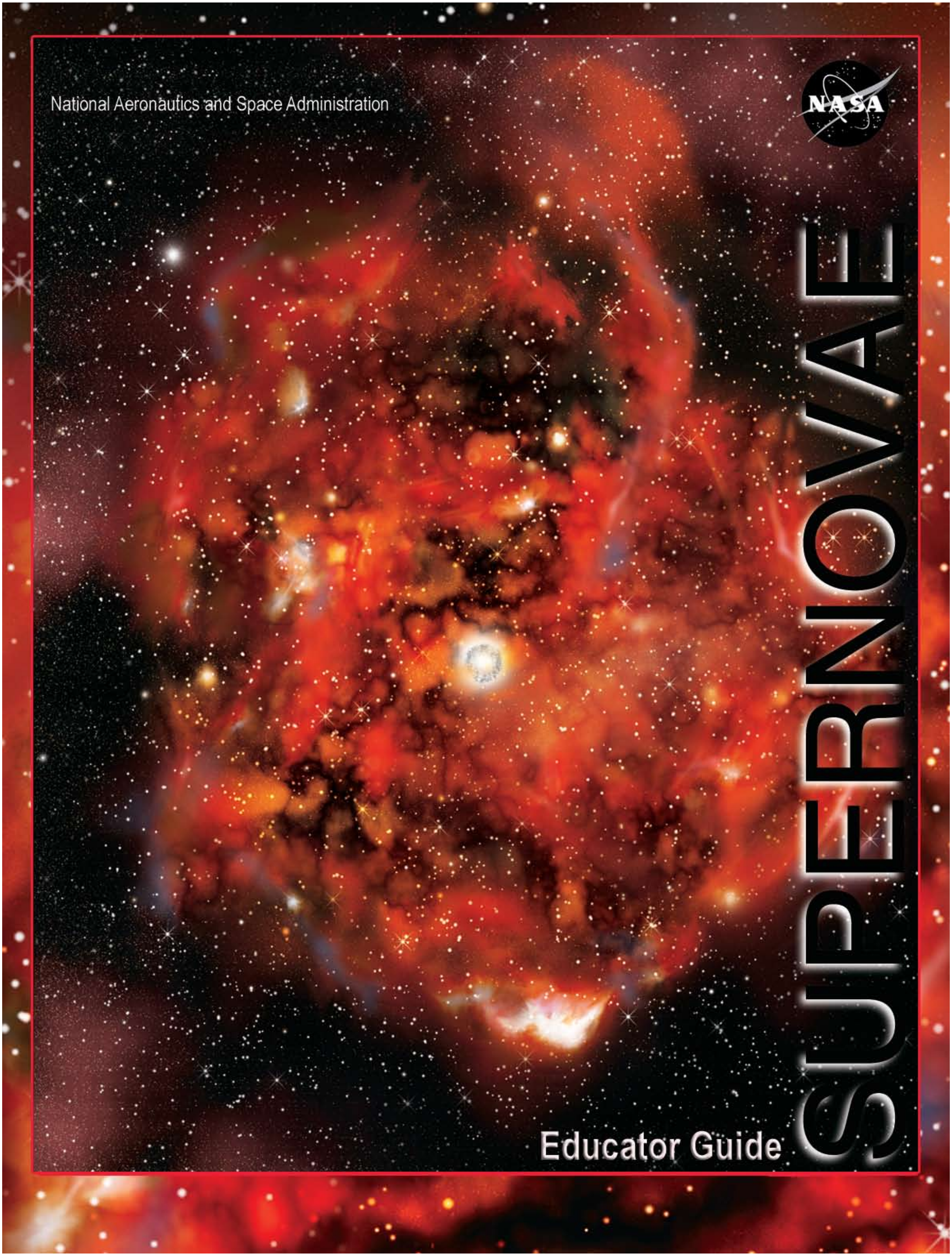
National Aeronautics and Space Administration

SUPERNOVAE

Educator Guide



SUPERNOVA EDUCATOR GUIDE

National Aeronautics and
Space Administration

http://glast.sonoma.edu http://xmm.sonoma.edu

Content

Supernova Educator Guide -- Layout and Design by Aurore Simonnet,
NASA Education and Public Outreach Group, Sonoma State University, CA

About this Guide

Busy educators sometimes have trouble finding ways to help their students feel the excitement of science in action. As a part of its educational effort, the NASA Education and Public Outreach group at Sonoma State University has put together an educational guide based on the science of NASA's Gamma-ray Large Area Space Telescope (GLAST) and the joint ESA/NASA XMM-Newton Observatory. The science specifically detailed in this guide involves multi-wavelength views of the dramatic explosion at the endpoint of the life of a massive star – i.e., a supernova. We also present an activity that relates the Earth's magnetic field to that of a **pulsar**, a rotating city-sized collapsed star that can be formed in the supernova's aftermath. There is also the opportunity to improve your science literacy skills by analyzing two news articles about pulsars. Both news articles are based on discoveries from XMM-Newton observations.

Since students remember and understand better when they actively engage in manipulating the concepts about which they are learning, we have included several hands-on activities to help keep their interest and reinforce their comprehension and retention of the scientific concepts behind the current observations of the XMM-Newton mission and the future observations of the GLAST mission. We have also included information about both missions, what kind of objects they will observe, and why astronomers are interested in them. To help you determine when these activities might be of most use to you in your science and/or math curriculum, we have included in the following pages a list of all of the national math and science standards with which each activity is aligned.

What will my students learn from these activities? This series of activities uses supernovae – distant explosions from dying stars – as an engagement to teach basic concepts in physical science and mathematics. Below is a summary of all of the activities in this guide.

Summary of Activities

Activity 1 - Fishing for Supernovae

Brief overview:
Students will play a card game similar to "go fish" in which they match multi-wavelength images of different supernova remnants.

Science Concepts:
- Different physical processes produce light of different wavelengths
- Scientists use different wavelengths of light to determine what is happening in the Universe

Duration: 1 hour

Essential Question: What do supernova remnants look like in different wavelengths of light?

Grades: 7 – 8

Activity 2 – Crawl of the Crab

Brief overview:
Students use two images of a supernova separated in time by several decades to determine the expansion rate of the glowing gas.

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

Duration: 1 hour

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

Grades: 9 – 12

Activity 3 – Magnetic Poles and Pulsars

Brief overview:

Students investigate magnetic fields in two and three dimensions, and compare the magnetic field of a pulsar to that of the Earth and other astronomical objects.

Science Concepts:
- Magnetic field lines form closed loops in three dimensions.
- When the rotation and magnetic axes of a neutron star are not aligned, pulsations can result.
- Like a pulsar, the Earth's magnetic and rotation axes are not aligned. However, the magnetic field of a pulsar is approximately one trillion times stronger than that on the Earth's surface.

Duration: 1-2 hours

Essential Questions:

- What does a dipole magnetic field look like in three dimensions?
- How do neutron stars emit pulses?
- How do the magnetic fields of the Earth and a pulsar compare?

Grades: 9 – 12

Activity 4 - Neutron Stars in the News -science literacy extension

Brief overview:
Students read and analyze two different articles about XMM-Newton discoveries involving neutron stars and their magnetic fields.

Science Concepts:
Even though magnetic fields on neutron stars are approximately one trillion times stronger than that on the Earth's surface, different types of neutron stars can have magnetic fields with strengths that differ by a factor of 10,000.

Duration: 1 hour

Essential Question: How do the magnetic fields of different types of neutron stars compare?

Grades: 8 – 12

National Science Education Standards For Supernova Activities

	Activity 1 — Grades 7-8 **Fishing for Supernovae**	**Activity 2 — Grades 9-12** **The Crawl of the Crab**	**Activity 3 — Grades 9-12** **Magnetic Poles and Pulsars**	**Activity 4 — Grades 8-12** **Neutron Stars in the News**
Science as Inquiry		• Abilities necessary to do scientific inquiry - *Use of technology and mathematics to improve, invest, and communicate* - *Recognize and analyze alternative explanations and models* • Understanding about scientific inquiry	• Abilities necessary to do scientific inquiry - *Identifying questions* - *Design and conduct investigations* - *Formulate and revise scientific explanations* • Understanding about scientific inquiry	• Abilities necessary to do scientific inquiry - *Recognize and analyze alternative explanations and models* • Understanding about scientific inquiry
Physical Science	• Properties and changes of properties in matter	• Conservation of energy and increase in disorder	• Motion and forces • Interactions of energy and matter	
Earth and Space Science		• Origin and evolution of the universe	• Origin and evolution of the Universe	
Science and Technology	• Understanding about science and technology		• Abilities of technological design - *Implement a proposed solution* - *Evaluate the solution and its consequences* - *Communicate the problem, process, and solution* • Understanding about scientific inquiry	
History and Nature of Science	• Science as a human endeavor • Nature of science knowledge	• Science as a human endeavor • Nature of science knowledge	• Science as a human endeavor • Nature of science knowledge	• Science as a human endeavor • Nature of science knowledge

Mathematics Standards for Supernova Activities

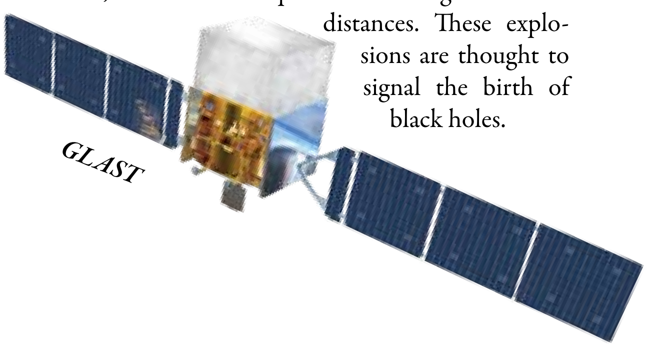
Activity 1 - Fishing for Supernovae: No math standards for this activity.
Activity 4 - Neutron Stars in the News: No math standards for this activity.

	Activity 2 **The Crawl of the Crab - Grades 9 - 12**	**Activity 3** **Magnetic Poles and Pulsars - Grades 9 - 12**
Algebra	• Understand patterns, relations, and functions • Represent and analyze mathematical situations and structures using algebraic symbols • Use mathematical models to represent and understand quantitative relationships	
Geometry	• Specify locations and describe spatial relationships using coordinate geometry and other representational systems • Use visualization, spatial reasoning, and geometric modeling to solve problems	• Specify locations and describe spatial relationships using coordinate geometry and other representational systems • Use visualization, spatial reasoning, and geometric modeling to solve problems
Measurement	• Understand measurable attributes of objects and the units, systems, and processes of measurement • Apply appropriate techniques, tools, and formulas to determine measurements	• Understand measurable attributes of objects and the units, systems, and processes of measurement • Apply appropriate techniques, tools, and formulas to determine measurements
Data Analysis and Probability	• Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them • Select and use appropriate statistical methods to analyze data • Develop and evaluate inferences and predictions that are based on data	• Develop and evaluate inferences and predictions that are based on data
Communication	• Organize and consolidate their mathematical thinking through communication • Communicate their mathematical thinking coherently and clearly to peers, teachers, and others	• Organize and consolidate their mathematical thinking through communication • Communicate their mathematical thinking coherently and clearly to peers, teachers, and others
Connections	• Recognize and use connections among mathematical ideas • Recognize and apply mathematics in contexts outside of mathematics	• Recognize and use connections among mathematical ideas • Recognize and apply mathematics in contexts outside of mathematics
Representation	• Create and use representations to organize, record, and communicate mathematical ideas • Select, apply, and translate among mathematical representations to solve problems • Use representations to model and interpret physical, social, and mathematical phenomena	• Create and use representations to organize, record, and communicate mathematical ideas • Select, apply, and translate among mathematical representations to solve problems • Use representations to model and interpret physical, social, and mathematical phenomena

What is the Gamma-ray Large Area Space Telescope (GLAST)?

The Gamma-ray Large Area Space Telescope (GLAST) is a NASA satellite planned for launch in 2008. GLAST is part of NASA's Science Mission Directorate. Astronomical satellites like GLAST are designed to explore the structure of the Universe, examine its cycles of matter and energy, and peer into the ultimate limits of **gravity: black holes**. GLAST is being built in collaboration between NASA, the U.S. Department of Energy, France, Germany, Italy, Japan, and Sweden. The project is managed from NASA's Goddard Space Flight Center in Greenbelt, Maryland. GLAST detects **gamma rays**, the highest energy light in the electromagnetic spectrum.

There are two scientific instruments on board GLAST: the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). The LAT is the primary instrument, and will survey the sky in high-energy gamma-ray light. It will also study many individual sources of gamma rays. The GBM will detect Gamma Ray Bursts, tremendous explosions coming from vast distances. These explosions are thought to signal the birth of black holes.



Who developed these activities?

The activities have been developed as part of the NASA Education and Public Outreach (E/PO) Program at Sonoma State University, under the direction of Professor Lynn Cominsky.

Contributors to this education unit include Professor Lynn Cominsky, Dr. Kevin McLin, Dr. Philip Plait, Sarah Silva, Kevin John, Linda Smith, and Aurore Simonnet. We would also like to acknowledge input from the Astrophysics Educator Ambassadors and our external evaluators at WestEd, under the direction of Dr. Edward Britton.

What is XMM-Newton?

XMM-Newton is an **X-ray** satellite launched into Earth **orbit** on December 10, 1999 by the European Space Agency (ESA). XMM-Newton is a fully-functioning observatory, carrying three very advanced X-ray telescopes. They each contain 58 high-precision concentric mirrors, nested to offer the largest possible collecting area to catch X-rays. Unlike many other telescopes, which only make images of the objects they observe, XMM-Newton takes both images and spectra. This means it can measure the energy of the X-rays emitted by an astronomical object, which allows scientists to determine many of its physical characteristics including temperature, composition, and density.

XMM-Newton was initially called just "XMM", which stands for "X-ray Multi-Mirror" due to the design of the mirrors. To honor one of history's most famous scientists, ESA attached the name of Isaac Newton to the XMM mission.

XMM-Newton can obtain spectra of far fainter objects than any previous spectroscopic X-ray mission because its mirrors have more collection area than those on any previous mission. The detectors onboard XMM-Newton are also very sensitive, allowing faint objects to be observed. A third advantage is that it has an unusual orbit that takes it out to nearly one third of the distance to the Moon. This highly elliptical orbit means that XMM-Newton can make long, uninterrupted observations, giving it the time it needs to see fainter astronomical objects.

Where can I get more information?

Appendix A on p. 41 gives a glossary of words listed in bold type. Appendix B on p. 42 of this booklet contains a list of additional resources.

