SUPERNOVA REMNANT A

IMAGE A1 – taken in 2019

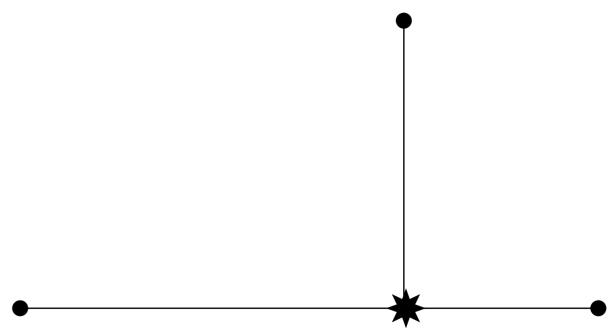
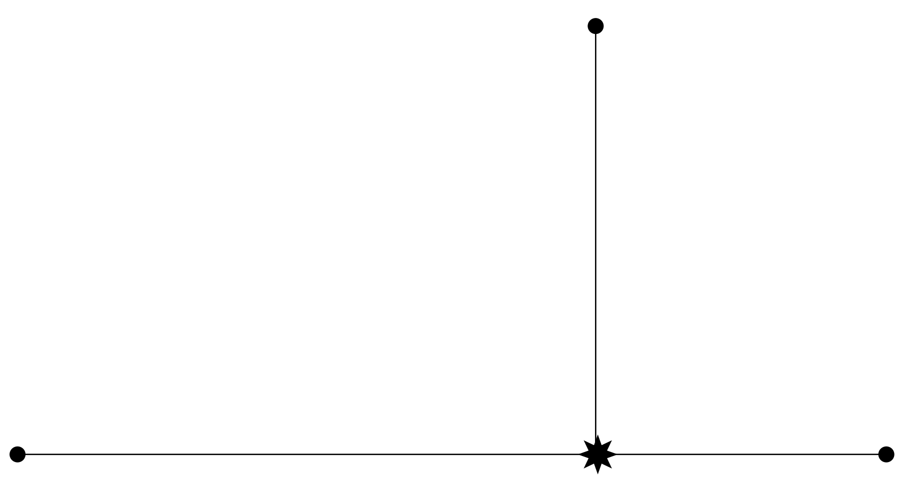


IMAGE A2 – taken in 2020



SUPERNOVA REMNANT B

IMAGE B1 – taken in 2018

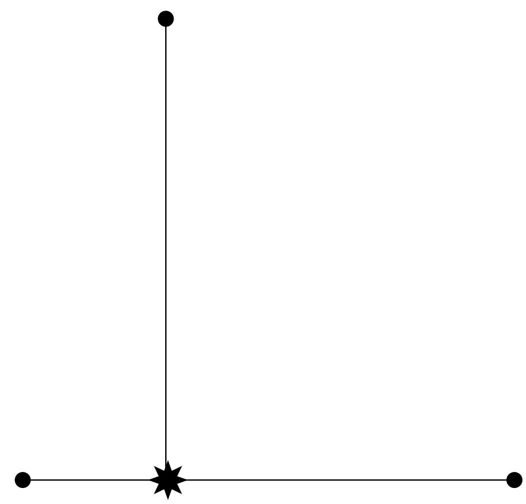
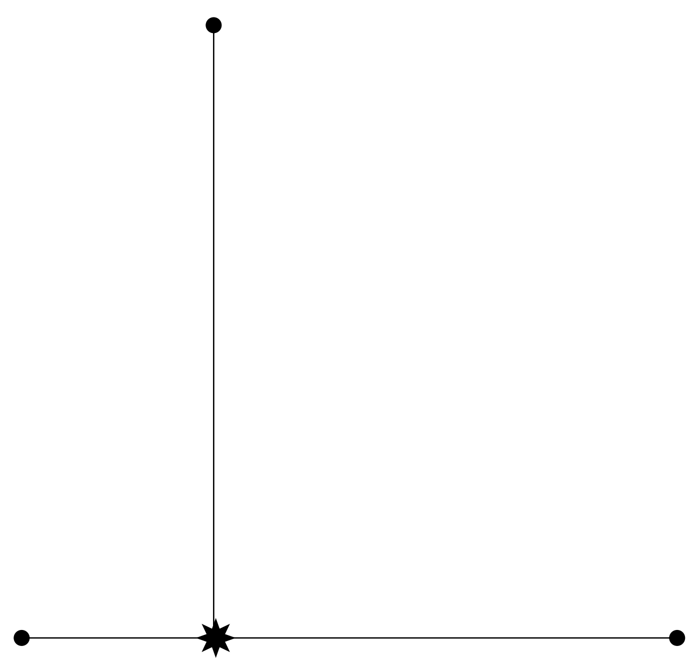


