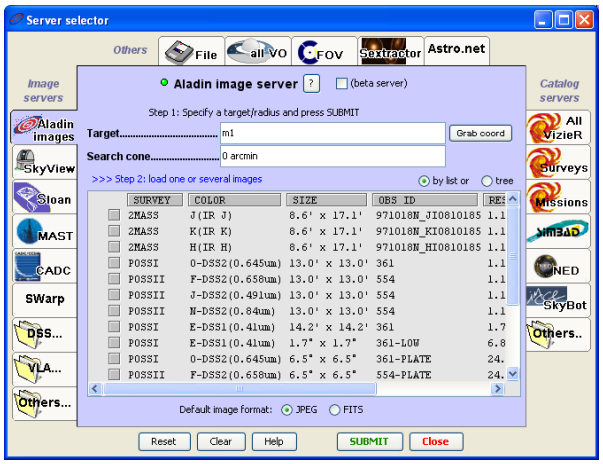

Fig 2: The server selector window with the list of available image.

We multiply this time by the velocity and obtain the linear size (the radius) of the nebula:

$R = 2.97 \cdot 10^{10}$ s $\cdot$ 1500 km/s =
$= 4.46 \cdot 10^{13}$ km.

5 Angular size of the nebula

In order to compute the angular size of the nebula we use the tool “dist” and track a vector from the center of the nebula to the outermost visible part.
The outer parts of the nebula are very faint, so we adjust the intensity distribution by increasing the contrast of the image.
The center of the nebula matches with the pulsar (marked on the image). Let the distance vector start from the pulsar and end it in the farmost region of the nebula you can see (probably in the upper right angle of the image).
The modulus of the projected angular distance vector ranges between 2.6’ and 2.8’. In the case of fig. 3 it is

r = 2.66’.

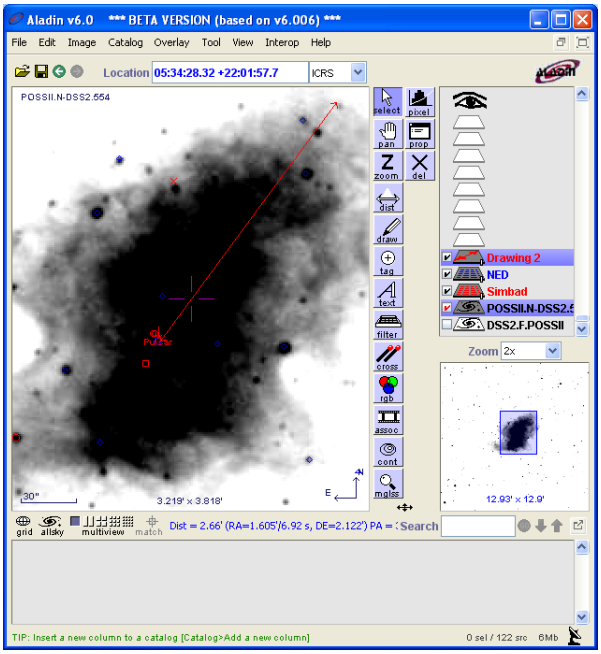

Fig. 3: the distance vector for computing the angular size of the nebula.

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6 Distance to the Crab Nebula

We now have both the linear and the angular size of the nebula: by comparing them we can compute its distance from us.
In order to obtain the distance in parsec we have to express the sizes in the proper units: the linear size in parsec and the angular size in radians.

$$1 \text{ pc} = 3.085 \cdot 10^{16} \text{ m}$$

$$R = 4.46 \cdot 10^{13} \text{ km} = 4.46 \cdot 10^{16} \text{ m} = \\ = 1.44 \text{ pc}.$$

Then

$$1 \text{ rad} = 206264''$$

$$r = 2.66' = 159.6'' = 7.73 \cdot 10^{-04} \text{ rad}.$$

We finally compute the distance to the Crab nebula:

$$d = R / r = 1.44 / 7.73 \cdot 10^{-04} = \\ = 1860 \text{ pc} = 1.86 \text{ kpc}.$$

The correct value of the distance to the Crab Nebula is about 2 kpc (6500 light years), very close to the value obtained with our simple analysis. In particular our value is a little low because of the approximations of our procedure.

7 Hubble Space Telescope images of the Crab Nebula

Aladin can access the archive of the Hubble Space Telescope and load its amazing images.
In order to load the images of the Crab Nebula open the server selector, then in the left column select “Hubble press release image”, in the field “target” enter “M1” and press “submit”.

The list of available images appears (fig. 4).

Fig. 4: Images of the Crab Nebula available in the Hubble Space Telescope Archives.

For example, if you want to see the pulsar you can load the image “Combined X-rays and optical images of the Crab Nebula” (fig. 5).

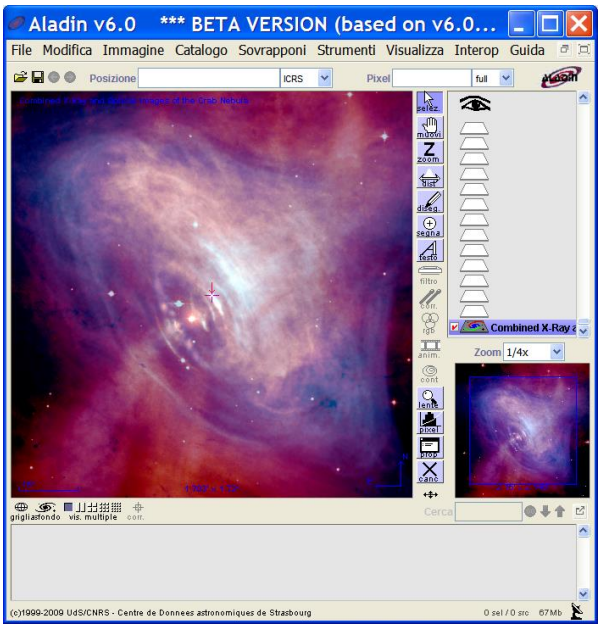

Fig. 5: Combined X-Rays and Optical images of the Crab Nebula.

By loading “A Giant Hubble Mosaic of the Crab Nebula”, you can see the amazing image of the entire nebula (fig. 6).

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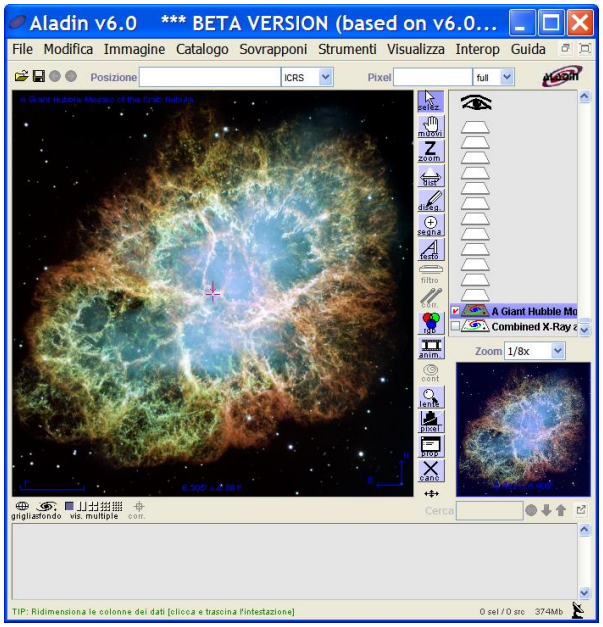

Fig. 6: Giant Hubble Mosaic of the Crab Nebula.

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