To learn more about GLAST and XMM-Newton education and public outreach, visit:

http://glast.sonoma.edu or http://xmm.sonoma.edu

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.

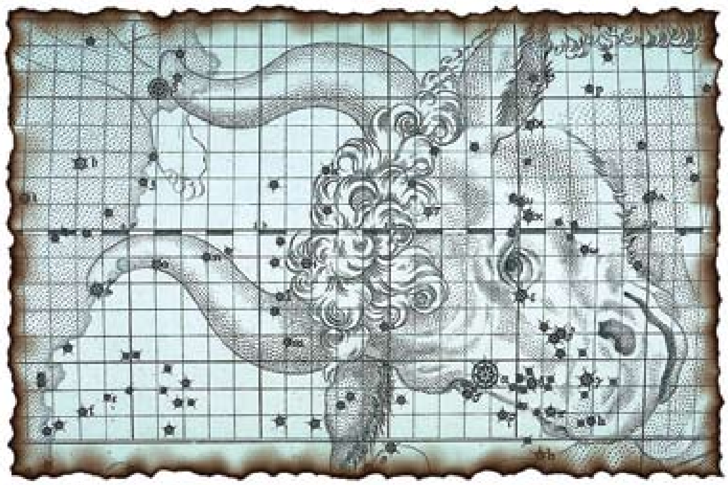
Crab nebula

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.

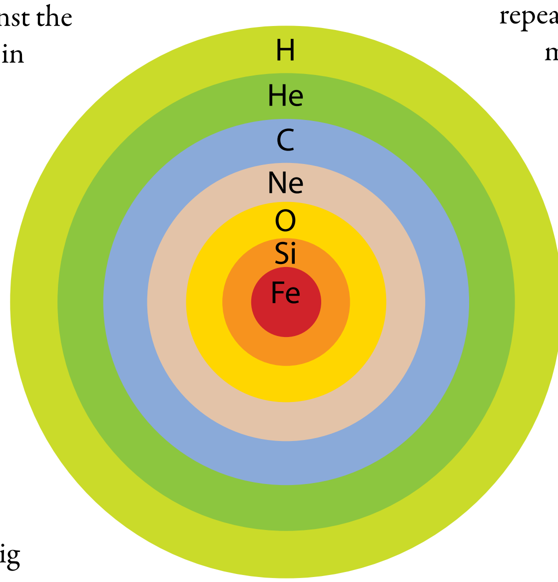
WHY STARS EXPLODE

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.

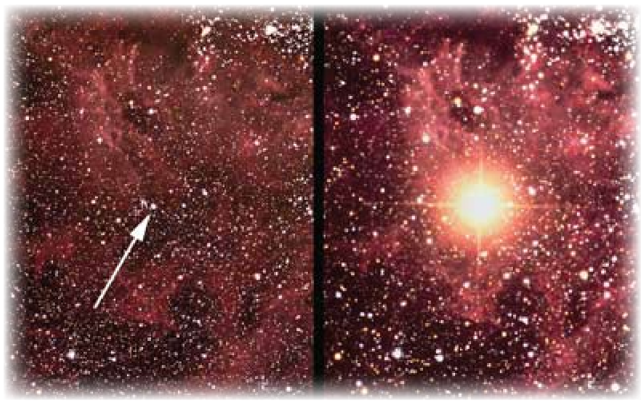
Initially, the star fuses hydrogen into helium. Like ash in a fire, the helium builds up in the core, but it does not fuse because helium takes a lot more pressure and heat than hydrogen does to fuse. If the star is massive enough, though, it can ignite helium fusion in its core. The helium fuses into 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.

1 Fishing for Supernovae

Duration:
1 hour

Essential Question:

- What do supernova remnants look like in different wavelengths of light?
- How do different supernovae remnants compare to each other?

Objectives

- Students will compare and contrast images of supernovae remnants taken in different energy bands

Science Concepts:

- Different physical processes produce light of different wavelengths
- Scientists use different wavelengths of light to determine what is happening in the Universe

Background Information

The images on the cards for this activity show the detected emission from a supernova remnant in three different energy regimes: x-ray, optical and radio. While the overall shape of the remnant is the same in each energy band, the processes underlying the emission can be quite different. The descriptions below are for supernova remnants with neutrons stars. However, not all remnants have neutron stars! In many cases, the physics is complex and still not well understood, so only an idealized case is discussed here. Interestingly, the non-thermal physical mechanism that creates the radio waves (the lowest-energy form of light) is very similar to that which creates gamma-rays (the highest energy form of light). The GLAST satellite, which will launch in 2008, will be able to make high resolution images of some of the larger remnants, after which we can add a fourth "card suit" for gamma rays!

The optical and x-ray images on the cards (and the front of the poster) show emission mostly from gas at the edge of the remnant. As the ejected material from the supernova encounters gas that already existed around the star, it creates shock waves, similar to the way a supersonic jet makes shock waves in the air. Inside these shocks the gas ejected from the exploded star is slowed, compressed, and heated to millions of degrees. This happens because, as the expanding supernova material collides with the existing gas surrounding the star, its kinetic energy – the energy of its motion outward from the supernova – is converted to random motions, or more simply, heat. The high temperature of the gas means the atoms are moving very rapidly, which leads to energetic collisions between them. The collisions are so energetic that they blast electrons completely off of the atoms. At that point we say that the atoms are ionized. When gas is this hot and the atoms bounce off each other at such high speeds, the gas emits X-rays.

As the remnant emits X-rays it loses energy. After all, X-rays are a form of radiation, like optical light, so they carry away a lot of the energy of the supernova into space. That loss of energy causes the remnant to cool. After several tens of thousands of years the outer shocked part of the remnant has cooled to only a few thousand degrees. The atoms in gas at this temperature are not moving fast enough to produce strong X-ray emission, but they are fast enough to excite (give energy to) each other. When an atom absorbs energy, its electrons jump from one energy level to another, like someone going up a staircase. After some time, the electron then falls back down to a lower level, and emits energy at a very specific wavelength. This type of emission is called line emission. In a hot, low density gas like that of an old supernova remnant, the emission lines typically seen are from excited and ionized forms of hydrogen, oxygen, nitrogen, sulfur, and other kinds of atoms. This can make supernova remnants appear to our eyes to glow with characteristic colors in visible light such as red or green.

This lower-temperature gas tends to be in the outer parts of the supernova remnant. The inner part of the remnant is still filled with million degree x-ray emitting gas. This is because the density inside the remnant is much lower than in the outer shocked parts, and the lower density causes the inner part of the remnant to cool much more slowly because collisions between the atoms are less frequent. In fact, it takes more than a million years for the hot bubble inside a supernova remnant to cool completely. Since these two types of emission depend on the temperature of the gas emitting them, they are sometimes collectively called thermal emission.

Radio emission (like gamma-ray emission) from supernovae is a different type of radiation process entirely. Radio waves and gamma-rays are not emitted by the gas due to its thermal properties. For radio waves, the gas is too hot, while for gamma-rays, the gas is too cool. Instead, the emission is produced both by the shock wave from the supernova explosion itself as it slams through the gas, and from the interaction of the electrons in the remnant with the magnetic field of the compact neutron star in its center, assuming one is present, or with the magnetized remnant material.

This neutron star is the remains of the core of the star that collapsed and is fantastically small and dense: while a typical neutron star is only a few kilometers across, it has about 40% more mass than the sun. A single teaspoon of neutron star material weighs as much as 100 million adult elephants, or a mountain a kilometer high! It spins rapidly, up to thousands of times per second, and can possess extremely strong magnetic fields. As the star's spin sweeps its magnetic field through the remnant, it picks up charged particles such as electrons, like a fisherman's net sweeps up fish. These particles are accelerated to speeds close to the speed of light as they ride along with the magnetic field.

When charged particles are accelerated like this, they emit radiation. However, the radiation is very different from the emission described for x-rays and visible light. This type of emission, called synchrotron emission, does not come out at one specific energy. Rather it is seen in a very broad, nearly flat continuous spectrum, spanning all the way from radio waves to gamma rays. Furthermore, in contrast to emission lines and thermal X-rays, synchrotron emission will not diminish as the remnant cools. It depends only on the spinning, magnetized neutron star, not on the temperature of the gas. Because of this peculiar property, synchrotron radiation is referred to as non-thermal emission. Spinning magnetized neutron stars are also called pulsars because they are seen to emit pulses of electromagnetic radiation as their **magnetic poles** sweep by our line of sight. Rapidly spinning objects contain a lot of energy, and as their rotation slows this energy is lost. Careful study of the synchrotron energy emitted by some supernova remnants shows that it matches the energy lost by the slowing spin of the neutron star. Therefore, astronomers conclude that late in the life of some supernova remnants, the energy comes from the neutron star itself. Examples of this kind of remnant are the Crab Nebula and the Vela supernova remnant.

However, that's not always the case. If the original supernova explosion is off-center (not a perfectly expanding sphere), it can give a "kick" to the neutron star, basically acting like a rocket. The neutron star can be ejected from the explosion at very high speeds, hundreds of kilometers per second. After hundreds of years, the neutron star can actually leave the supernova remnant. In those cases, the main source of energy for the gas is gone. These supernova remnants still glow from their own heat, but they tend to be (but are not always) much fainter than pulsar-energized remnants.

By examining supernova remnants at different energies, astronomers learn different things about them. Their ages, energy, chemical content, and much more can be determined by multi-wavelength observations. That's why NASA, ESA, and other space agencies continue to launch high-energy observatories to complement ground-based optical and radio observations; it's only when seen at these different energies that the Universe reveals its secrets.

Duration: 15 minutes per game

You should read the instructions below as well as those in the student handout.

Materials

- For each group of 2-3 students; one copy of Table 1 and one set of cards copied from this guide (see Appendix C on p. 44) or downloaded from: ***http://xmm.sonoma.edu/edu/supernova/***

Procedure:

Students are assumed to have been introduced to the electromagnetic spectrum, so that they will understand that the images shown on the cards are measurements of different wavelengths of light from supernova remnants.

Download the file with the card images from:
http://xmm.sonoma.edu/edu/supernova/
print one set of cards for each group of 2-3 students and hand each group one deck of cards.

Important Note: The colors on the cards labeled "Radio" and "X-ray" are false color representations of the intensity of the light emitted in the remnant. The colors themselves have no significance, and were chosen to make the images look pretty. It is the brightness or faintness that is important on these cards.

Show the students the card images and explain that they will be playing a game in which they will try to match cards so that they get all three different types of light for a given supernova remnant.

- Explain that the visible light image is similar to what they would see if they could detect supernovae with their eyes, and that the visible light comes from material that is around 10,000 Kelvin.
- Explain that the x-ray emission is similar to the visible light, but comes from material that is around 10,000,000 K (one thousand times hotter than visible light.)
- In contrast, tell them that the radio emission comes from the interaction of electrons with magnetic fields in the remnant.

Have each small group of students look through the deck of cards and compare the images of the different supernova remnants to each other, and to other images of the same remnant in a different wavelength of light.

When the students are done playing the game, hand out Table 1 to continue the discussion.

Assessment:

Points	Fishing for Supernovae
4	Students are able to correctly infer relationships between distance, age and the appearance of the images of the supernova remnants. Students are able to compare and contrast the images of the supernova remnants at different wavelengths, and also to compare and contrast the images of the different supernovae.
3	Students are able to correctly infer relationships between distance or the age and the appearance of the images of the supernova remnants. Students are able to compare and contrast the images of the supernova remnants at different wavelengths, and also to compare and contrast the images of the different supernovae
2	Students are able to compare and contrast the images of the supernova remnants at different wavelengths, and also to compare and contrast the images of the different supernovae.
1	Students are able to compare and contrast the images of the supernova remnants at different wavelengths, or to correctly compare and contrast the images of the different supernovae.
0	Students are not able to make any valid comparisons or inferences.

Pre-activity Discussion:

Students may benefit from reading the introductory material to this guide or material found on the following websites:

- *http://imagine.gsfc.nasa.gov/docs/science/know_l1/supernovae.html*
- *http://imagine.gsfc.nasa.gov/docs/science/know_l1/pulsars.html*
- *http://curious.astro.cornell.edu/supernovae.ph*p

After the students have looked at the cards, ask them to answer the following questions about supernovae:
a) What similarities and differences do you see between images of one supernova remnant in the different wavelengths of light?
b) What similarities and differences do you see between the different supernova remnants?

Answers to Pre-activity Discussion:

a) Some of the images of the same supernova remnant appear similar to each other. Others have brighter edges than centers in some wavelengths (e.g. radio) but look more filled in the centers (e.g. Kepler and Tycho). Some appear totally different in different bands, but some of this may be due to different sized images.
b) Most of the remnants appear circular in shape, but there are some exceptions. Some remnants appear very irregular in shape(e.g., Puppis A), and at least one has several concentric circles (1987A).

Post-Game Discussion:

After the students are done playing the game (at least once), ask them to study the cards and to look at Table 1. Explain that one **light year** (about 9.5 trillion km) is the distance that light travels in one year. So Supernova 1987A, which we first saw on Earth in the year 1987, really occurred 168,000 years before 1987. Also, tell the students that angular sizes of objects in the sky, as we see them from Earth are measured in radians or degrees, where π radians = 180 degrees. One degree can be further subdivided into 60 **arcminutes** (written 60'); each arcminute can be subdivided into 60 **arcseconds** (written 60"). These are the scales that appear on the cards for each image. For two objects of the same physical size, the angular size that we see from Earth is inversely related to the distance to the source: angular size (in radians) = (physical size)/(distance). They will need to understand this in order to answer the questions in the student handout.

Answers to Post-Game Discussion:

a) Tycho was seen to explode on 11/11/1572 and Kepler was seen to explode on 9/10/1604. (This is a little more than 32 years apart.)
b) The diameter of Tycho (~8') is about twice that of Kepler (~4').
c) Since Tycho is about 2 times closer to Earth than Kepler, it will appear about two times larger than Kepler, even though they both exploded at approximately the same time and are expanding at the same rate.
d) Cas A is 2500 light years further away than Tycho but 3000 light years closer than Kepler, and it appears from Earth to have exploded only 100 years after Kepler. Its diameter should therefore be intermediate between those of Tycho and Kepler. Measuring the image on the card confirms this prediction (~6'). Note: in this discussion, we are ignoring the small differences in time when the supernovae were first seen on Earth (~50-100 years) as their distances from Earth are much greater (at least 7500 light years.)