IMAGE B2 – taken in 2020



SUPERNOVA REMNANT C

IMAGE C1 – taken in 2015

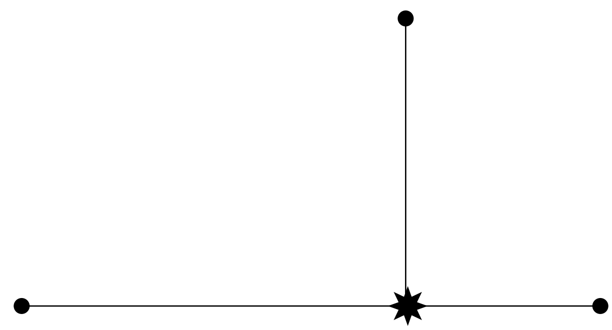
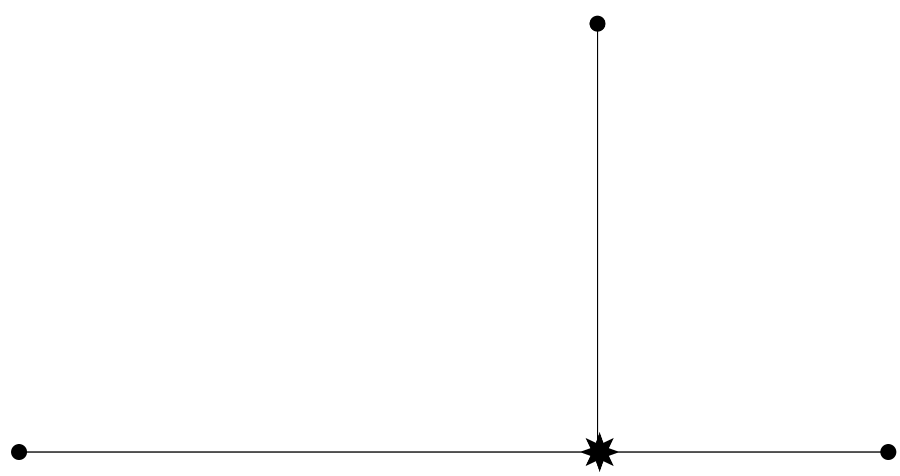


