The Crab Nebula

Adapted from `http://www.astro.lsa.umich.edu/Academics/Undergrad/labs.php`

Introduction

Today, we will study the famous Crab nebula, which is in fact the remnants of the bright supernova of 1054. This supernova was recorded by Chinese astronomers to have been visible during the day for 23 days and in the nighttime sky for two years. In 1968, radio astronomers Staelin and Reifenstein found the neutron star at the core of the nebula. The star's magnetic field causes it to emit beams of light from its magnetic poles. As these beams sweep by, the neutron star appears to blink on and off, and so we call it a "pulsar."

Part I: Finding the Crab Nebula's Age

For this part of the lab, you will need the photographs taken of the Crab nebula in 1973 and 2000 so that you can find the rate of expansion.

1. You must first obtain the scale for each photograph. Measure the distance between stars A and B, estimating to the nearest 0.1mm. Knowing that the angular distance between the stars is 385 arcseconds, find the scale of each photo in units of [arcsec/mm].

Date	Distance between Marked Stars (mm)	Photographic Scale (arcsec/mm)

2. Find the location of the pulsar on the photos, marked by a four-point star. Construct a table as follows:

Knot	Grp	r ('73)	θ ('73)	r ('00)	θ ('00)	$d\theta$	ω ("/yr)	ΔT (yr)
1	1	...	...	...	...	...	...	...
1	2	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...

   Four structures in the Crab nebular are enumerated on the photographs. Use a millimeter ruler to measure the distance of each knot, to the nearest 0.1 mm, from the pulsar on both photos. Convert to arcsec using the scale from step 1.

3. For each knot, calculate the average speed of the ejected material in [arsec/yr] using the following formula for angular velocity:

$$w = d\theta/dt \tag{18}$$

4. Now, solve for the total time since the explosion using the simple relation

$$\Delta T = \theta/w\,. \tag{19}$$

   Find the estimated expansion time for each knot. Write your four values for ΔT on the chalkboard, along with your group number.

5. Finally, we measure ΔT by taking the average of all values. Furthermore, we determine our uncertainty as follows:

$$\sigma_{\Delta T} = \sqrt{\frac{\sum (\Delta T_i - \bar{\Delta T})^2}{N(N-1)}}\,. \tag{20}$$

6. Compare your value for the date of the supernova event to the accepted value of 1054. What does this suggest about the expansion velocity of the nebula? Explain.

7. In a similar manner, determine $\bar{\omega}$ and its uncertainty.

Part II: The Distance to the Crab Nebula

In its actual motion, v, across the plane of the sky, a knot can be considered as having traversed a tiny fraction of the circumference of the celestial sphere. (The total circumference is $2\pi d$, where d is the distance from the observer to the nebula.) Thus, we can set up a relation between the angular and spactial velocities:

$$w/360^\circ = v/2\pi d \tag{21}$$

We have found the angular rate of expansion, w, of the Crab Nebula. Therefore, if we measure v, we can solve for the distance, d. To accomplish this, we will use the the spectral properties of a supernova remnant and our knowledge of Doppler shifts.

Look at the spectrum of the Crab Nebula. In this negative image, the bright emission lines of the nebula and laboratory comparison spectra above and below show as dark lines. The spectrum is produced by the bright filament of the nebula. Notice that each of the filaments is either red-shifted or blue-shifted, with nothing in between. This occurs because we are seeing material that is either at the very near side of the nebula, rushing towards us, or material at the back side of the nebula, rushing away. The filaments are on the outer edges of the nebula.

8. Examine carefully the region around the [OII] 3727 line on the Crab Nebula Spectra. First calculate the spectral scale using the 3690Å and the 3719Å palladium lines in Å/mm.

9. Measure (in mm) the maximum Doppler shift between the blueshifted and redshifted branches of the [OII] 3727 "necklace". Use the scale you found in the previous step to convert to Å.

10. Use the Doppler formula to calculate the relative velocity between the approaching and receding filaments in km/s. Show your calculation.

$$\frac{\Delta\ell}{\ell} = \frac{v}{c} \tag{22}$$

11. What final step must we perform to determine the expansion velocity? Perform it.

12. Use equation 21 to calculate the distance to the Crab Nebula in light years. Show your work, and be careful with units.

13. Use error propagation to calculate your uncertainty in the distance.

Thinking Questions

14. When calculating the date of the supernova explosion, what did you assume about the velocity of the gaseous knots?

15. When calculating the spatial velocity of expansion in km/s and the distance to the Crab Nebula, what have you assumed about the shape of the nebula?

16. With the high resolution of radio telescopes, namely the Very Long Baseline Interferometer, you can use the method of expansion parallax for supernova remnants that are much farther away from us than the Crab Nebula. Supernova 1987A exploded in the large Magellanic Cloud and was first observed on February 23, 1987. At that point, the remnant had a radius of zero. 5.2 days later, the remnant had a radius of 0.0022". The radial velocity of the nebula was 36,000 km/s. What distance does this suggest to the Large Magellanic Cloud?