Table 1: Supernova Properties

Supernova	Pulsar	Date Supernova Light Reached Earth	Distance (light years)	Fact 1	Fact 2	Fact 3
SN 1987a	N	23-Feb-1987	160,000	Located on the outskirts of the Large Magellanic cloud, a nearby dwarf galaxy.	Though core-collapse supernovae should result in a neutron star, to date there is no evidence of one in SN1987.	25 neutrinos were detected from the explosion of SN 1987a, providing strong experimental evidence for theoretical models.
Cas A	N	300 y ago	10,000	The youngest known supernova remnant in our galaxy.	The strongest extra-solar radio source in the sky.	Since astronomers in the 1600s did not recognize this supernova, current astronomers believe it may have been heavily obscured by debris.
Crab	Y	4-Jul-1054	6,000	When discovered in 1053 it was visible with the naked eye for 23 days in daylight and 653 nights before fading from view.	It also may be the basis of two Anasazi Indian petroglyphs found in the U.S. southwest.	The pulsar at the center of the nebula emits radiation at a frrequency of 30 times per second.
Cygnus Loop	N	10,000 y ago	15,000	The Cygnus Loop is about 3.5 degrees across: that's seven full moons!	The blast is still traveling at 180 km/s (400,000 mi/hr.)	The fact that the Cygnus Loop is relatively near and unusually free from obscuring dust means that it can be observed at a wider range of wavelengths than is usual for galactic SNRs.
Kepler	N	09-Oct-1604	13,000	The most recent supernova to be observed in our own galaxy, it was obser ved four years before the invention of the telescope. This supernova remnant is named after Johannes Kepler, an astronomer who is famous for describing the motion of the planets in our Solar System.		There have been six known supernovae in our Milky Way over the past 1,000 years. Kepler's is the only one for which astronomers do not know what type of star exploded.
Puppis A	N	3000 y ago	7000	The brightest radio source in the constellation of Puppis.		
SN 1006	N	1-May -1006	7,000	SN 1006 was recorded in Switzerland, Egypt, Iraq, China, Japan, and possibly North America.		
Tycho	Y	11-Nov-1572	7,500	This supernova is named after Tycho Brahe, an astronomer who is famous for his unaided (just using his eyes) observations of the night sky.		
Vela	Y	10,000 y ago	1000	Astronomers wondered why the pulsar was not located at the center of the Vela supernova until X-ray observations showed that the SNR was bigger then expected and the pulsar was really at the center.	The small bright spot on the upper right of the X-ray image is actually another SNR along the same line of sight, affectionately referred to as "Vela Jr."	
N132d	N	3,000 y ago	160,000	The N132D supernova remnant appears to be colliding with a giant molecular cloud, which brightens the southern rim of the remnant	The X-ray image shows an expanding shell of oxygen.	N132d is the brightest SNR in the Large Magellanic Cloud galaxy

Student Handout

Fishing for Supernovae

In this activity you will play a “Go Fish” game with a deck of cards that has images on it that show supernova remnants (what is left over after stars explode) in different wavelengths of light.

There’s a lot of information for scientists to gather, collect and classify to be able to understand the universe and how it works. No one scientist or group of scientists can do it all. Scientists all over the world collaborate to get this job done and to find new things happening in the Universe.

Today you will get to help with this adventure. Scientists have used many different types of telescopes to collect data from supernovae in visible, x-ray and radio light. Each supernova in your deck of cards has images taken by a visible light telescope, a radio telescope and an x-ray telescope. Your job is to draw and discard cards until you can match the three different images of each supernova remnant.

Rules of the Game

1. Dealer deals 5 cards to each player and puts the rest of the cards in the middle of the table
2. All players look through their cards for matches. A match is the same supernova in visible, radio and x-ray light. When a player gets a match, the matched card sets are put down so that all players can see the match. (Matches may also be completed using the two wild cards, which can take the place of any card in the game and are fishable).
3. The player to the left of the dealer goes first. Looking at the cards left in the hand, he or she decides what card is needed to make a match. He or she then asks another player if he or she has that card. If the player guesses correctly, he or she may go again.
4. The player must give up the card if he or she has it. If not, the player says “search the stars”. At that point the person whose turn it is picks a card from the pile in the middle of the table.
5. At the end of a turn, if a player has more than 5 cards, he or she must discard down to five cards.
6. The next person to the left takes a turn, repeating steps 3 to 6
7. The first player to get 3 matches wins the game.

9. The winner gets bragging rights to be “The best astronomer in the class!”

After you are done playing the card game, take a look at the Table 1 which provides fun facts and Supernova Properties and then discuss the following questions in your groups:

a) Compare the images of Tycho and Kepler in x-ray wavelengths. Studies have shown that they are each expanding at around the same rate. When did the light from these supernovae reach the Earth?

b) Which supernova appears larger (has a larger diameter in arcminutes) as seen from Earth?

c) Do you have any hypothesis about the difference in the sizes?

d) Using the data in Table 1 for Cas A, and assuming that it is expanding at the same rate as both Tycho and Kepler, how do you think its diameter will compare? Explain your reasoning. Now look at the x-ray image on the card and check your prediction. Were you correct?

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

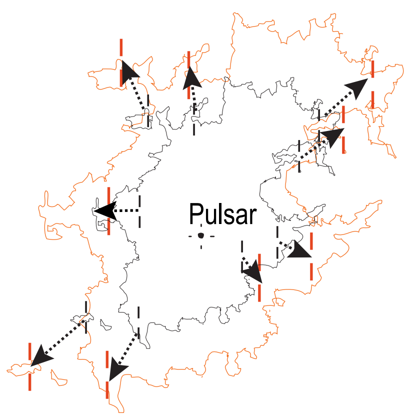
Science Concepts

- 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

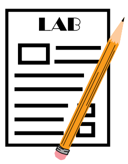
In this activity, your students will compare two images of the Crab Nebula taken more than 40 years apart. By measuring the motion of some of the knots of glowing gas they'll be able to determine the date of the supernova explosion that set the Crab into motion.

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.

Additional Information:

Two versions of this activity are available. In one version, the student will analyze digital images on their computer screen using freely available imaging software and an Excel spreadsheet. You can find this version on the CD under the filename ***SN_Activity2_onscreen.pdf***. More detailed instructions are in that write-up. The other version of this activity is done via handouts.

The digital version involves measuring the coordinates of the pulsar and knots in the nebula, and using the distance formula to get the expansion amounts. This can be done by hand, or the students can use a pre-programmed Excel spreadsheet. The level of math involved is therefore under the teacher's control. The student can calculate the other steps needed to calculate the ages found, again by hand or using the spreadsheet. This version is available on the enclosed CD. The version using hardcopies of the images is below.



In the printed version the students measure the distances of knots from the pulsar directly, so less formal math is needed. Testing has shown that measuring the knots is slightly faster using this method, but doing the math takes slightly longer. The printed version of this exercise is designed for teachers who do not have access to sufficient numbers of computers for their students, but other teachers may still choose to use it for pedagogical reasons.

Educator Tip: In both versions of the exercise, students will make a series of measurements. It is inevitable that some of the measurements will be less accurate than others. Encourage the students to examine their data and determine if any data points appear to be inaccurate. If they find any suspect measurements, they can re-measure the distances. Have a student who did not do the original measurement make the second measurements, so they are not biased. If they cannot improve the results, it is okay to throw out some data; this is what scientists do when they cannot make good measurements. Just make sure they have 8 or 9 data points that are good, or else their conclusions might be compromised.

Procedure:

Materials for each team of 2 or 3 students:

- Calculator
- Ruler
- Printed images of the Crab Nebula from 1956 and 1999 (supplied) p. 21-22
- Graph paper
- Student Handout p.19 and Worksheet p.23 (one per student)

1) Pre-class: Read through the Background Information section, and go over the Student Handout and Worksheet. Students should work in teams of 2 or 3, so print out enough Handouts and Worksheets for the students. Each team also needs a copy of both Crab Nebula images (1956 and 1999). You should make the printouts using the original image: don't just make one printout and then photocopy it; the contrast will be too low to see details. Make sure that the pulsar, labeled stars, and labeled knots are visible. If the knots cannot be seen well, change the contrast on the image or the printer. If you are still having trouble, use an imaging display program (such as GIMP– see the computer-based version of this exercise for more information) to change the contrast.

2) In class: With the students, go over information about supernova remnants provided in the Background Information section. Tell them that by simply measuring the changes between two images, they will be able to determine the age of an astronomical object. Go over any vocabulary (such as "knot," etc.). Before they start to make their measurements, stress that not all the knots are easy to measure, so they should be careful, and they should also pay particular attention to any tips given in the exercise.

3) Post-class: With the class, go over the students' results, and compare them to the "true" age of the Crab. How many students were close, how many were way off? Discuss possible places where errors could creep in, including general methods used or particular knots which may have caused problems. Tell them that methods such as the ones they used are also utilized by real scientists to find the ages of many astronomical objects.

Lesson Adaptations:
Measuring the knots involves some visual acuity. Students who are visually impaired can record the measurements instead of making them.

Assessment:

Points	Diagnostics
4	Students are able to correctly (within 10%) calculate the age of the Crab nebula, the rate of expansion of the nebula, the change in separation of the knots from the pulsar, and to carefully measure the positions of the knots.
3	Students are able to calculate the rate of expansion of the nebula, the change in separation of the knots from the pulsar, and to carefully measure the positions of the knots.
2	Students are able to calculate the change in separation of the knots from the pulsar, and to carefully measure the positions of the knots.
1	Answers and calculations are incorrect and incomplete, measurements are inaccurate and incomplete
0	Students are not able to do any of the above tasks.

Answer Key - "The Crawl of the Crab"

Note: these answers were based on printouts of the images, which may vary from printer to printer. You should perform the exercise yourself on your own printouts, and check the student answers against your own. Use the answers below as a guideline, not as a hard-and-fast answer sheet.

1

knot	Distance from Pulsar (cm)	
	1956	*1999*
1	4.55	4.95
2	3.28	3.45
3	1.92	2
4	3.35	3.54
5	2.48	2.67
6	1.15	1.25
7	2.95	3.1
8	2.56	2.72
9	2.72	2.8
10	3.65	3.81

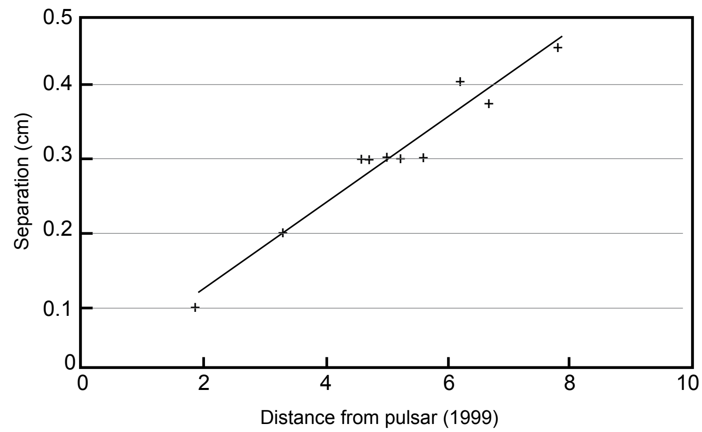
2

knot	Change in Separation from 1956 to 1999 (cm)
1	0.4
2	0.17
3	0.08
4	0.19
5	0.19
6	0.1
7	0.15
8	0.16
9	0.08
10	0.16

a) The variation should be large, as the expansion speed of each knot is not correlated with any other knot.

b) Yes: the farther the knot is from the pulsar, the faster its expansion speed.

c) The expansion speed should increase linearly with distance from the pulsar (with some scatter due to measurement error). For an explosion, parts that move faster will move farther in a given time. So now, a thousand years later, the knots that are farther away will have a higher speed than those closer in.



3

knot	Expansion rate (cm/year)
1	9.1×10^{-3}
2	3.9×10^{-3}
3	1.8×10^{-3}
4	4.3×10^{-3}
5	4.3×10^{-3}
6	2.3×10^{-3}
7	3.4×10^{-3}
8	3.7×10^{-3}
9	1.8×10^{-3}
10	3.7×10^{-3}

Elapsed Time: 43.75 years

4

Knot	Age of nebula (years)	Year of the explosion
1	541.7	1240.8
2	888.3	1211.6
3	1094.3	1299.1
4	815.5	1364.7
5	615.1	1372.0
6	547.1	1167.8
7	904.6	1269.9
8	744.1	1357.4
9	1531.95	467.1
10	1042.3	956.7

Age of nebula
AVERAGE: 851.9 years

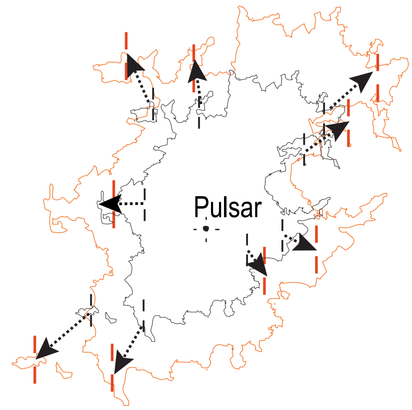
Year of the explosion
AVERAGE: 1147.1

STUDENT HANDOUT

THE CRAWL OF THE CRAB - 2

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.



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.

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?