IMAGE C2 – taken in 2020



SUPERNOVA REMNANT D

IMAGE D1 – taken in 2017

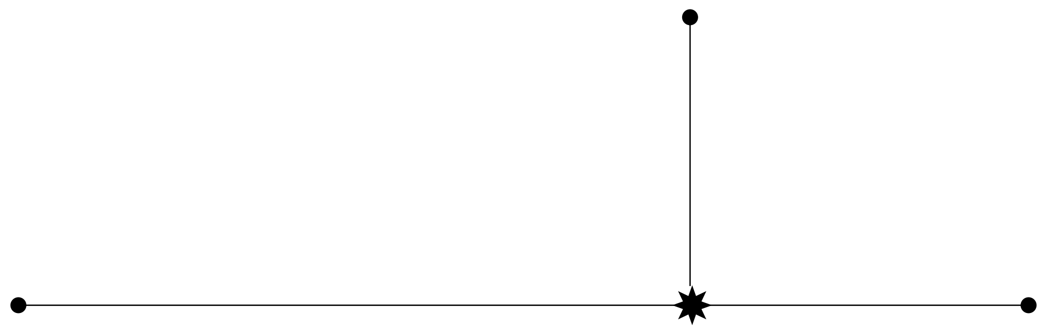


IMAGE D2 – taken in 2020

SUPERNOVA REMNANT E

IMAGE E1 – taken in 1983

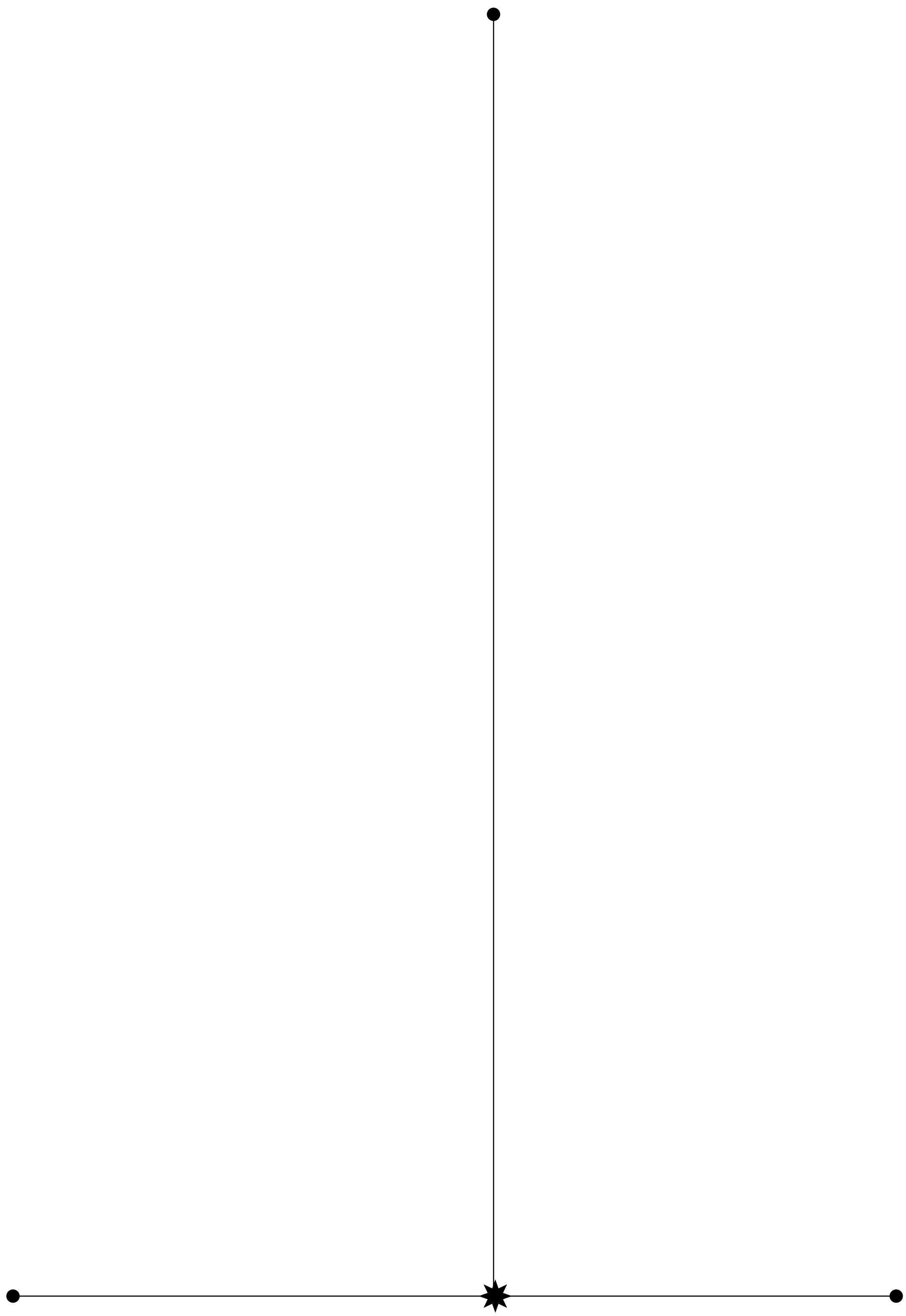
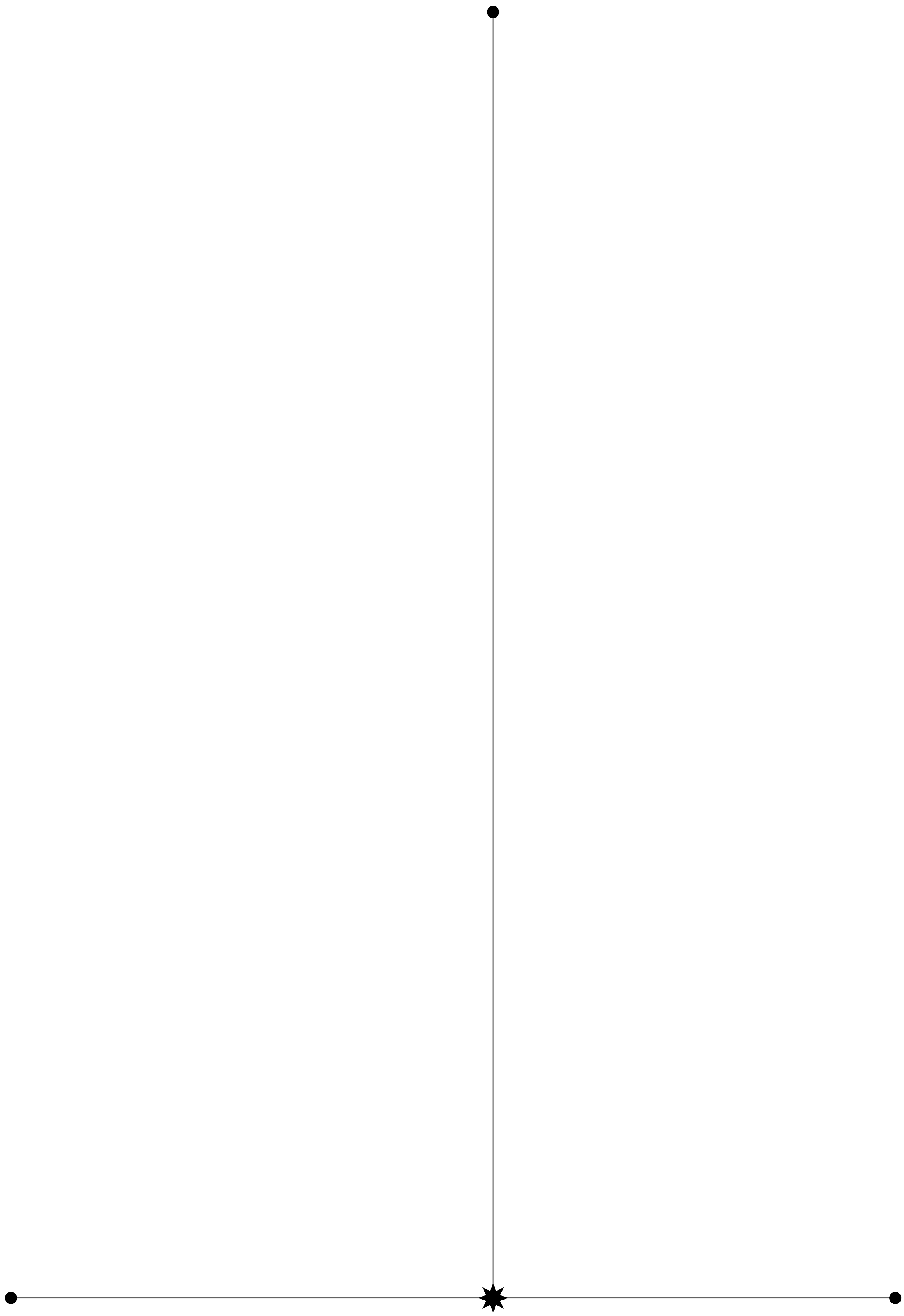
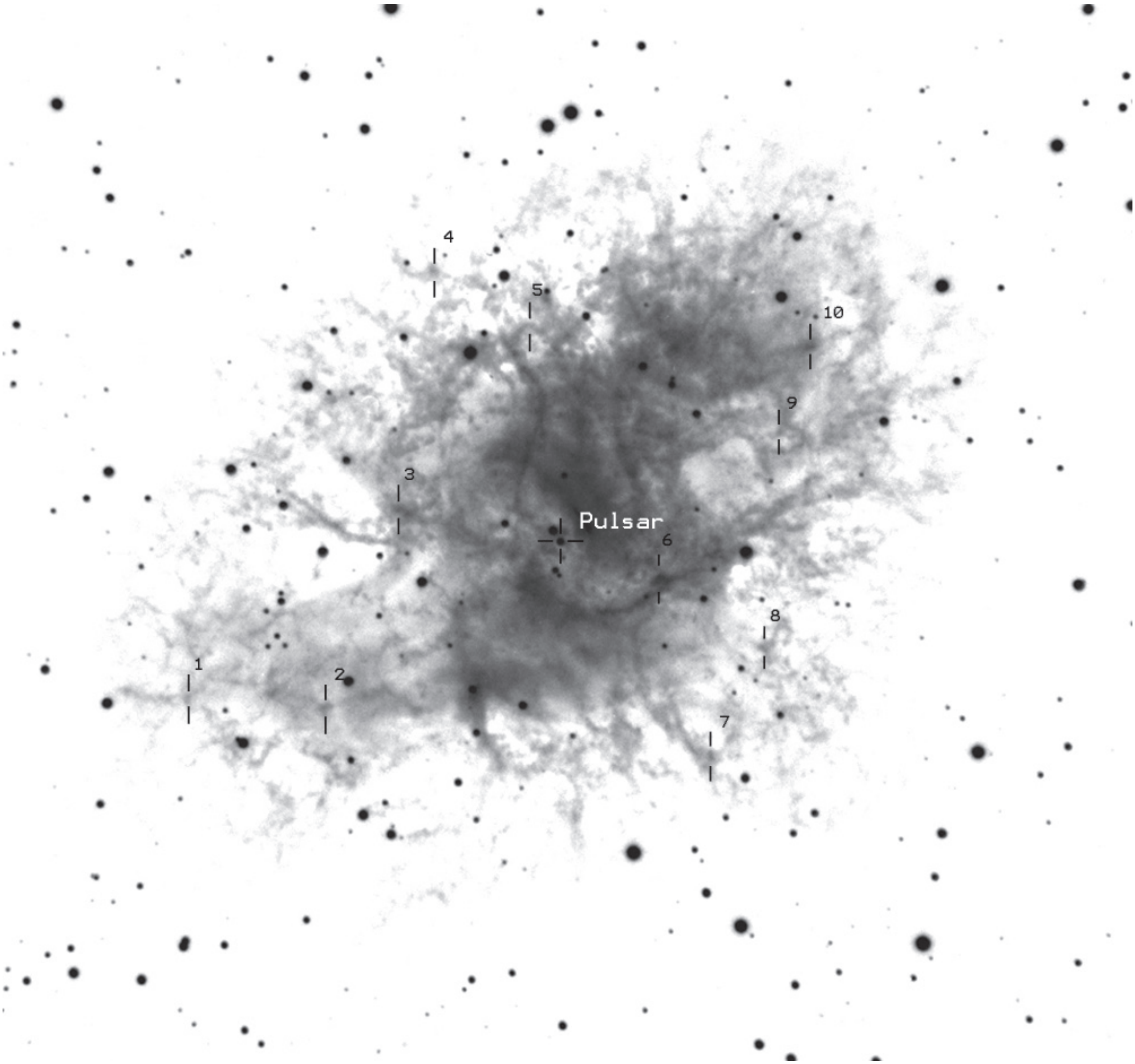