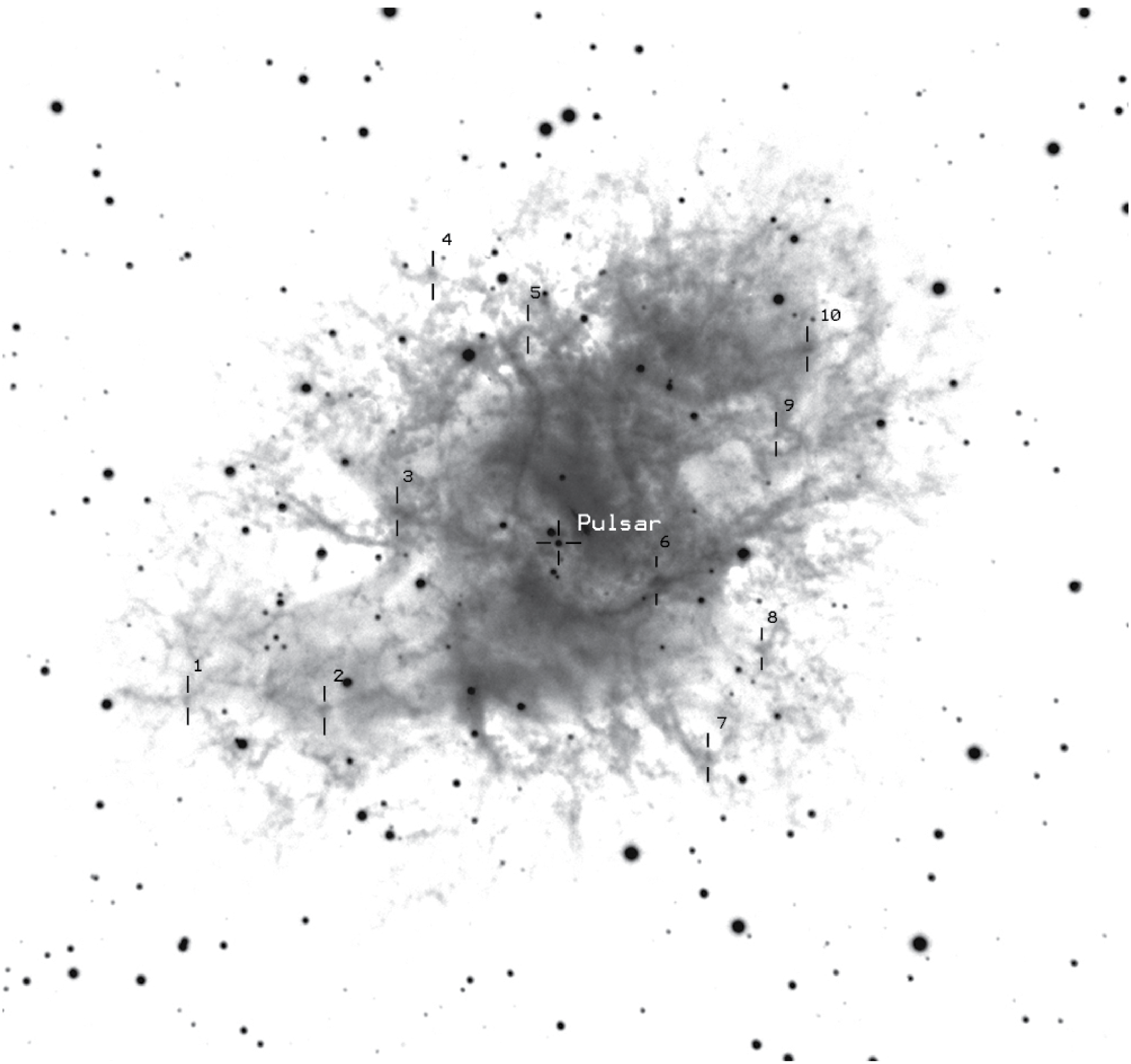
Calculate the average age of the nebula using the ages you derived for each of the knots.

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

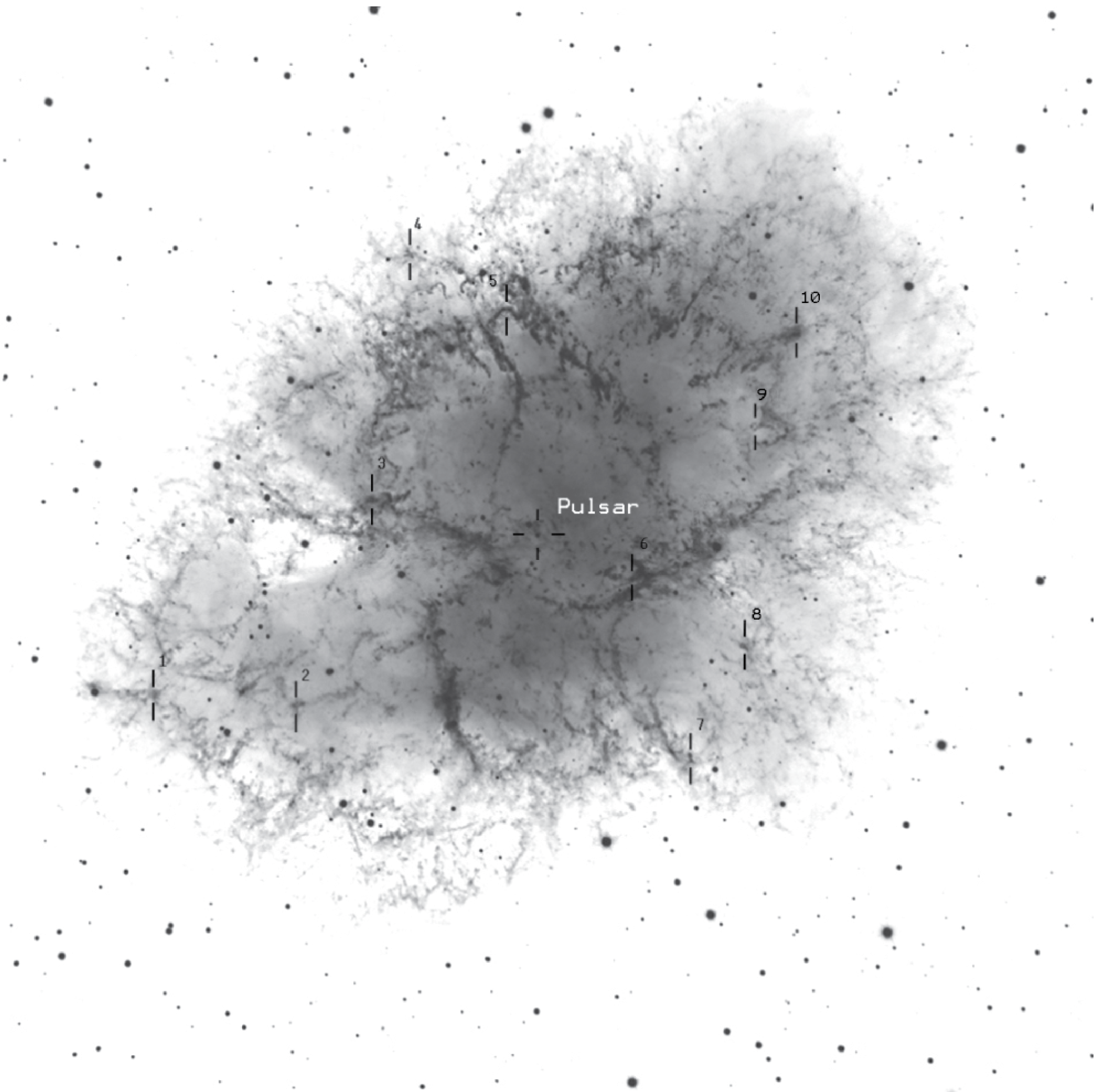
Calculate this number for each knot, and find the average year.

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

The Crab in 1956



The Crab in 1999



STUDENT WORKSHEET

THE CRAWL OF THE CRAB

Name: ____________

Datee: ____________

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)

3

knot	Expansion rate (cm)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

3

Elapsed Time _______________ (years)

4

Knot	Age of nebula (years)	Year of the explosion
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

AVERAGE: ___________ (years)

AVERAGE: ________________

3 MAGNETIC POLES AND PULSARS

Duration: Two 45 min sessions

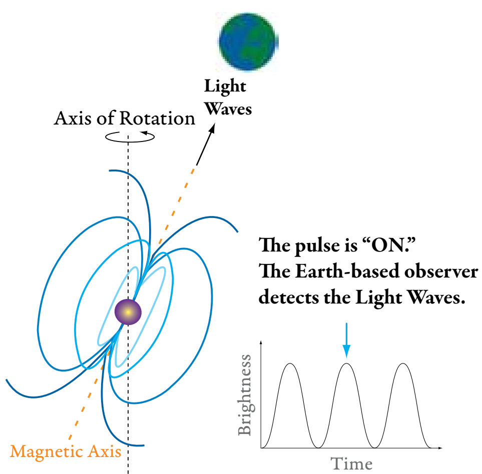
Background information:

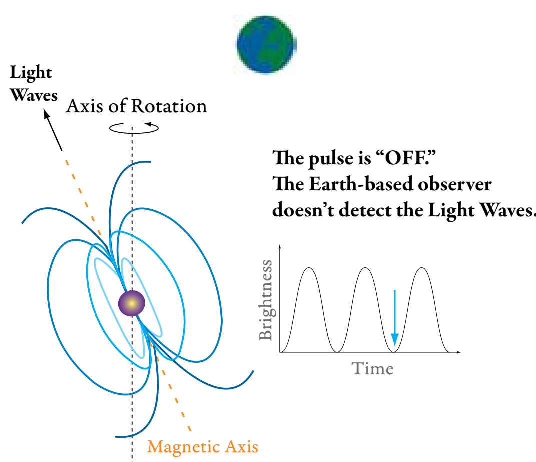
At the end of a star's life, what's left behind depends on the mass of the star's core. A star like the Sun is destined to become a white dwarf; a compressed ball of white-hot matter with about the mass of the Sun, but the size of the Earth. The enormous gravity of the white dwarf compresses it, but the star is held up by quantum mechanical forces that act on electrons inside it.

However, if the core of the star is greater than 1.4 times the mass of our Sun, then the quantum mechanical forces on the electrons cannot support it, and the core collapses to what's called a neutron star. Instead of the quantum mechanical forces on the *electrons* supporting the star, similar forces on the *neutrons* support it. A neutron star is incredibly dense, with twice the mass of the Sun squeezed into a ball only a few miles across.

If the core of the star is more than about 3 times the mass of the Sun, even the forces on the neutrons can't support it. In fact, no force known can stop the collapse. In this case the core compresses down into the Universe's ultimate dead-end: a black hole.

This exercise is concerned with neutron stars. In fact, it deals with a specific kind of neutron star; one that spins rapidly and has a strong magnetic field. Such a neutron star is called a "pulsar."





A pulsar is a rotating neutron star that emits electromagnetic radiation and charged particles from its magnetic poles. The rotational and magnetic axes are not necessarily aligned in a pulsar. As the pulsar spins about its rotational axis, at least one of the magnetic poles sweeps through the observer's line of sight. When the magnetic pole is pointed towards the observer, increased light will be observed. When the magnetic pole is pointed away from the observer, the light will be considerably dimmer. As the pulsar spins, this creates the appearance that the neutron star is turning on and off, causing the light streaming out along the magnetic poles to appear pulsed (hence the name "pulsar").

If neutron stars are made of neutral particles, how can they have magnetic fields?

Neutron stars are not totally made of neutrons – they have a "crust" with plenty of electrons, protons, and other particles. These charged particles can maintain the magnetic field. Plus, a basic property of magnetism is that once a magnetic field is made, it cannot simply disappear. Stars have magnetic fields because they are composed of plasma, very hot gas made of charged particles. When the star collapses to become a neutron star, it retains that "relic" magnetic field. And since the star gets smaller, the magnetic field gets stronger, since in a sense the field gets denser, more compressed. That is why neutron stars not only have magnetic fields, but why they they have such strong fields.

Essential Questions:

- What does a (**dipole**) magnetic field look like in three dimensions?
- How do neutron stars emit pulses?
- Extension: How do the magnetic fields of the Earth and a pulsar compare?

Objectives:

Students will...

- observe and draw magnetic field lines in two and three dimensions
- construct a model of a pulsar and observe pulsations
- Extension: compare the geometry of their pulsar model to that of the Earth

Science Concepts:

- Magnetic field lines form closed loops in three dimensions
- When the rotation and magnetic axes of a neutron star are not aligned, pulsations can result
- Extension: Like a pulsar, the Earth's magnetic and rotation axes are not aligned. However, the magnetic field of a pulsar is approximately one trillion times stronger than that on the Earth's surface, and pulsars rotate 10,000 to 100,000 times faster than the Earth. As a result the Earth does not appear to pulse.

Procedure:
(You should read the instructions below as well as those in the student handout. This handout contains more details.)

Note to the teacher: Students are expected to have a basic knowledge of (dipole) magnets and magnetic poles. This activity has two parts in which the students can participate, and one demonstration to be performed by the teacher.

This activity has the following components:

A. Seeing Magnetic Fields	B. Make Your Own Pulsar
In-class (2D) and classroom demonstration (3D), and an extension demonstration using refrigerator magnets.	Make your own pulsar, and a transfer activity that compares the Earth to a pulsar

Assessment:

Points	A. Seeing Magnetic Fields	B. Make Your Own Pulsar
4	Students are able to correctly draw iron filing patterns and answer all questions	Students are able to make the pulsar model and answer all questions
3	Students are able to correctly draw iron filing patterns but cannot extrapolate to three dimensions	Students are able to make the pulsar model and answer the first three questions
2	Students are able to correctly draw iron filing patterns but cannot identify poles or extrapolate to three dimensions	Students are able to make the pulsar model and understand the origin of the pulsations
1	Students are able to correctly draw iron filing patterns but cannot answer questions	Students are able to make the model but cannot answer any questions
0	Students cannot draw the iron filing patterns correctly	Students cannot make the model or answer any questions

A. Seeing Magnetic Fields

Duration: 30 minutes

Pre-activity Discussion:

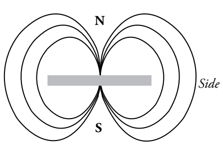
Students may benefit from reading the introductory material to this guide or material found on the following websites:
http://imagine.gsfc.nasa.gov/docs/science/know_l2/supernovae.html
http://imagine.gsfc.nasa.gov/docs/science/know_l2/pulsars.html

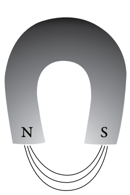
Ask your students the following questions about magnets:
a) How many types of magnetic poles are there?
b) What are they called?
c) How many poles does a magnet have?

Show them examples of common household magnets and ask them to identify the poles.

Answers to Pre-activity Discussion:

a) Two
b) North and South
c) Any number, although dipole magnets have only two poles (by definition). Other common household magnets (e.g., refrigerator magnets) can have many poles. These are not called dipole magnets.





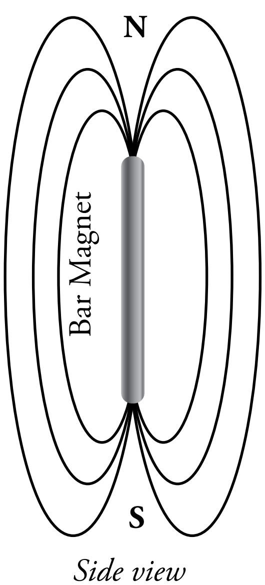


Figure 1: Possible drawings to represent field lines.

Procedure:

Distribute one set of magnets, a sheet of paper, a plastic sandwich bag and a container of iron filings to each group of students. Explain that they will be using the iron filings to "see" the magnetic field lines near the magnet. Have the students lay the plastic bag on top of the white sheet of paper, and take turns putting each magnet inside the bag, one at a time. Once a magnet is inside the bag, students can then carefully sprinkle the iron filings onto the top surface of the bag.

WARNING: The students must put the magnets inside the plastic bags before sprinkling on the filings or it will be very difficult to remove them from the magnet's surface!