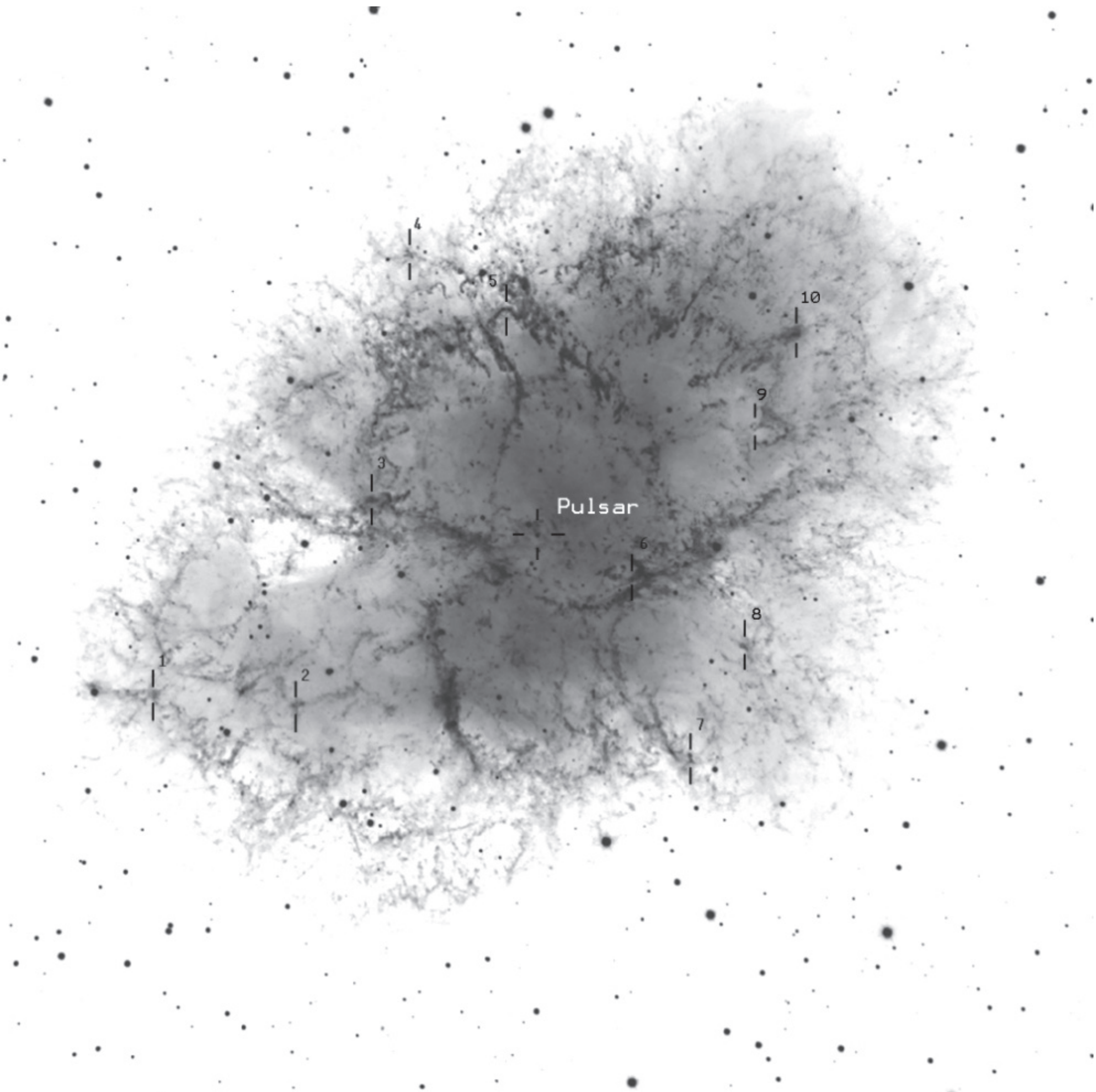
IMAGE E2 – taken in 2020



The Crab in 1956



The Crab in 1999



INTRODUCTION TO SUPERNOVAE

According to the Annals of the Sung Dynasty (the Sung-shih), on the first day of the chi-ho reign period, during the 5th month, on the chi-chou, a "guest star" appeared to the south east of Tian-kuan. The guest star was so bright that it could be seen during the daytime, and it remained so for 23 days. After that, it gradually dimmed, finally fading from visibility after two years. Japanese records also mention the star.

Crab nebula

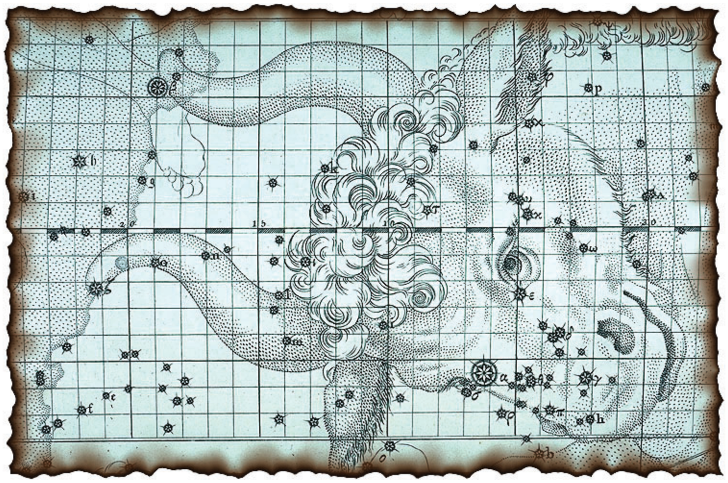
This impressive object may have also been recorded in disparate cultures around the globe, including Europe, Asia, and possibly even North America. However, the date given in the Chinese annals, by our modern reckoning, would have been July 4, 1054. At that time Europeans were in the throes of the Dark Ages, and the Norman Invasion was just a few years away. Perhaps they were too occupied with worldly concerns to mark down the appearance of a celestial visitor (though the Bayeux Tapestry, created just a few years later, has a clear depiction of Hally's comet). Perhaps whatever record existed has been lost. In any case, no definitive European record of the event has ever been found.

Since the appearance nearly a millennium ago of the Sung "guest star" there have been only two other similar objects seen in our **Galaxy**. One occurred in 1572 in the constellation Cassiopeia. This was observed by the Danish astronomer Tycho Brahe and bears his name. It became bright enough to be visible in full daylight. The other star appeared in the constellation Ophiuchus in 1604 and was studied by Tycho's student and collaborator, Johannes Kepler, though it was seen earlier by several other people. Kepler's star, while not as bright as Tycho's, was still as bright as Jupiter. Since the appearance of Kepler's star, no others have been seen in the Galaxy.

This does not mean, however, that no additional similar objects have been observed. In 1885 a new star appeared in the center of the Milky Way's companion galaxy M31, in the constellation of Andromeda. It reached a peak brightness of 6-7th **magnitude**, making it easily visible in small telescopes against the background glow of the galaxy itself. The object is important for historical reasons: it was used to argue, incorrectly, that the great spiral nebula of Andromeda was not a galaxy in its own right, but instead a much smaller object inside the Milky Way. The astronomer Harlow Shapley, in a famous 1920 debate with Heber Curtis on the nature of the spiral nebulae, assumed the "new star" was a relatively low-energy event, and that meant it was close by as such things go. His argument was later shown to be wrong. Edwin Hubble measured the distance to the Andromeda nebula and proved it was well outside our Galaxy, and was, in fact, an independent system of stars – a galaxy on a par with the Milky Way. The great distance of Andromeda meant that the star seen in 1885 was very energetic indeed.

Though these guest stars are rare events in any given galaxy, the universe contains many, many galaxies. With the advent of large telescopes in the 1920s and 30s it was soon noticed that guest stars could be seen quite often if one looked at many galaxies. The fact that the guest stars were nearly as bright as the galaxies in which they occurred meant that they were enormously energetic. Their great brightness and release of energy prompted the astronomer Fritz Zwicky to dub them **supernovae**, because they appeared similar to, but far brighter than, the "novae" seen in our galaxy. Supernova is the name by which we still call them today, though we now know they have nothing in common with novae except a name: supernovae are exploding stars, whereas a nova is the much smaller explosion of the atmosphere of a **white dwarf** star that is acquiring matter from a nearby binary companion star.

The Crab Nebula is located just above the star marking the tip of the lower horn of Taurus, the Bull.



Recent observations of supernovae similar to the one seen in Andromeda in 1885 have allowed us to measure the vast size and expansion rate of the universe. To our great surprise, these extremely distant supernovae indicate that the expansion is accelerating, rather than slowing down. These observations indicate that approximately 70% of the energy in the universe is something never before observed, with properties heretofore only imagined in the most speculative of our theories of nature. Far from showing that the universe is small, as Shapley argued, supernovae have shown us that the universe is not only vast, but much stranger than we had imagined.

If you point a telescope toward the patch of sky described in the Chinese records from 1054, just a few **degrees** north and east of Aldebaran, the "eye" of Taurus, the bull, you will find a faintly glowing cloud. This is the Crab **Nebula**. It is the remains of a star that exploded some 7000 years ago. The explosion was seen on Earth only 1000 years ago because it was so distant that its light required 6000 years to reach us; the Sung inhabitants were seeing the explosion 6000 years after it happened. The Crab Nebula is a **supernova remnant**, the debris from an exploded star. It is still expanding today at more than 1000 km/s. Inside the nebula is the Crab pulsar, the compact remnant of the core of the exploded star. The pulsar is a highly magnetized, rapidly spinning **neutron star**, a class of object that is among the most bizarre found in nature. A mere teaspoon of the Crab pulsar would weigh more than a billion tons.

In the remainder of this education unit, you will explore the amazing properties of supernovae and neutron stars. You will also begin to learn about some of the tools scientists use to understand them.

The activities and explanations in this unit all deal with the explosions of massive stars. These are called Type II supernovae. There is another type of supernova, called Type I, which involves the explosion of a small, dense core of a more sunlike star (in fact, the supernova of 1885 was just this type of explosion). While fascinating in their own right, Type I supernovae are not covered in this unit.

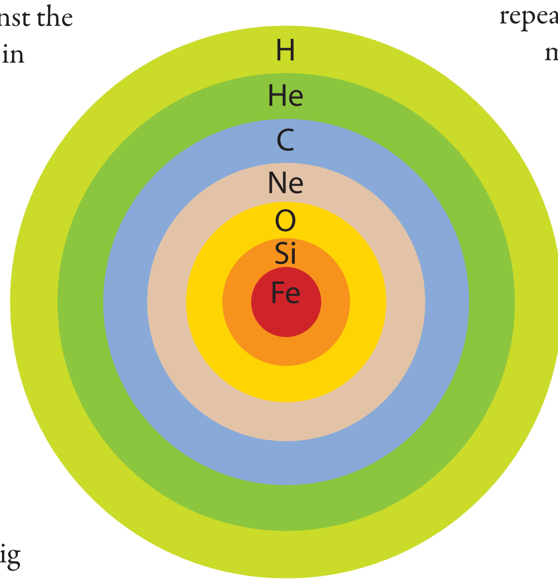
WHY STARS EXPLODE

The stars in the sky seem eternal and unchanging.

But that's an illusion. Like all things, stars are born, live out their lives, and eventually die, doomed to fade away. Stars like the Sun, which have a relatively low mass, age gracefully and die quietly after billions of years. But massive stars, with more than ten or so times the mass of the Sun, "do not go gently into that good night, but instead rage, rage against the dying of the light". They explode in a catastrophic detonation, sending their outer layers screaming outwards at a few percent of the speed of light: what astronomers call a supernova.

The seeds of a star's ultimate destruction are planted deep in its core, where its energy is generated. Stars are giant balls of gas, and when a gas is compressed it heats up. Because stars are so big they have a lot of gravity, so at the core of a star the pressure is intense. This means they get very hot, hot enough to smash together **atomic nuclei**. And when nuclei collide, they can stick together in a process called fusion. This process releases a lot of energy (in fact, it's what makes hydrogen bombs explode), which heats up the core. In a stable star like the Sun, the inward crush of gravity is balanced by outward pressure caused by the heat.

Already we see that the mass of the star is important: it provides the gravity needed to compress the core. The higher the mass of the star, the more the core is compressed, and the hotter it can get. Fusion reactions depend strongly on temperature; the higher the temperature, the faster the reaction proceeds. As we'll see, this is critical later in the star's life.



Near the end of a massive star's life, the fusion occurs in shells around the core, like the layers of an onion.

Initially, the star fuses hydrogen into helium. Like ash in a fire, the helium builds up in the core, but it does not fuse because helium takes a lot more pressure and heat than hydrogen does to fuse. If the star is massive enough, though, it can ignite helium fusion in its core. The helium fuses into carbon, which then starts to pile up in the core. In very massive stars this process repeats again and again, fusing lighter elements into heavier ones: hydrogen to helium, helium to carbon, carbon to neon, neon to oxygen, oxygen to silicon, silicon to iron. The star's core starts to look like an onion, with layers nested inside one another.

At every step, the process generates more heat, and the fusion goes ever faster. A star may fuse hydrogen into helium for millions or billions of years, but by the time it starts to fuse silicon into iron, it may take mere days. As iron piles up in the core, the star is headed for disaster.

Why? Because up until iron, all the fusion reactions have produced energy in the form of heat. However, there is not enough heat and pressure to fuse the iron nuclei, so once iron builds up in the core, the star's source of energy shuts off. Worse, the **electrons** in the core combine with the **protons** in the iron nuclei to form **neutrons** - and the electrons were crucial to give the star support as well. When they are removed from the star's core, things quickly go bad.

Without a source of support, the core suddenly collapses. In a thousandth of a second the tremendous gravity of the core collapses it down from thousands of kilometers across to a ball of compressed matter just a few kilometers in diameter. This is a bit like kicking the legs out from under a table. Just like when Wile E. Coyote suddenly realizes he is no longer over solid ground and starts to fall, the outer layers of the star come rushing down. They slam into the compressed core at a significant fraction of the speed of light.

This does two things: it sets up a huge rebound, sending the outer layers of the star back out, and also releases a vast number of **neutrinos,** subatomic particles that carry away most of the energy of the collapse. The gas from the outer layers absorbs only a small fraction of these neutrinos, but that's still a lot of energy: it's like lighting a match in a fireworks factory. The outer layers of the star explode upwards, and several **solar masses** of doomed star (containing the elements that were produced before the explosion) tear outwards at speeds of many thousands of kilometers per second.