Materials:

For each group of 2-3 students;

- At least 2 or 3 different types of household magnets (bar, horseshoe, refrigerator)
- 1 sheet of white paper
- 1 plastic sandwich bag
- iron filings in a small container with a lid.

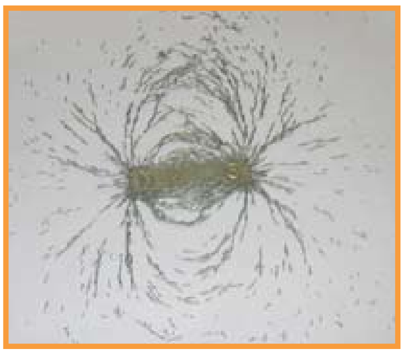
Prepare the Magnetic Globe according to the instructions given on p.30 in "Magnetic Globe Demo" and have it ready to show the students when they are done with their activity.

Answers to in-class activity questions:

1) The patterns represent the magnetic field lines. Since iron filings are little magnets, they align with the field lines so that the north pole ends of the filings are attracted to the south pole of the magnets (and vice versa.)

2) The answer will differ depending on the magnets used. In general, bar magnets will have two poles, one at each end. Horseshoe magnets will have two strong poles at the ends of the "U" but may also have a weaker pole at the bottom of the "U". Refrigerator magnets are alternating stripes of poles of differing polarity. The poles are located where the field is the strongest, and this can be seen by observing the locations where the most iron filings are present.

3) It is not possible to tell which pole is North or South using this experiment. You would need a compass or another magnet whose poles you know are labeled correctly in order to distinguish between pole types.



Bar magnet

Refrigerator magnet

Horse shoe magnet

Post-activity Discussion and Demonstration of Magnetic Globe:

Go around and ask your students the following questions while looking at their drawings:

1) Do you see patterns in the iron filings? What types of patterns?

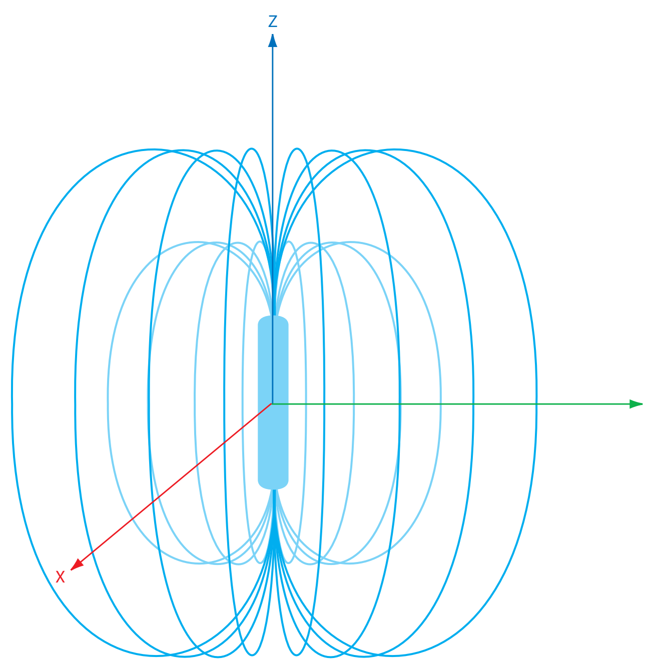
2) Can you show me your drawings of the magnetic field above or below the piece of paper for a bar magnet? For a refrigerator magnet?

Now show them the magnetic globe and discuss the similarities and differences between what the field lines look like in three dimensions compared to their drawings.

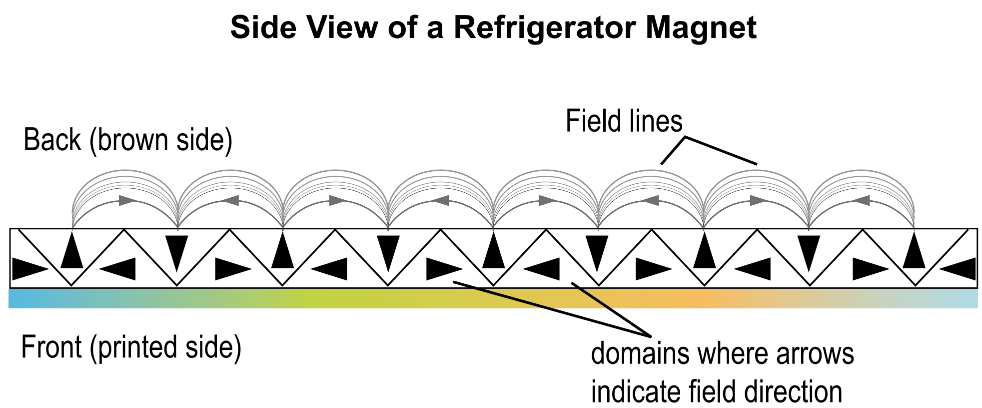
Answers to Post-Activity Discussion

1) There should be more filings near the poles. The filings should make loops for the bar magnets, and stripes for the refrigerator magnets. (See pictures above.)

2) The patterns above and below the piece of paper should look similar for the bar magnet. The field is very weak above the refrigerator magnet (above the printed side) but stronger below the magnet, so that it will stick to the refrigerator door. Here is an illustration of the three-dimensional pattern for a bar magnet.



Here is an illustration of the field lines and the magnetic domains for a refrigerator magnet.



Credit: The Board of Regents of the University of Wisconsin System.

Extension Demonstration:

Take two similarly sized refrigerator magnets and turn them face-to-face so the brown sides are touching. Move one quickly over the other one, and if they are lined up correctly, you will hear a "clicking" noise as they "jump" and reattach to adjacent stripes of poles. If you then rotate one magnet by 90 degrees and repeat, you will not hear the noise (or feel the "jump") and the magnets will slide smoothly past one another. Ask your students to explain this phenomenon.

Explanation:

When the stripes of alternating poles are aligned, they experience a repulsive force which causes the magnets to "jump" to the next position in which the opposite poles are aligned. When you rotate one magnet by 90 degrees, the stripes are not able to align and a weak attraction is felt between the two magnets, which then easily slide past one another.

MAGNETIC GLOBE DEMO

Materials:
- 1 – 2.5" diameter foam rubber Earth Globe (can be any similar foam rubber ball)
- 1- neodymium magnet – 1" sphere or cube
- Exacto or other very sharp cutting knife
- 2 or 3 pins with round plastic heads
- ~100 "clamped" staples (i.e., staples that have been produced by a stapler as if they were going through paper, except without the paper)

Globe Assembly:

1. Using the knife, cut a small (approximately one inch) slit to the center of the globe.

2. Insert the magnet into the center of the sphere.

3. Align the poles of the magnet as closely as possible to the correct orientation of the Earth's real magnetic poles. This can be done by placing about 3 "clamped" staples on each end of the globe, then moving them over the sphere until they stick out almost straight off of the globe. Another way to determine the poles is by using a compass just as you would to find the real Earth's poles. Place the compass against the globe, and follow the needle to the north pole. Once you have located the poles, rotate the magnet until the north pole is in the approximate location of the Queen Elizabeth Islands.

4. Seal up the seam on the rubber ball using two or three pins with plastic heads to bind the sides together as one would with fabric.

5. Slowly drop the "clamped" staples on the sphere, placing them so that they do not criss-cross along the latitude direction of the Earth globe. Make sure your globe looks like the image shown here.

What this globe ball demonstrates:

The staples provide a three dimensional representation of the magnetic field lines of our Earth. The Earth's magnetic field is a configuration known as a "dipole field." This type of field is also observed from common magnets, such as bar magnets, but most representations of this field configuration appear in textbooks or are done on pieces of paper using iron filings and therefore are only experienced in two dimensions.

Many objects in space have dipole magnetic fields that are geometrically similar to that of the Earth. However, the strength of magnetic dipole fields in space vary dramatically – from fractions of a Gauss (solar surface) to billions of Gauss (magnetic white dwarf stars.) The most extreme magnetic fields in the Universe are seen from neutron stars known as magnetars (approximately one thousand trillion or 10^{15} Gauss). The strength of the magnetic field is proportional to the density of field lines in a given region: areas with a greater density of field lines have stronger fields. In this case, the field lines are represented by staples and so the field is stronger where the staples are closer together.

Using the magnet in the globe you can show your students that a stronger magnetic field source will have the staples aligned closer to each other. To properly demonstrate this, the magnet must be spherical in shape. Use a second magnet, or pull the magnet out of the foam rubber globe, and repeat the experiment with the staples placed directly on the magnet.

Resources:
See Appendix B on p. 42.

STUDENT WORKSHEET

SEEING MAGNETIC FIELDS

Datee: ______ Name: ______

In this activity you will use iron filings and magnets to “see” the magnetic field around the magnet. You may be surprised by what you see!

Lay the plastic bag on top of the white sheet of paper, and take turns putting each magnet inside the bag, one at a time. Once a magnet is inside the bag, you can then carefully sprinkle the iron filings onto the top surface of the bag.

WARNING: DO NOT SPRINKLE THE FILINGS DIRECTLY ON THE MAGNET!

On a separate sheet of paper, draw the patterns that you see for each magnet. If you cannot see the pattern very well, try using more or fewer filings, or tap the piece of paper.

After each drawing, remove the magnet from the plastic bag and use the paper and bag to return the filings to the container.

In-class activity questions:

1) What are the patterns showing you? Why are the iron filings making these patterns?

2) How many poles does each magnet have? How do you know where the poles are located?

3) Can you tell which poles are North or South in this experiment? Explain.

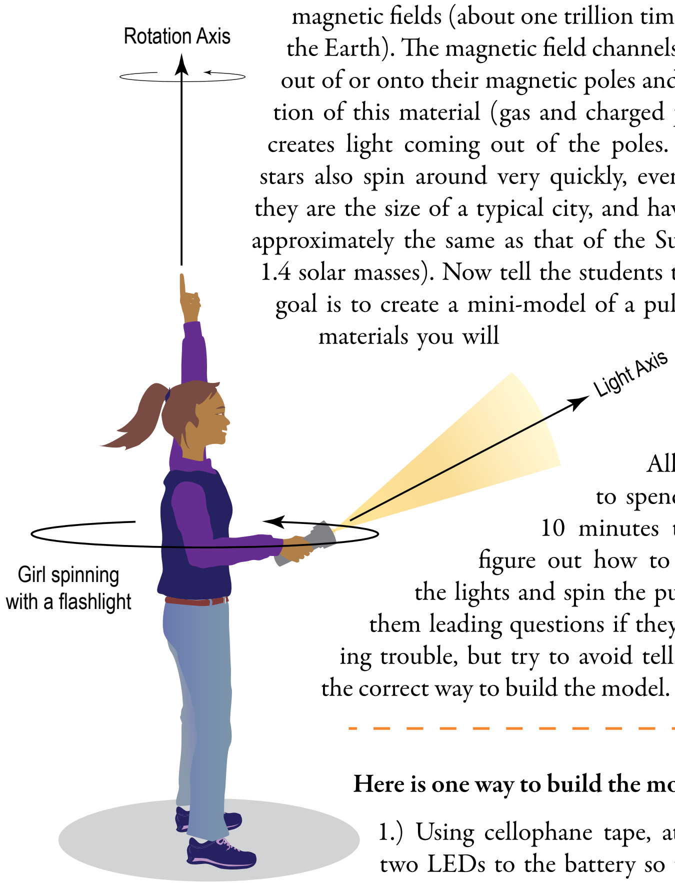
After discussing your results with your teacher, try to draw what you think the magnetic field would look like above and below the paper (plastic bag) for each of your magnets.

B. Make Your Own Pulsar

Duration: 20 minutes

Pre-activity Discussion and Demonstration:

In this activity your students are going to make a mini-model of a rotating neutron star, called a "pulsar." To do the demonstration, you will need a flashlight or some other type of light source. Turn on the flashlight and hold it in your hand, pointing out away from your body. Spin around a few times (see drawing). Ask the students what type of light pattern they see. They should answer that they see a pulse or flash of light as the flashlight beam crosses their line-of-sight. Explain to them that pulsars make light pulses in a similar fashion – the direction that the light beam shines is not the same direction as the axis around which you are rotating, similar to a lighthouse or a search beam. Explain to the students that neutron stars emit light beams because they have very strong magnetic fields (about one trillion times that of the Earth). The magnetic field channels material out of or onto their magnetic poles and the motion of this material (gas and charged particles) creates light coming out of the poles. Neutron stars also spin around very quickly, even though they are the size of a typical city, and have a mass approximately the same as that of the Sun (really 1.4 solar masses). Now tell the students that their goal is to create a mini-model of a pulsar using materials you will give them. Allow them to spend at least 10 minutes trying to figure out how to light up the lights and spin the pulsar. Ask them leading questions if they are having trouble, but try to avoid telling them the correct way to build the model.



Here is one way to build the model:

1.) Using cellophane tape, attach the two LEDs to the battery so that they face in opposite directions. Make sure that one lead of the LED is touching the positive side of the battery and the other lead is touching the negative side.

2.) Using either the modeling clay or aluminum foil make a round ball that encases the battery while exposing the LEDs. Note: If you are going to use aluminum, please make sure that the battery and the LED leads are completely encased by tape otherwise the LEDs will not light up..

3.) Insert the toothpick or skewer into the ball. Spinning the ball using the toothpick or skewer produces pulses.

Procedure:

This activity can be done alone or in pairs. The materials list below gives the quantities for each pulsar. Distribute the materials to each group or individual. Tell them that their goal is to use the materials in order to make a pulsar that can be spun around in order to see the flashes of light as it goes by just like they saw the flashlight beam when you spun around.

Materials:

For each pulsar you will need;

- different colors of light emitting diodes (LEDs)
- 1 watch battery
- Cellophane (Scotch) tape
- Modeling clay or aluminum foil
- Toothpick or skewer

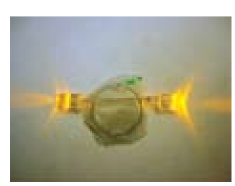
Answers to In-class Activity Questions:

1) The model makes pulsations because the rotation axis (the axis defined by the skewer) is not aligned with the axis along which the LED lights are located. It is this offset which creates the pulses.

2) You see maximum light when the pulsar beam is aimed in your direction. You see minimum light when the beam is facing away from you.

3) The period of the pulsar is about five seconds. This is the time during which the neutron star rotates around once.

Two pulsar prototypes your students may design:



STUDENT WORKSHEET

MAKE YOUR OWN PULSAR

Datee: ____________ Name: ____________

In this activity, you are challenged to take the materials given to you and use them to create your own mini-model of a pulsar. The goal is to then spin it around and see the pulses!

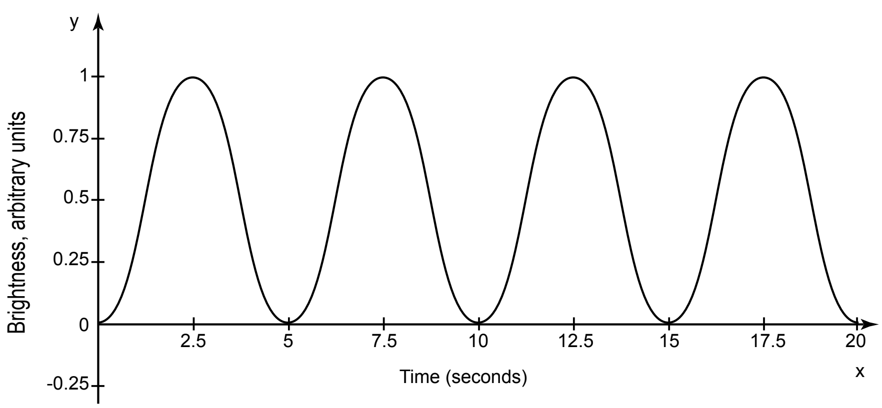
Study the materials that are given to you – create a design that you think will turn the pulsar's lights on. Draw your design on a separate piece of paper. Now try making your pulsar by using your design. Did the lights turn on? If not, go back to the drawing board and rethink your design.

How can you spin the pulsar so that you see pulses as it turns? Add this information to your drawing and show your drawing to your teacher.

In-class Activity Questions:

1) Why does your model pulsar pulse? In other words, why do you see pulsations and not continuous light from your model?

2) Now look at the graph below which shows several pulses from a pulsar. What direction does the pulsar beam point when you see the maximum light? Minimum light?



3) Looking at the graph above, what is the period of the pulsar? What does the period of the pulsar represent?

Transfer Activity

Comparing the Earth to a Pulsar

Duration: 20 minutes

Background Information:

Similar to a pulsar, the Earth has magnetic poles that are not aligned with the geographic poles around which the Earth rotates. At the present epoch, the angle between the two axes (magnetic and rotation) is around 11 degrees. The south magnetic pole, however, is located farther from the south geographic pole than the separation between the poles in the north. The north magnetic pole of the Earth (where the compass needle points) is currently located in the Canadian arctic at approximately 83° north latitude, and 115° west longitude, not at the geographic North pole of the Earth. This is illustrated in the figure below on the student handout.

The Earth's magnetic field is about 1 x 10^{-4} Tesla, too weak to channel large volumes of material directly onto its poles. However, the Earth has something that a neutron star does not: an atmosphere! When charged particles from the Sun reach the Earth's atmosphere, they interact with atmospheric molecules in oval regions around the magnetic poles, creating bright, colorful aurorae (known as "auroral ovals.") Further details about aurorae are outside the scope of this activity unit, but you can read more about them in the student handout below and at the following websites:

http://spaceweather.com/aurora/gallery.html
http://www.northern-lights.no/english/what/oval.shtml
http://cse.ssl.berkeley.edu/SegwayEd/lessons/auroras/index.html
http://sprg.ssl.berkeley.edu/aurora_rocket/education/crt/index.htm

Procedure:

Show your students the pictures of aurorae below and/or video clips of aurorae found on the above web sites, along with the illustration of the Earth on the student handout. Ask your students to recall what they have learned about how pulsars create beams of light. Ask the students if any have ever seen an aurora? If so, ask them where they were when they saw one. Then have them break into small groups to do the activity described in detail on the student handout.

Answers to Transfer Activity questions:

1) Aurorae typically occur in regions bounded by oval rings centered on the Earth's magnetic poles. This includes countries such as Canada and Russia. The magnetic field lines bring the charged particles to the Earth's atmosphere in these locations.

2) Auroral ovals increase in size and intensity and are thus easiest to see during times of intense solar activity, such as solar flares, which are more numerous during "solar maximum." The next solar maximum is predicted to occur in 2011.

3) No, the Earth's aurorae do not appear as pulses. The Earth rotates too slowly, the region from which the light is emitted is too spread out, and the auroral light is not very bright.

4) The planet Jupiter has aurorae that occur in oval-shaped regions around its magnetic poles, similar to the Earth. Jupiter also has an auroral region where its magnetic field connects to that of its moon Io. You can see images of these aurorae at: *http://apod.nasa.gov/apod/ap980123.html*

5) Magnetic white dwarf stars are sometimes seen to pulse. Read more about these stars: *http://imagine.gsfc.nasa.gov/docs/science/know_l2/cataclysmic_variables.html*

6) Although Jupiter's field is much stronger than the Earth's, it does not rotate very quickly compared to neutron stars. Also, it has an atmosphere with which the charged particles interact. It therefore has aurorae similar to the Earth. White dwarfs have stronger fields, no atmosphere, and rotate rapidly. Pulsations have been seen from some white dwarfs in binary systems, such as AE Aquarii.

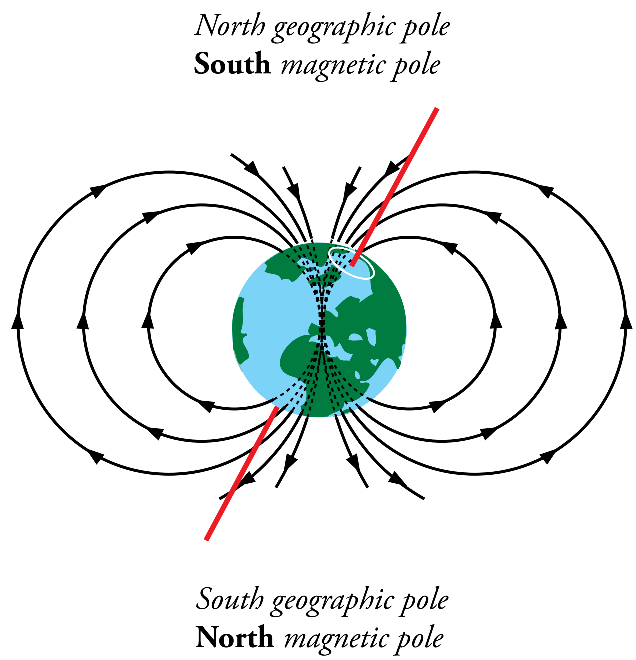
STUDENT WROKSHEET

COMPARING THE EARTH TO A PULSAR

In this activity, you are going to learn about similarities and differences between the Earth and a pulsar and use the properties of these objects to make predictions about light emissions from other objects in the Universe.

Below are some photographs of aurorae. Your teacher may also show you some videos of aurorae on the Earth. Aurorae are caused when charged particles from our Sun follow the magnetic field lines of the Earth down into the atmosphere, interacting with molecules of Nitrogen and Oxygen to make beautiful colors. The number of charged particles from the Sun that reach the Earth increases during periods of solar flares, as well as during the spring and fall of each year.

Examine the drawing to the right of the Earth which shows its magnetic poles and the North and South geographic poles. Use what you have learned about pulsars, the Earth and aurorae to answer the following questions on a separate sheet of paper:



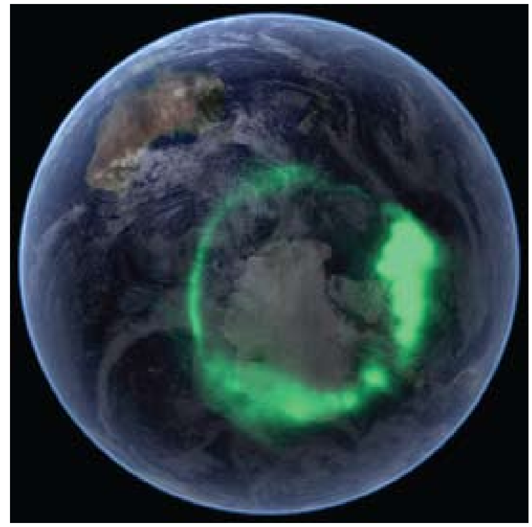
1) Over what countries do you think aurorae typically occur? Why?

2) When do you think aurorae will be easier to see?

3) Do you think someone in outer space sees the aurorae from the Earth as pulses? Why or why not?

Aurorae images credit: Jan Curtis - copyright

credit: Jan Curtis - copyright



credit: NASA - IMAGE

Here is a table that summarizes some of the properties of the Earth vs. a typical pulsar and two other cosmic objects: the planet Jupiter and a white dwarf star:

Object	Magnetic Field-Strength (Tesla)	Radius (km)	Rotation
Earth's field at ground level	0.5×10^{-4}	6.40×10^{3}	24 hours
Jupiter field	10^{-1}	7.10×10^{4}	10 hours
White Dwarf AE Aquarii	10^{4}	6.40×10^{3}	33 s
Neutron star surface	10^{8}	1.00×10^{1}	10^{-3} s to 100 s

4) Looking at the values in this table, do you think the planet Jupiter will have aurorae like the Earth or will it pulse like a pulsar?

5) What do you predict for the white dwarf AE Aquarii?

6) Explain your reasoning.

4 Neutron Stars in the News

Duration:
1 hour

Essential Questions:

- How do the magnetic fields of different types of neutron stars compare?

Objectives:
Students will...

- read and analyze two different articles about XMM-Newton discoveries
- get a better understanding of neutron stars and their magnetic fields

Science Concepts:

Even though magnetic fields on neutron stars are approximately one trillion times stronger than that on the Earth's surface, different types of neutron stars can have magnetic fields with strengths that differ by a factor of 10,000.

Brief Overview: Students read and analyze two different articles about XMM-Newton discoveries involving neutron stars and their magnetic fields. This is a science literacy extension

Procedure:

Have your students read the two articles below individually in class or send them home as homework. When they are done, they should answer the questions in the student handout. Gather the students into small groups in class for further discussion and a summative group presentation.

Summarize:

Dead Star's Magnetism: This article describes the first measurement of the magnetic field directly from the surface of an x-ray emitting neutron star, 1E1207.4-5209. It is thirty times weaker than expected from previous radio measurements, or about 6×10^6 Tesla.

Starquake: This article describes the measurement of the magnetic field of the "magnetar" XTE J1810-197 which has torn itself apart in a "starquake" due to its extremely large field of 3×10^{10} Tesla.

People and Science:

Dead Star's Magnetism: These measurements were made by Italian Prof. Giovanni Bignami and his team using the XMM-Newton satellite.

Starquake: These measurements were made by Turkish Prof. Tolga Guver and his team using the XMM-Newton satellite.

Compare and contrast:

The magnetic field in the first article was 6×10^6 Tesla, whereas in the second article, the "magnetar" had a field of 3×10^{10} Tesla. The first magnetic field is about 120 billion (1.2×10^{11}) times that of Earth; the magnetar's field is about 600 trillion (6×10^{14}) times that of Earth.

Predict:

Scientists will try to use XMM-Newton and other observatories to find other neutron stars and measure their magnetic fields. They will also try to observe other magnetars during flares to measure their magnetic fields. It is possible that the magnetars have much stronger fields because they are very young objects – only 10,000 years old, which is very young by astronomical standards. The neutron star in the first article may be much older, and its magnetic field has gotten weaker over time. Or it may just have been originally created with a much weaker field. More observations may help decide between these two possibilities.

Assessment:

Points	Neutron Stars in the News (both articles)
4	Students are able to accurately summarize each article, determine the people and instruments who contributed to each study, and to compare and contrast the magnetic fields measured for the two different neutron stars. They are also able to make reasonable predictions as to further investigations.
3	Students are able to accurately summarize each article, determine the people and instruments who contributed to each study, and to compare and contrast the magnetic fields measured for the two different neutron stars
2	Students are able to do any two of the three required elements described above.
1	Students are able to do any one of the required elements.
0	Students are not able to provide correct responses to any of the required elements.

STUDENT HANDOUT

IN THE NEWS

Directions:

Read the articles on p. 39 and 40, and as a group answer the questions below *on a separate sheet of paper*. After you are done reading the articles, and answering the questions, get into small discussion groups as assigned by your teacher. Discuss your individual responses to the questions. Choose one person in the group to record this discussion and choose another person to report back to the class. Together, design a short presentation for the class. You will have 5 minutes for your presentation. Be creative!

Summarize:

Using your own words, summarize the information in each article. Don't forget to include the science topics discussed and why scientists are interested in these topics.

People and Science:

Who are the scientists that did the work discussed in each article? What instruments did they use?

Compare and contrast:

What is the difference in the strength of the magnetic field measured from the two different types of neutron stars? How do the measurements of the neutron star magnetic fields compare to that at the Earth's surface (which is 0.5×10^{-4} Tesla)?

Predict:

What other types of measurements do you think scientists will try to make? Do you have any predictions as to why the measurements of the magnetic fields of the two neutron stars are so different?

Article 1

11 June 2003

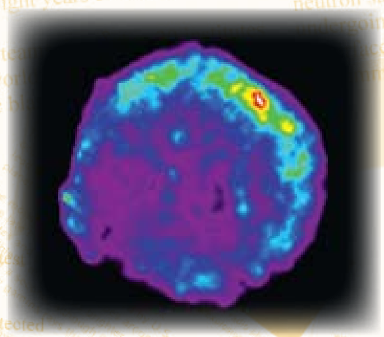
XMM-Newton makes the first measurement of a dead star's magnetism

Using the superior sensitivity of ESA's X-ray observatory, XMM-Newton, a team of European astronomers has made the first direct measurement of a neutron star's magnetic field. The results provide deep insights into the extreme physics of neutron stars and reveal a new mystery yet to be solved about the end of this star's life.

A neutron star is a very dense celestial object that usually has something like the mass of our Sun packed into a tiny sphere only 20-30 kilometres across. It is the product of a stellar explosion, known as a supernova, in which most of the star is blasted into space, but its collapsed heart remains in the form of a super-dense, hot ball of neutrons that spins at a incredible rate.

Despite being a familiar class of object, individual neutron stars themselves remain mysterious. Neutron stars are extremely hot when they are born, but cool down very rapidly. Therefore, only few of them emit highly energetic radiation, such as X-rays. This is why they are traditionally studied via their radio emissions, which are less energetic than X-rays and which usually appear to pulse on and off. Therefore, the few neutron stars which are hot enough to emit X-rays can be seen by X-ray telescopes, such as ESA's XMM-Newton.

One such neutron star is 1E1207.4-5209. Using the longest ever XMM-Newton observation of a galactic source (72 hours), Prof. Giovanni Bignami of the Centre d'Itude Spatiale des Rayonnements (CESR) and his team have directly measured the strength of its magnetic field. This makes it the first ever isolated neutron star where this could be achieved. All previous values of neutron star magnetic fields could only be estimated indirectly. This is done by theoretical assumptions based on models that describe the gravitational collapse of massive stars, like those which lead to the formation of neutron stars. A second indirect method is to estimate the magnetic field by studying how the neutron star's rotation slows down, using radio astronomy data.