These pictures shows the location of Supernova 1987a before it exploded (left), and during the explosion (right)

As the star explodes, the expanding gas deep inside is so hot that it can undergo temporary fusion, creating elements as heavy as uranium. This, plus other **radioactive** elements created in the explosion, dumps even more energy into the gas, causing it to glow. The expanding gas is called a supernova remnant; it will expand for hundreds of thousands of years, eventually cooling and becoming so thin it merges with the tenuous gas between the stars. Sometimes the gas from the remnant will hit and mix with gas that is forming new stars, seeding it with the heavy elements formed in the explosion. The iron in your blood and the calcium in your bones were formed in the supernova explosion of a massive star millions of years before the formation of the Earth itself.

The Elephant Trunk Nebula
David De Martin (http://www.skyfactory.org), Digitized Sky Survey

And what of the core? Like the life of the star itself, the fate of the core depends on its mass. In relatively low-mass stars like the Sun, the star never explodes at all. The core is not massive enough to fuse helium, so helium simply builds up. Or perhaps helium does fuse, but then the star is not massive enough to fuse the resulting carbon. In any event, the outer layers of the star are blown off by a solar wind over millions of years, and the naked core, unable to generate its own heat, simply cools and fades away. A star that consists of this revealed core is called a white dwarf.

If the core is more massive, between 1 and 3 times the Sun's mass then things are different. The pressure from the collapse slams electrons into protons, creating neutrons. The core shrinks to a size of a few kilometers across, and is comprised almost totally of these neutrons. The collapse is halted by the neutrons themselves, which resist the pressure. Not surprisingly, this object is called a neutron star.

And for more massive cores? Even the neutrons cannot resist the pressure created by more than about 3 times the Sun's mass when it collapses. The core implodes, and nothing can stop it. Its gravity increases hugely, and anything that gets too close will be drawn in, even light. It has become a black hole.

This is more than just a guess. By studying supernovae, supernova remnants, and other exotic objects, astronomers have discovered all this and much more. If you want to continue reading about this and get more information, check out the Resources list in Appendix B.

THE CRAWL OF THE CRAB

2

Duration:
1 hour

Essential Question:

How can the date of a supernova explosion be determined using images of the expanding remnant?

Objectives:

Students will...

- be able to use a ruler to measure distances and use correct numbers of significant digits
- see that astronomical objects change over time
- plot data to observe trends
- examine data and make conclusions about data quality
- determine the year that the supernova occurred

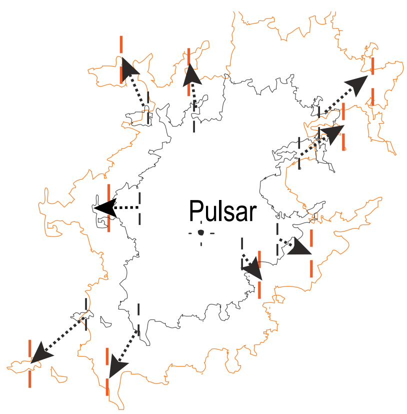
Science Concepts

- Astronomical objects change over time
- The change in some astronomical objects can be observed and measured
- The expansion of a supernova remnant can be used to determine its age

Background Information

A supernova explosion generates a tremendous amount of energy. A tiny fraction of this energy goes into blowing the outer layers of the star outwards... but in a supernova event, even a tiny fraction can mean a lot of energy!

When a massive star explodes, its outer layers are ejected at speeds of thousands of kilometers per second. The total mass of the gas ejected can be ten or more times the mass of the Sun! As the shock wave from the explosion rips through the star, the gas forms long filaments and relatively small clumps called **knots**. These formations can be observed for a long time, even centuries after the explosion. If you could trace the motion backwards in time, you would see they all come from a central point, where the star originally exploded (see figure below). Many times, that location is marked by the collapsed core of the star, the part that didn't explode outwards. This collapsed "cinder" of the explosion may be a black hole or a fantastically dense and rapidly spinning "pulsar." Pulsars are so-named because to us here on Earth they appear to flash on and off as beams of emission sweep past us, like the beams of light from a lighthouse (see Activity 3, "Magnetic Poles and Pulsars," for more information).



As the gas in the Crab expands, it moves away from the central pulsar. The expansion depicted here is exaggerated, and is not to scale.

The expanding gas moving away from the central object is called the "supernova remnant" (SNR), or sometimes generically as a nebula (which is Latin for "cloud"). Images of these SNRs show them to be quite lovely, glowing in different colors, strewn with filaments and knots. But besides their otherworldly beauty, they also reveal interesting and important information about the supernova event itself.

Some of this information can be deduced simply by examining images. SNRs have been a favorite target of astrophotographers for decades, and one in particular is a favorite: the Crab Nebula (usually just called the Crab). It's relatively bright, making it easy to photograph, and is up high in the sky for many northern observers. Located in the constellation of Taurus the bull, it's even visible by binoculars in the winter months in the northern hemisphere and much of the southern hemisphere.

At first glance, images of the Crab Nebula taken at different times look pretty much the same. Sure, more recent images may look better due to advances in imaging, telescopes, and processing of pictures. But there are also differences in the images which are intrinsic to the Crab itself, changes due to physical changes in the nebula.

Most people think of astronomical objects as being static, unchanging. But remember, the gas in the Crab is expanding at thousands of kilometers per second! Its vast distance (6000 **light years** or so) shrinks this motion to an apparent crawl, but over time, the expansion will make itself known.

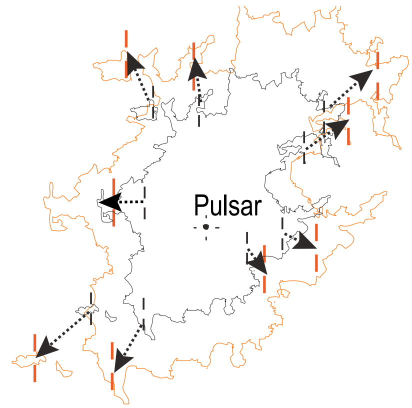
Overview

In this activity, your students will compare two images of the Crab Nebula taken more than 40 years apart. By measuring the motion of some of the knots of glowing gas they'll be able to determine the date of the supernova explosion that set the Crab into motion.

The idea is relatively simple. Between the times of the two images, the Crab has expanded. The students will measure the distance between a series of knots and the central point of the explosion, marked now by the presence of a pulsar. The difference between the two measurements is due to the expansion of the gas during the time interval between the images. Since that distance can be measured, and the time interval is known, the expansion rate can be determined. Since rate = distance / time, and the rate and distance are known, the amount of time the knots have been expanding can be calculated. In other words, by measuring the differences between the images, the age of the nebula (and hence its "birthday") can be found.

STUDENT HANDOUT

THE CRAWL OF THE CRAB - 2



As the gas in the Crab expands, it moves away from the central pulsar. The expansion depicted here is exaggerated, and is not to scale.

Introduction

Two images of the Crab Nebula supernova remnant, taken 46 years apart, clearly show the expansion of the gas due to the explosion. In this exercise, you will determine the age of the Crab by measuring how much it has expanded over that period of time. You will convert the amount of expansion to a rate of expansion, and from there work backwards to determine the year the star exploded to form the Crab Nebula. In a sense, you're trying to find the "birthday" of the Crab-- except this method isn't accurate enough to find the exact day, so really you're finding the birth *year* of the Crab.

Procedure:

First, examine both images. They are presented in grey scale (what most people erroneously call "black and white"), and are reversed such that bright objects like stars are black, and dark objects like the background sky appear white. This is an old astronomer's trick to make faint detail easier to see. You can see that the gas is not smooth; there are filaments and knots of gas scattered throughout the nebula.

One image was taken in February 1956, and the other in November 1999. Both images look similar at first glance, but if you look carefully you'll see some differences. The images are at the same scale; the nebula itself has changed during the time interval between the two images. It is this change that you will measure, and from that determine when the Crab was born.

1 Near the center of the nebula is a star marked "pulsar". That is the collapsed core of the star that originally exploded. We can assume for this exercise that all the gas started at that star, so you will measure the expansion relative to the pulsar.

On both images, there are 11 knots of gas marked. Starting with the image from 1956, carefully measure the distance in centimeters (to the nearest 0.05 cm or better if you can) of each knot from the pulsar.

Repeat these measurements for the 1999 image. Some of the knots are extended, or spread out a bit. For knots like that, pick an obvious feature to measure, like the center of the knot, or the edge on one side. Make sure you pick the same feature in both images! If you don't your measurements will not be accurate. On the worksheet there is room for you to make short comments on what part of the knot you measured. This might help you if you need to go back and remeasure.

-------------- **Tips** --------------

Tip 1: measure each knot in both images before going on to the next knot rather than measuring all the knots in one image and then in the other. That way, you can be more consistent in the way you measure each knot.

Tip 2: it might help to measure the knots on the 1999 image first, since it has better resolution and shows the structure of the knots more clearly.

Tip 3: sometimes measuring to the edge of a knot is easier than measuring to the center.

2

Now it's time to measure how much the nebula expanded: subtract the separation between each knot and the pulsar in 1956 from the angular separation in 1999. You can use centimeters for this measurement; the images have been scaled so that one cm is the same angular size on each of them. That means that one centimeter is the same physical distance in both images. Why is this important?

a. Examine the numbers you just calculated. Are the expansion amounts all roughly the same (within, say, 10% of each other), or is there a large variation? Do you expect all the numbers to be about the same?

b. Now look at the amount of expansion for each knot compared to the distance of the knot from the pulsar. Do you see any trends?

c. To see if any trends exist, plot on your graph paper the expansion amount for each knot versus its distance from the pulsar in the 1999 image. Using your ruler, draw in a best-fit line to the points. Can you make any general statements about a relationship between the distance from the pulsar for a given knot and its speed of expansion? Try to think of a physical reason for this.

3

To determine the age of the nebula, you need to find the expansion rate, the amount it has expanded versus time (this is, in a sense, the speed of expansion on the sky).

Given the dates of the two images (February 11, 1956 and November 10, 1999) calculate the time elapsed between them to the nearest 0.1 years. After that, divide the expansion amounts or separation you calculated in Question 2 by the time difference to get an expansion rate in centimeters/year.

4

Now that you have the rate of expansion, you can calculate the age of the nebula. Starting with:

rate = distance / time

which can be rearranged to:

time = distance / rate

Use the expansion rate (in centimeters/year) you calculated in Question 3, and the distance of each knot from the pulsar (in centimeters) for 1999 you found in Question 1, to calculate the age of the nebula.

Are the ages all roughly the same (within, say, 10% of each other), or is there a large variation? Why would this be?

Calculate the average age of the nebula using the ages you derived for each of the knots.

Given the date of the image you used to find the age, in what year did the star explode to form the Crab Nebula?

Calculate this number for each knot, and find the average year.

Scientists think the star that formed the Crab nebula blew up in 1054. How close was your answer?

STUDENT WORKSHEET

THE CRAWL OF THE CRAB

Datee: ____________ Name: ____________

1

knot	Distance from Pulsar (cm)		
	1956	*1999*	*Comments*
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

2

knot	Change in Separation from 1956 to 1999 (cm)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

a)

b)

c)