Tycho Supernova remnant, XMM-Newton, 2006

In the case of 1E1207.4-5209, this direct measurement using XMM-Newton reveals that the neutron star's magnetic field is 6×10^6 Tesla, 30 times weaker than predictions based on the indirect methods.

How can this be explained? Astronomers can measure the rate at which individual neutron stars decelerate. They have always assumed that 'friction' between its magnetic field and its surroundings was the cause. In this case, the only conclusion is that something else is pulling on the neutron star, but what? We can speculate that it may be a small disc of supernova debris surrounding the neutron star, creating an additional drag factor.

The result raises the question of whether 1E1207.4-5209 is unique among neutron stars or the first of its kind. The astronomers hope to target other neutron stars with XMM-Newton to find out.

X-rays emitted by a neutron star like 1E1207.4-5209, have to pass through the neutron star's magnetic field before escaping into space. En route, particles in the star's magnetic field can steal some of the outgoing X-rays, imparting on their spectrum tell-tale marks, known as 'cyclotron resonance absorption lines'. It is this fingerprint that allowed Prof. Bignami and his team to measure the strength of the neutron star's magnetic field.

These results were published in the 11 June 2003 issue of Nature.

Article 2

21 September 2007

‘Starquake’ reveals star’s powerful magnetic field

by David Shiga

Some neutron stars have such powerful magnetic fields that they rip themselves open due to magnetic forces, a new study confirms.

A neutron star is the dense core left behind when a massive star explodes as a supernova. Made of subatomic particles called neutrons, the stars are so dense that a teaspoonful of their material would weigh 500 million tonnes.

The spins of some neutron stars decrease rapidly, suggesting they boast extremely powerful magnetic fields that radiate electromagnetic energy that slows their rotation. This type of neutron star is called a magnetar.

But it was always possible that the neutron stars might be slowing down for other reasons, for example as a result of spewing charged particles out into space.

Now, new observations of a candidate magnetar have confirmed that it has a magnetic field of 3 x 10^{10} Tesla – or 600 trillion times the strength of Earth’s field – powerful enough to explain the ‘starquake’ it experienced in 2003. The study team was led by Tolga Guver of Istanbul University in Turkey.

“It’s the first independent confirmation that a magnetar is truly a magnetar,” team member Feryal Ozel of the University of Arizona in Tucson, US, told New Scientist. “These are the most magnetic objects in the universe, by orders of magnitude.”

The incredibly strong magnetic fields of some neutron stars can rip the stars open (Illustration: NASA)

Violent starquakes

The researchers used the European Space Agency’s XMM-Newton spacecraft to measure X-rays from a neutron star called XTE J1810-197, which lies about 10,000 light years from Earth in the constellation Sagittarius.

It was discovered in 2003 when it had a major outburst, suddenly becoming more than 100 times brighter than normal in X-rays. The event was similar to magnetic starquakes seen on other candidate magnetars.

The idea is that the crust of the neutron star buckles and cracks due to the tremendous magnetic forces exerted by the star’s own magnetic field. But there were other possible explanations of these outbursts, such as sudden changes to the cloud of charged particles called the magnetosphere that surrounds the stars.

Short lives

By analysing the spectrum of X-rays coming from XTE J1810-197 since its 2003 outburst, Guver’s team determined the existence of a hot spot about 7 kilometres wide at the neutron star’s surface. The spot was heated to about 5 million degrees by the outburst, and has been cooling since then. This is consistent with the starquake theory, in which the part of the neutron star’s crust that buckles releases tremendous energy and heats up its surroundings.

Jules Halpern of Columbia University in New York City, US, says further studies of such outbursts may reveal why magnetars have such short lives. The known magnetars all appear to be very young – most are less than 10,000 years old.

“It may be the case that hundreds of outbursts over the lifetime of the star are responsible for dissipating most of the magnetic field,” he told New Scientist. “After that . . . they may turn into ordinary radio pulsars or some other type of neutron star.”

This article was printed in New Scientist, September 2007

APPENDIX A

GLOSSARY

A

Arcminute: an angular unit of measurement. There are 360 degrees in a circle, 60 arcminutes in a degree, and 60 arcseconds in an arcminute.

Arcsecond: see arcminute.

Atom: the basic unit of an element composed of a nucleus made of protons and neutrons, and an outer cloud of electrons.

B

Black hole: One type of black hole is formed from the collapsed core of a star after it goes supernova. Its gravity is so intense not even light can escape from inside the event horizon.

D

Degree: a coordinate on the sky corresponding to latitude on the Earth.

Dipole: an object (such as a magnet) that has two opposite poles separated by some distance.

E

Electron: a negatively charged subatomic particle.

G

Galaxy: a collection of gas, dust, and billions of stars bound together by their own gravity.

Gamma Ray: a very high energy photon (particle of light).

Gravity: the force exerted by one massive body on another. The force of gravity from an object depends on its mass and inversely on how far you are from it.

K

Knot: a small region of gas in a nebula that has a higher density than the gas around it.

L

Light year: the distance light travels in one year; approximately 9.5 trillion (9.5×10^{12}) kilometers.

M

Magnetic pole: Either of two regions usually near opposite ends of a magnet where the magnetic intensity is greatest.

Magnitude: a brightness scale used by astronomers to measure stars. It is a logarithmic scale, where the difference in magnitudes is actually a brightness factor of 2.512.

N

Nebula *(pl. nebulae)*: A diffuse mass of interstellar dust and gas.

Neutrino: a fundamental particle produced in massive numbers by the nuclear reactions in stars; they are very hard to detect because the vast majority of them pass completely through the Earth without interacting.

Neutron: a uncharged subatomic particle that, along with protons, make up atomic nuclei.

Neutron star: the extremely dense core of a star after it has exploded as a supernova. A neutron star has a mass of 1.4 solar masses to as much as three times the mass of the Sun, but may be only a few kilometers across.

Nucleus *(plural: nuclei)*: the core of an atom, generally made up of protons and neutrons.

O

Orbit: the path an object takes when it is influenced by the gravity of another object.

P

Proton: a positively charged subatomic particle usually found in the nucleus of an atom.

Pulsar: a rapidly rotating neutron star with a strong magnetic field, which emits twin beams of energy that sweep through the observer's field of view like beams from a lighthouse.

R

Radioactivity: a form of instability in nuclei of certain isotopes which causes them to spontaneously change their structure and to emit radiation in so doing.

S

Solar Mass: a unit of mass where the mass of the Sun is 1. Generally used for the mass of stars and galaxies. One solar mass is 2×10^{30} kg.

Solar System: a collection of planets, moons, comets, etc. which orbits a star. Our solar system is roughly 10^{10} kilometers (10^{13} meters) across.

Supernova (*plural: supernovae*)**:** the titanic explosion of a massive star at the end of its life. The outer layers explode outward, creating a supernova remnant, while the inner core collapses to become a neutron star or black hole.

Supernova remnant (SNR): the expanding gas left over from a supernova.

W

White dwarf: the dense core of a star like the Sun as it ends its life. A white dwarf has as much mass as the Sun, but the diameter of the Earth.

X

X-ray: a high energy photon (particle of light).

REFERENCES AND RESOURCES

Activity 1

Imagine The Universe:
http://imagine.gsfc.nasa.gov/docs/science/know_l1/supernovae.html
http://imagine.gsfc.nasa.gov/docs/scienc e/know_l1/pulsars.html

Curious About Astronomy? Ask An Astronomer:
http://curious.astro.cornell.edu/supernovae.php

Hyperphysics:
http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html

Activity 2

"Laboratory Exercises in Astronomy – The Crab Nebula", Owen Gingerich, Sky and Telescope magazine, November 1977, p. 378.
"The Crab Nebula", Julia Plummer and Shannon Murphy, University of Michigan, 2003.
http://helios.astro.lsa.umich.edu/Course/Labs/crab/crab-full.html

"The Crab Nebula", a lab exercise written by Brent Studer, Kirkwood (Iowa) Community College, 2006.
http://www.avalon.net/~bstuder/crab_lab.html

Crab Nebula image (1956) © 1990-2002, Malin/Pasachoff/Caltech, photograph from Hale 5-meter plates by David Malin.
Crab Nebula image (1999) © 1999, European Southern Observatory, photograph by Richard Hook and Robert Fosbury.
http://www.eso.org/outreach/gallery/vlt/images/Top20/Top20/top1.html

History of the Crab Nebula:
http://www.seds.org/messier/more/m001_sn.html and http://www.seds.org/messier/m/m001.html

Wikipedia:
http://en.wikipedia.org/wiki/Crab_Nebula

Animation of Crab expansion:
http://antwrp.gsfc.nasa.gov/apod/ap011227.html

Hubble press release:
http://hubblesite.org/newscenter/newsdesk/archive/releases/1996/22/

Bitesize Astronomy:
http://www.badastronomy.com/bitesize/crab_expand.html and http://www.badastronomy.com/bitesize/crab_pulsar.html

Activity 3

Jovian aurorae:
http://apod.nasa.gov/apod/ap980123.html

Information on aurorae and solar flares:
http://spaceweather.com

North magnetic pole position and movement:
http://gsc.nrcan.gc.ca/geomag/nmp/northpole_e.php

Auroral oval:
http://www.sec.noaa.gov/pmap/

(Activity 3)

Collection of aurora photographs:
http://www.geo.mtu.edu/weather/aurora/images/aurora/jan.curtis/index.html

Solar Cycle information:
http://solarscience.msfc.nasa.gov/predict.shtml

"Neutron Stars and Pulsars"
http://imagine.gsfc.nasa.gov/docs/science/know_l1/pulsars.html

"Gene Smith's Astronomy Tutorial, Supernovae, Neutron Stars & Pulsars"
http://cassfos02.ucsd.edu/public/tutorial/SN.html

Wikipedia entry for supernova
http://en.wikipedia.org/wiki/Supernova

"What is the strongest magnetic field ever known?"
http://www.astronomycafe.net/qadir/ask/a11654.html

"Neutron Stars and Pulsars"
http://www.eclipse.net/~cmmiller/BH/blkns.html

"The Crab Pulsar"
http://csep10.phys.utk.edu/astr162/lect/pulsars/pulsars.html

"ESA's XMM-Newton makes the first measurement of a dead star's magnetism" - ESA press release, June 2003.
http://www.esa.int/esaCP/Pr_38_2003_p_EN.html

Where to find Neodymiun magnets
http://www.kjmagnetics.com

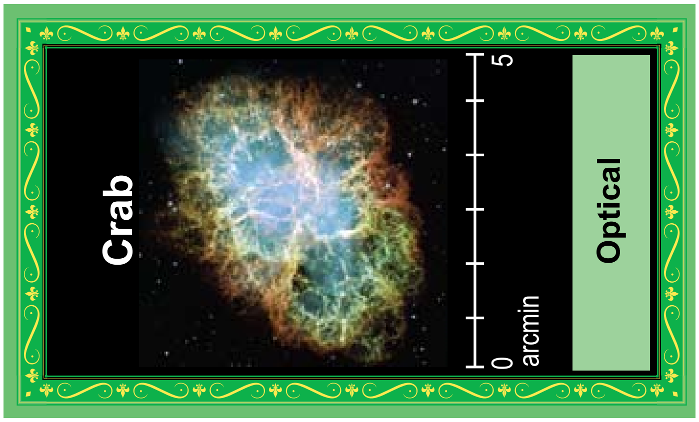
Where to find foam balls
http://www.orientaltrading.com

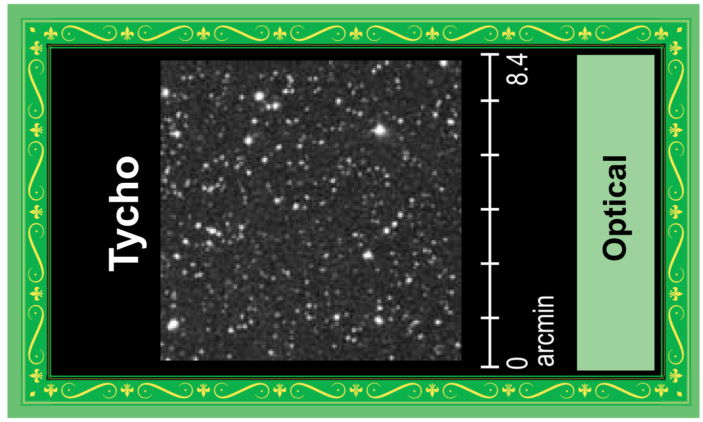
Activity 4

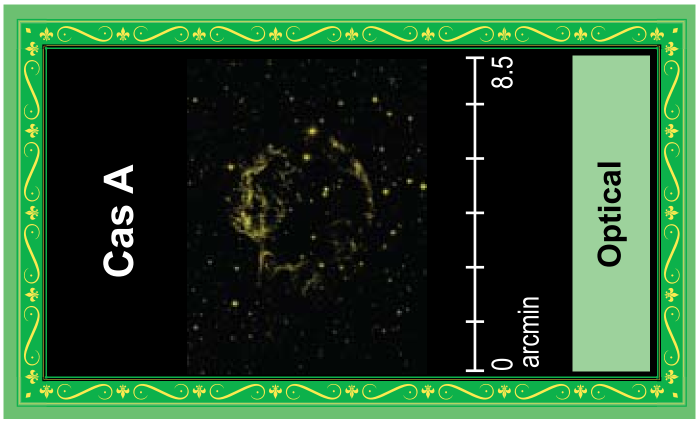
In the News: XMM-Newton: Dead Star's magnetism – Nature magazine, June 2003
Superficial resonance, Frits Paerels - NATURE|VOL 423 | 12 JUNE 2003 |www.nature.com/nature p. 697

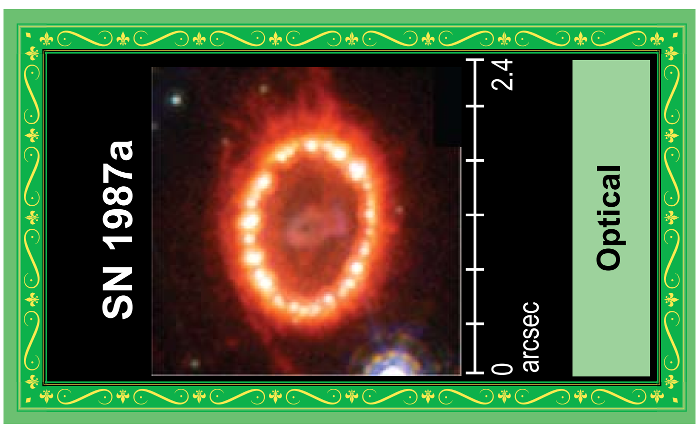
"Starquake" reveals Powerful Magnetic Field – New Scientist magazine, September 2007
Journal reference: The Astrophysical Journal Letters (vol 667, p 73)
http://space.newscientist.com/article/dn12678-starquake-reveals-stars-powerful-magnetic-field.html

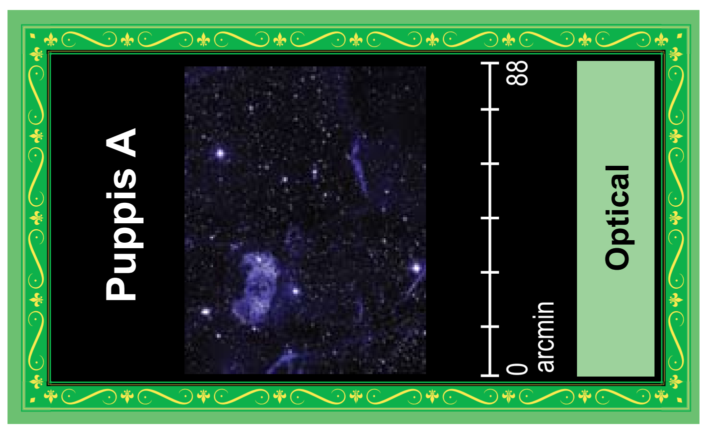
Activity 1: Fishing for Supernovae Playing Cards

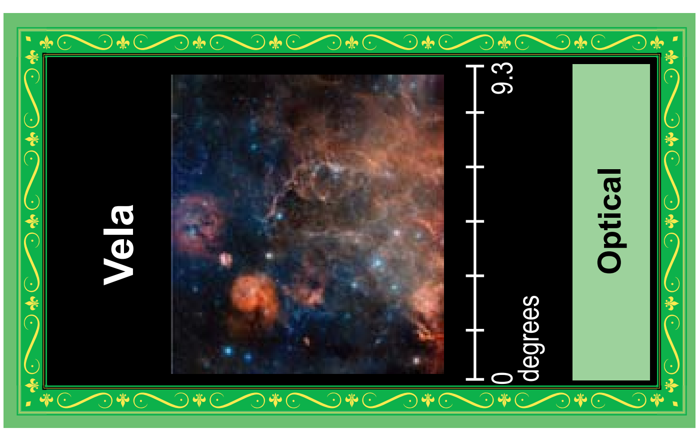


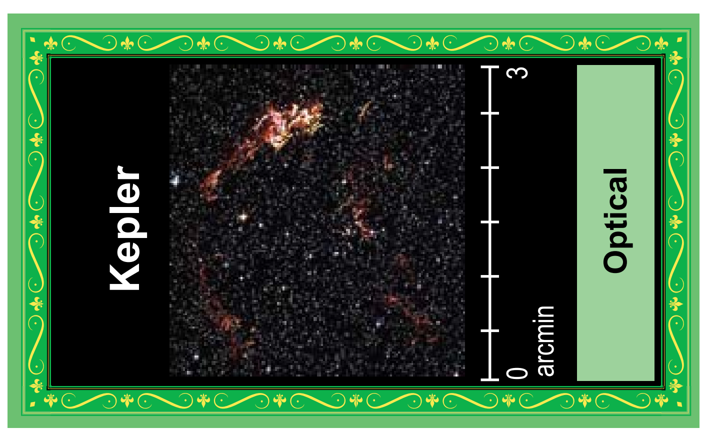




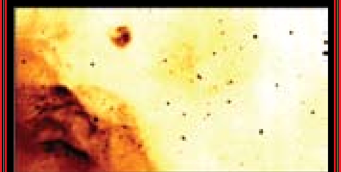








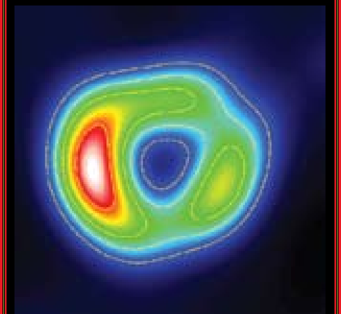
Vela



0 — 7 degrees

Radio

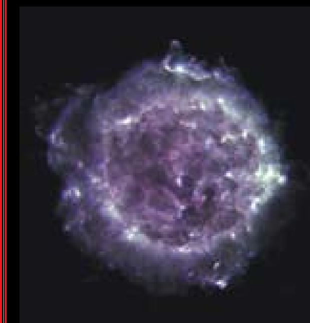
SN 1987a



0 — 2.4 arcsec

Radio

Cas A



0 — 6 arcmin

Radio

Crab

0 — 7 arcmin

Radio

Kepler

0 — 5 arcmin

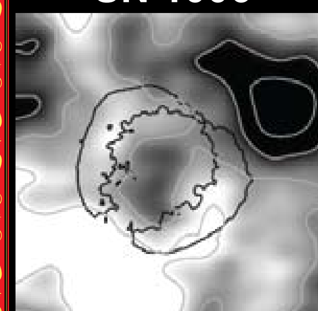
Radio

Puppis A

0 — 8 arcmin

Radio

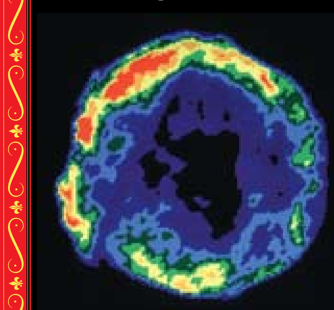
SN 1006



0 — 6 arcmin

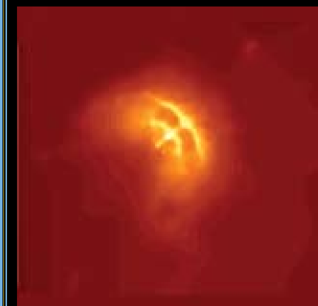
Radio

Tycho



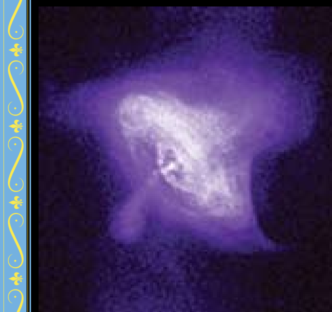
0 — 17 arcmin

Radio


Vela
0
3.5
arcmin
X-Ray


SN 1987a
0
2.4
arcsec
X-Ray

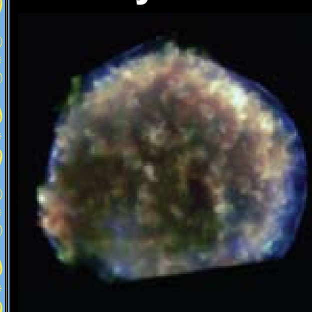

Cas A
0
6.9
arcmin
X-Ray


Crab
0
2.5
arcmin
X-Ray

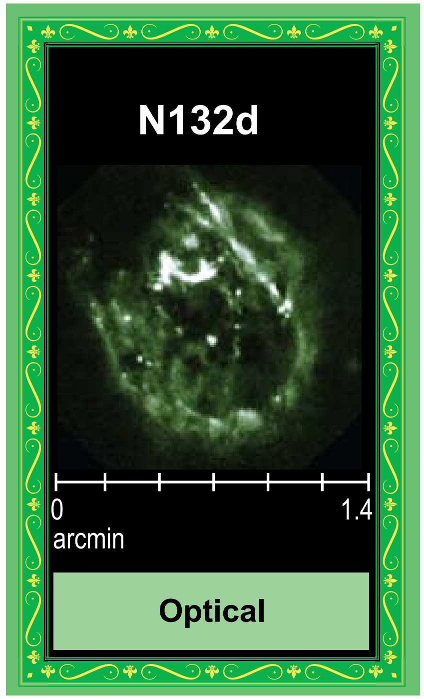

Kepler
0
5
arcmin
X-Ray

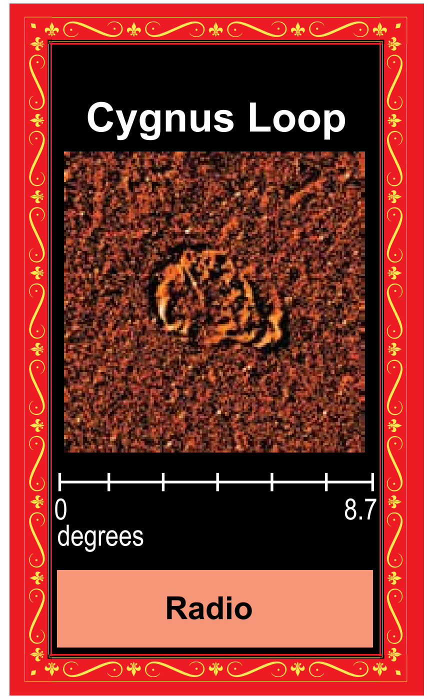

Puppis A
0
88
arcmin
X-Ray

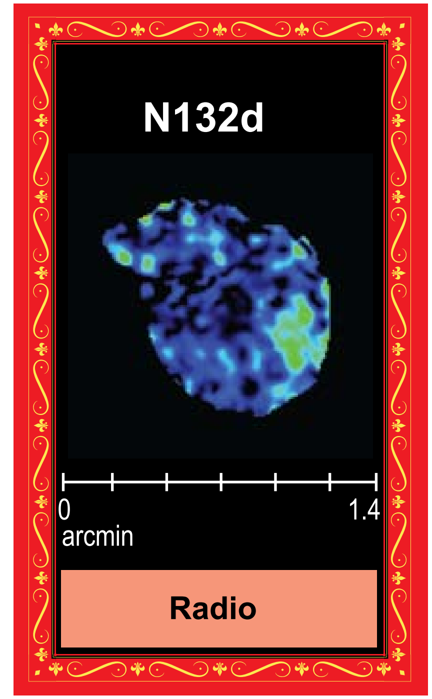

SN 1006
0
36
arcmin
X-Ray

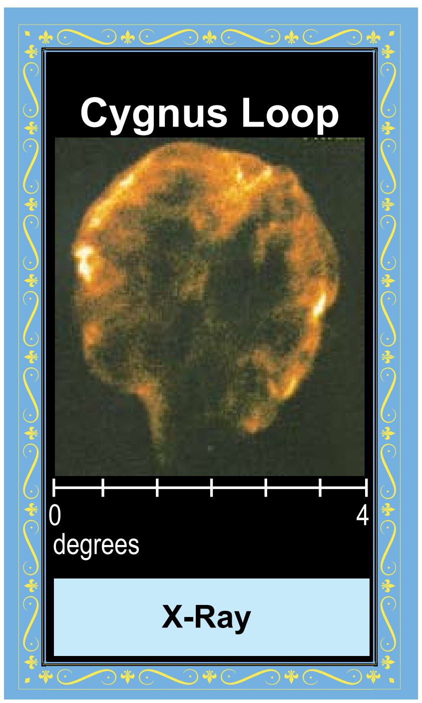

Tycho
0
9.6
arcmin
X-Ray

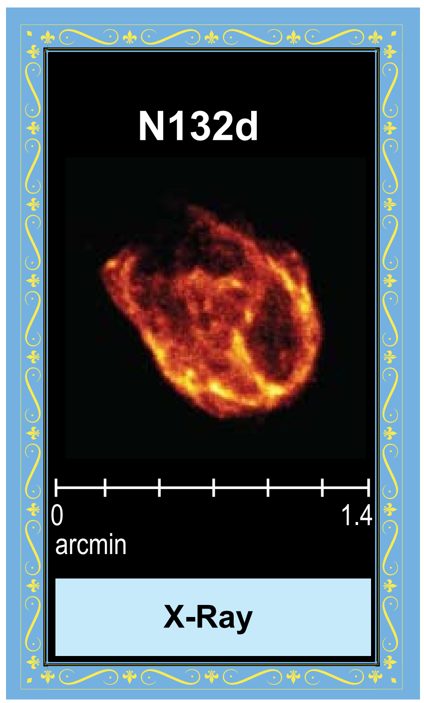

Cygnus Loop
0
3
degrees
Optical

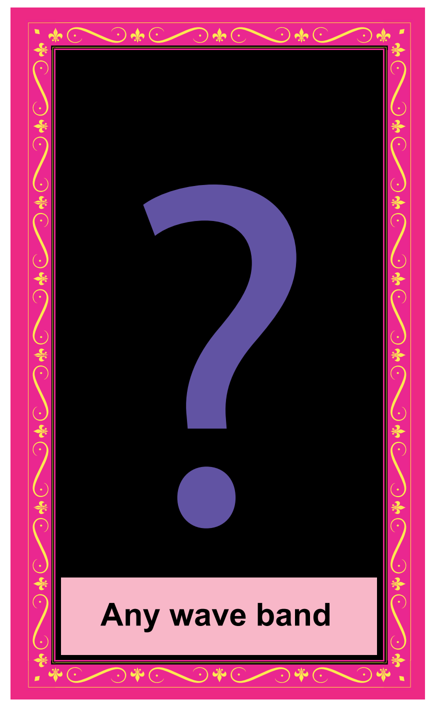

N132d
0
1.4
arcmin
Optical

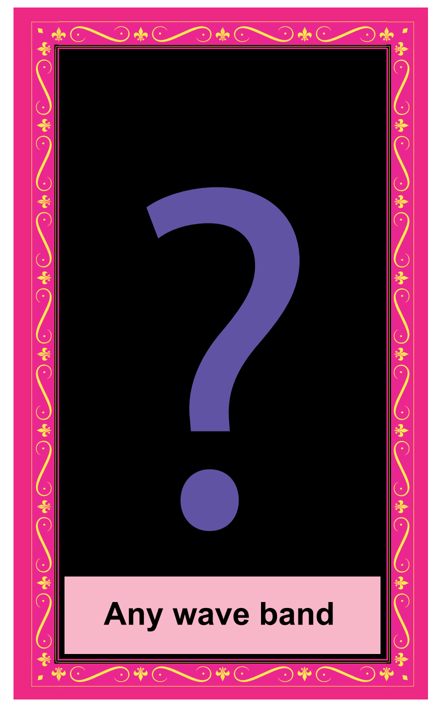

Cygnus Loop
0
8.7
degrees
Radio


N132d
0
1.4
arcmin
Radio


Cygnus Loop
0
4
degrees
X-Ray


N132d
0
1.4
arcmin
X-Ray


?
Any wave band


?
Any wave band